# Fuzzy set macroinvertebrate temperature model for Freshwater wadeable streams in Oregon and Washington

Jen Stamp, Tetra Tech (6.6.2023)

**Background**

Development of the fuzzy set temperature model for macroinvertebrate samples from freshwater wadeable streams in Oregon and Washington was an exploratory exercise spurred by a desire to distill information from the multitude of thermal preference metrics (n=33) into a numerical output that includes level of membership in classes (for example, partial membership in very cold and cold classes). Instead of assigning samples to BCG levels (USEPA 2016), the model assigns samples to temperature classes. Development of the fuzzy set temperature model was a natural extension of the calibration of the Pacific Northwest Maritime Region (PNMR) BCG model (Stamp 2022) and Oregon/Washington thermal tolerance work, which has included running a regional thermal tolerance analysis, assigning over 500 taxa to thermal preference categories (Stamp et al., in progress) and development of the Macroinvertebrate Temperature Tolerance Index (MTTI) (Hubler et al., in progress).

We don’t foresee the fuzzy set temperature model being published in peer-reviewed literature but think it could become a valuable supplement/additional line of evidence for the following applications:

* evidence for a particular thermal regime and to corroborate whether stream/riverine segments are maintaining beneficial use support of cold-water habitat required for various salmonid fish species
* identifying stream reaches that have cold water microhabitats and localized refugia that might otherwise be missed by measures of temperature alone
* identifying where thermally tolerant taxa have replaced thermally sensitive taxa, which may help determine causes of impairments (e.g., are there signals from the BMI community that biodiversity at a site is primarily thermally limited, versus other water and habitat quality factors?).
* help biologists refine hypotheses on how and where stream biota are likely to be affected by changing stream temperatures from climate change and shifting land use patterns, which will impact bioassessment indices used by Clean Water Act programs.

**Dataset**

The macroinvertebrate dataset was comprised of samples collected from freshwater wadeable streams in Oregon and Washington during a summer index period (primarily July-September, with some spillover into June and October). We used the same calibration and validation datasets (n=3289 and n= 369, respectively; Figure 1) that were used to develop the MTTI (Hubler et al., in progress). Sites ranged from valley bottoms to mountain streams, and spanned wide elevation, slope and temperature gradients. Watersheds were largely forested, with anthropogenic disturbance mostly concentrated in lower elevation areas in the Puget Lowland and Willamette Valley. Data came from a mix of sources, including state biomonitoring agencies (Oregon Department of Environmental Quality (ODEQ) and Washington Department of Ecology (WSDOE), federal agencies (U.S. EPA, U.S. Geological Survey (USGS), National Park Service (NPS), U.S. Forest Service (USFS)), the National Aquatic Monitoring Center (NAMC), and cities, counties and tribes that contribute to the Puget Sound Stream Benthos (PSSB) database. Samples were collected using either targeted-riffle (TR) or reach-wide (RW) collection protocols (Hayslip 2007) and had sampling areas of at least 0.74 square meters (8 square feet). All but USGS targeted a minimum subsample of 500 total organisms (USGS had a subsample target of 300 organisms). To harmonize the multiple datasets, regional taxonomists updated names of taxa that were affected by recent changes in taxonomic nomenclature, corrected misspellings, standardized naming schemes and checked final taxa names for concordance with current standard taxonomic effort in the Pacific Northwest (Wisseman et al. 2015).

Chart, scatter chart

Description automatically generated**Figure 1. Macroinvertebrate sampling sites used in the development of the fuzzy set temperature model (and also used in the development of the MTTI). Black dots represent the calibration sites used in MTTI model development (n=3289). Red dots represent independent validation sites (n=369).**

**Model calibration**

Taxa were assigned to thermal preference categories per Stamp et al. (in progress). There were seven thermal preference categories: cold and warm stenotherms, cold, cool, cool/warm and eurythermal. Thermal preference metrics were calculated with the BioMonTools R package (Leppo 2020; <https://github.com/leppott/BioMonTools>). For richness metrics, potentially redundant taxa (also referred to as non-distinct taxa) were not counted.

There are four temperature classes: very cold, cold, cool and warm. They are based on the Maximum Weekly Maximum Temperature (MWMT) values from the NorWeST modeled stream temperature dataset[[1]](#footnote-1) (Isaak et al. 2016, 2017), which relates to numeric water temperature standards in Oregon and Washington (16/18/20°C) (Table 1) and captures the time of the year when streams are warmest and salmonids and other aquatic biota are closest to their physiological limits. They also correspond well with community-level breakpoints in an exploratory TITAN analysis run by Sean Sullivan on the macroinvertebrate dataset (Appendix A). Streams with ‘very cold’ macroinvertebrate communities are likely to support spawning & juvenile rearing of bull trout, salmon & steelhead (< 16°C MWMT); ‘cold’ streams are likely to meet core coldwater fish habitat requirements (16-17.9°C MWMT); ‘cool’ streams are likely to support salmonid spawning, rearing, and migration (18-19.9°C MWMT); and ‘warm’ streams are expected to support indigenous warm water species (>20°C MWMT) (Table 1).

Table . Summary of Oregon and Washington regulatory temperature standards (Sturdevant 2008, Washington State 2020).

|  |  |  |  |
| --- | --- | --- | --- |
| Oregon | | Washington | |
| Beneficial Use | 7-day average maximum (°C) | Category | Highest 7-DADMax (°C)\* |
| Bull trout spawning & juvenile rearing | 12°C | Char Spawning and Rearing | 12°C |
| Salmon & steelhead spawning | 13°C |  | |
| Core coldwater habitat | 16°C | Core Summer Salmonid Habitat | 16°C |
|  |  | Salmonid Spawning, Rearing, and Migration | 17.5°C |
|  |  | Salmonid Rearing and Migration Only |
| Salmon & trout rearing & migration | 18°C | Non-anadromous Interior Redband Trout | 18°C |
| Migration corridor (salmon & steelhead) | 20°C | Indigenous Warm Water Species | 20°C |
| Lahontan cutthroat or redband trout |

\*7-DADMax = 7-day average of the daily maximum temperatures

Due to limited time and resources, in this phase of work, we were not able to work through sample worksheets with regional biologists to calibrate the model. Instead, we selected metrics and initial thresholds based on patterns in the box plots in Appendix B. We will be asking regional biologists to review fuzzy set thermal classification assignments as part of their assessments moving ahead. It will be updated as needed pending feedback we receive.

Rules for version 1 of the model are shown in Table 2. The ‘cold stenotherm + cold’ and ‘warm + warm stenotherm’ metrics were used most frequently, since they were most effective at discriminating between the four thermal classes (Appendix B). Figure 2 depicts how the fuzzy set temperature model rules work as a logical cascade (similar to a BCG model). If a sample fails any of the rules in the very cold class, it gets bumped to the cold class, and so on.

**Table 2. Rules for version 1 of the Oregon/Washington fuzzy set temperature model. The numbers in parentheses represent the lower and upper bounds of the fuzzy sets (for more details, see Appendix C).**

|  |  |  |
| --- | --- | --- |
| **Thermal class** | **Metric** | **Rule** |
| very cold | # cold stenotherm taxa | ≥ 2 (1-3) |
| # cold stenotherm + cold taxa | ≥ 6 (4-8) |
| % cold stenotherm + cold taxa | ≥ 20% (15-25) |
| % cold stenotherm + cold indiv | ≥ 5% (2-8) |
| % warm + warm stenotherm taxa | ≤ 10% (5-15) |
| % warm + warm stenotherm indiv | ≤ 5% (2-8) |
| cold | # cold stenotherm + cold taxa | ≥ 3 (1-5) |
| % cold stenotherm + cold taxa | ≥ 5% (3-7) |
| % cold stenotherm + cold indiv | ≥ 1% (0-2) |
| % cold stenotherm + cold + cool taxa | ≥ 35% (30-40) |
| % warm + warm stenotherm taxa | ≤ 15% (10-20) |
| % warm + warm stenotherm indiv | ≤ 20% (15-25) |
| cool | % warm + warm stenotherm taxa | ≤ 30% (25-35) |

Timeline

Description automatically generated with medium confidence

**Figure 2. Flow chart depicting how the fuzzy set temperature model rules work as a logical cascade**.

The quantitative output includes probability of membership (ranging from 0 to 1) in a primary and secondary class, as shown in Table 3 and described in Appendix C. A sample can be 100% assigned to a single thermal class, or tied between adjacent classes, or have a majority assigned to one class over one or more others (for example, the Test 1 sample in Table 3 is in the cool class but has partial membership in the warm class, which could indicate that the sample is starting to show signs of thermal alteration). We’ve added the fuzzy set temperature model to the BCGcalc R package (Leppo 2018; <https://github.com/leppott/BCGcalc>) and Shiny app (<https://tetratech-wtr-wne.shinyapps.io/BCGcalc/>) so that practitioners can test it with their own data[[2]](#footnote-2).

**Table 3. Example of an output from the fuzzy set temperature model.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **SampleID** | **Thermal Class** | **Primary Therm** | **Primary Membership** | **Secondary Therm** | **Secondary Membership** |
|  |
| Test 1 | Cool\_Warm | Cool | 0.67 | Warm | 0.33 |  |
| Test 2 | VeryCold | VeryCold | 1 | NA | 0 |  |

**Next steps**

This was (and still is) an exploratory exercise. Moving ahead, we’ve asked regional biologists from the Maritime NW BCG workgroup to generate fuzzy set temperature outputs and evaluate them as their workload permits, in combination with MTTI values. If there are sites in their datasets at which thermal alteration is known to have occurred, we’ll look into those to see whether the fuzzy set thermal model is able to effectively detect changes in the thermal regime at those sites over time. If the model is not performing well, pending feedback from the workgroup, we will improve it as resources permit.

**Literature cited**

Hayslip, Gretchen, editor. 2007. Methods for the collection and analysis of benthic macroinvertebrate assemblages in wadeable streams of the Pacific Northwest. Pacific Northwest Aquatic Monitoring Partnership, Cook, Washington. <https://s3.us-west-2.amazonaws.com/prod-is-cms-assets/pnamp/prod/2007_0612PNAMP_macroinvert_protocol_final.pdf>

Hubler et al., in progress. Macroinvertebrate Temperature Tolerance Index.

Isaak, D.J.; Wenger, S.J.; Peterson, E.E.; Ver Hoef, J.M.; Hostetler, S.W.; Luce, C.H.; Dunham, J.B.; Kershner, J.L.; Roper, B.B.; Nagel, D.E.; Chandler, G.L.; Wollrab, S.P.; Parkes, S.L.; Horan, D.L. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S. Fort Collins, CO: Forest Service Research Data Archive. [https://doi.org/10.2737/RDS-2016-0033.](https://doi.org/10.2737/RDS-2016-0033)

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, S. Parkes-Payne. 2017. [The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams](https://www.fs.usda.gov/treesearch/pubs/55586). Water Resources Research, 53: 9181-9205. https://doi.org/10.1002/2017WR020969

Leppo, E. 2018. BCGcalc R package (<https://github.com/leppott/BCGcalc>)

Leppo, E. 2020. BioMonTools R package (https://github.com/leppott/BioMonTools)

Stamp, J. 2022. Calibration of the Biological Condition Gradient (BCG) for Macroinvertebrate Assemblages in Freshwater Wadeable Streams in the Pacific Northwest Maritime Region of Oregon and Washington. Prepared for US EPA Office of Science and Technology and US EPA Region 10.

Stamp et al. (soon to be submitted to Ecological Indicators). Relationships between benthic macroinvertebrates and water temperature in freshwater wadeable streams in Oregon and Washington.

USEPA (US Environmental Protection Agency). 2016. [A Practitioner’s Guide to the Biological Condition Gradient: A Framework to Describe Incremental Change in Aquatic Ecosystems. Office of Water, Washington DC.](http://www.epa.gov/wqc/practitioners-guide-biological-condition-gradient-framework-describe-incremental-change-aquatic) EPA 842-R-16-001.

Wisseman, R., Sullivan, S., Pfeiffer, J. and S. Salter. 2015. Northwest Standard Taxonomic Effort.

https://www.pnamp.org/project/northwest-standard-taxonomic-effort

## Appendix A - TITAN ANALYSIS

For more information, contact Sean Sullivan (ssullivan@rhithron.com).

TITAN analysis:

* 3875 samples in the PRIME dataset with matched MWMT\_93\_11 modeled temp.
* Taxonomic data were collapsed to a ‘Coarse” OTU; which is largely Genus and species with the exceptions of Acari and Oligochaeta are left at coarse taxonomic resolution.
* Then run through a program DPAC (Cuffney *et al.* 2007; Meredith *et al.* 2019) to consolidate taxa.
* Removed any taxa not occurring in at  least 5% (193) samples ( Culled 425 taxa)
* Resulting dataset:

3875 samples

174 Taxa

Permutations and bootstraps=250

(Baker *et al.* 2015; Baker & King 2010)

Divided data to < or> 17 degrees- no additional taxa were removed from analyses. Similar to (King *et al.* 2016)

* RESULTS:

148 taxa are ‘pure and reliable’ indicators as increasers and decreasers (WHOLE DATASET)

82 (filter=1, in attached spreadsheet) Decreasers (decrease as temperature increases)

66 (filter =2, in attached spreadsheet) Increasers (increases as temperature increases)

THRESHOLDS

Filtered for Pure and Reliable TAXA ONLY

0-14 Degrees MWMT

14-17 Degrees MWMT

17-21 Degrees MWMT

>21 Degrees MWMT

Thoughts:

These values correspond semi-well with the Fish thresholds.

While the analyses presented above does not meet the ‘minimum’ bootstraps suggested by Baker et al. I think that these data present a compelling argument that the previously defined thresholds established for fish are protective of the benthic invertebrate community, and demonstrate that the categorical thresholds communicate well between fish and invertebrate….supporting our work further and that the use of an inference model, developed from WAOpt or GAM, would serve to be translated to the fish thresholds.

Chart, line chart

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Baker, M.E. & King, R.S. (2010) A new method for detecting and interpreting biodiversity and ecological community thresholds. *Methods in Ecology and Evolution* 1, 25–37.

Baker, M.E., King, R.S. & Kahle, D. (2015) TITAN2: Threshold Indicator Taxa Analysis. R package version 2.1.

Cuffney, T.F., Bilger, M.D. & Haigler, A.M. (2007) Ambiguous taxa: Effects on the characterization and interpretation of invertebrate assemblages. *Journal of the North American Benthological Society* 26, 286–307. [https://doi.org/10.1899/0887-3593(2007)26[286:ATEOTC]2.0.CO;2](https://nam10.safelinks.protection.outlook.com/?url=https%3A%2F%2Fdoi.org%2F10.1899%2F0887-3593(2007)26%5B286%3AATEOTC%5D2.0.CO%3B2&data=04%7C01%7CJen.Stamp%40tetratech.com%7C51b057986cc340cc56e708d925d56a73%7Ca40fe4baabc748fe8792b43889936400%7C0%7C0%7C637582420810073834%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=H3xX0%2F%2B8tb6tCSLN2X1Ug3%2FoPAgROPFksvFOMwgC58s%3D&reserved=0)

King, R.S., Scoggins, M. & Porras, A. (2016) Stream biodiversity is disproportionately lost to urbanization when flow permanence declines: Evidence from southwestern North America. *Freshwater Science* 35, 340–352. [https://doi.org/10.1086/684943](https://nam10.safelinks.protection.outlook.com/?url=https%3A%2F%2Fdoi.org%2F10.1086%2F684943&data=04%7C01%7CJen.Stamp%40tetratech.com%7C51b057986cc340cc56e708d925d56a73%7Ca40fe4baabc748fe8792b43889936400%7C0%7C0%7C637582420810073834%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=TIhbgebo5EZz9LwpdBVQ3XDl8mfhvFq%2BaGhI1ij%2BrnA%3D&reserved=0)

## Meredith, C.S., Trebitz, A.S. & Hoffman, J.C. (2019) Resolving taxonomic ambiguities: Effects on rarity, projected richness, and indices in macroinvertebrate datasets. Ecological Indicators 98, 137–148. [https://doi.org/10.1016/j.ecolind.2018.10.047](https://nam10.safelinks.protection.outlook.com/?url=https%3A%2F%2Fdoi.org%2F10.1016%2Fj.ecolind.2018.10.047&data=04%7C01%7CJen.Stamp%40tetratech.com%7C51b057986cc340cc56e708d925d56a73%7Ca40fe4baabc748fe8792b43889936400%7C0%7C0%7C637582420810083793%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C1000&sdata=LhsMfQyrkFkVckp3gRIdeA1KH%2FOOCJiXQJdHjAszsFI%3D&reserved=0)

## Appendix B – thermal preference box plots

Candidate thermal indicator metrics. Thermal preference assignments are described in Stamp et al. (in progress).

|  |
| --- |
| Metric |
| # cold stenotherm taxa |
| # cold taxa |
| # cool taxa |
| # cool/warm taxa |
| # warm taxa |
| # warm stenotherm taxa |
| # eurythermal taxa |
| # cold stenotherm + cold taxa |
| # cold stenotherm + cold + cool taxa |
| # cool/warm + warm + warm stenotherm taxa |
| # warm + warm stenotherm taxa |
| % cold stenotherm indiv |
| % cold indiv |
| % cool indiv |
| % cool/warm indiv |
| % warm indiv |
| % warm stenotherm indiv |
| % eurythermal indiv |
| % cold stenotherm + cold indiv |
| % cold stenotherm + cold + cool indiv |
| % cool/warm + warm + warm stenotherm indiv |
| % warm + warm stenotherm indiv |
| % cold stenotherm taxa |
| % cold taxa |
| % cool taxa |
| % cool/warm taxa |
| % warm taxa |
| % warm stenotherm taxa |
| % eurythermal taxa |
| % cold stenotherm + cold taxa |
| % cold stenotherm + cold + cool taxa |
| % cool/warm + warm + warm stenotherm taxa |
| % warm + warm stenotherm taxa |



































































## Appendix C – BACKGROUND on FUZZY SET THEORY

BCG quantitative models have been constructed for over ten different regions based on modern mathematical set theory and logic (called “fuzzy set theory”). Fuzzy set theory is directly applicable to environmental assessment and has been used extensively in engineering applications worldwide (e.g., Demicco and Klir 2004) and environmental applications have been explored in Europe and Asia (e.g., Castella and Speight 1996, Ibelings et al. 2003).

Mathematical fuzzy set theory allows degrees of membership in sets, and degrees of truth in logic, compared to all-or-nothing in classical set theory and logic. Membership of an object in a set is defined by its membership function, a function that varies between 0 and 1. To illustrate, we compare how classical set theory and fuzzy set theory treat the common classification of sediment, where sand is defined as particles less than or equal to 2.0 mm diameter, and gravel is greater than 2.0 mm (Demicco and Klir 2004). In classical “crisp” set theory, a particle with diameter of 1.999 mm is classified as “sand”, and one with 2.001 mm diameter is classified as “gravel.” In fuzzy set theory, both particles have nearly equal membership (approximately 0.5) in both classes (Demicco and Klir 2004). Very small measurement error in particle diameter greatly increases the uncertainty of classification in classical set theory, but not in fuzzy set theory (Demicco and Klir 2004). Demicco and Klir (2004) proposed four reasons why fuzzy sets and fuzzy logic enhance scientific methodology:

* Fuzzy set theory has capability to deal with “irreducible measurement uncertainty,” as in the sand/gravel example above.
* Fuzzy set theory captures vagueness of linguistic terms, such as “many,” “large” or “few.”
* Fuzzy set theory and logic can be used to manage complexity and computational costs of control and decision systems.
* Fuzzy set theory attempts to model human reasoning and decision-making, which is critically important for defining thresholds and decision levels for environmental management.

The BCG models use mathematical fuzzy logic to replicate human reasoning. Each linguistic variable (e.g., “high taxa richness”) is defined quantitatively as a fuzzy set (e.g., Klir 2004). Lower and upper (“fuzzy set”) bounds are set for each metric based on distributions of biological metrics across BCG levels. Each metric receives a membership value ranging from 0 to 1, depending on where the value falls in relation to the bounds. The rule threshold falls in the middle of these bounds. Metric values that are less than or equal to the lower bound receive a membership value of 0, while metric values that are greater than or equal to the upper bound receive a membership value of 1. In the example shown in Figure C1, the example rule for total taxa richness is ≥ 20 (15-25) (the lower bound is 15 and the upper bound is 25), which means –

* If there are 15 or fewer total taxa in the sample, the metric membership value is 0.
* If there are 25 or more total taxa in the sample, the metric membership value is 1.
* If the number of total taxa falls within the lower and upper bounds, the metric membership value will range from 0 to 1 (e.g., if there are 20 total taxa, the membership value will be 0.5; if there are 17 total taxa, the membership value will be 0.2; if there are 23 total taxa, the membership value will be 0.8).

Chart, line chart

Description automatically generated

**Figure C1. Illustration of the lower and upper (“fuzzy set”) bounds for an example metric, total taxa richness. Each metric receives a membership value ranging from 0 to 1, depending on where the value falls in relation to the bounds. In this example, the BCG rule for total taxa richness is ≥ 20 (15-25) (the lower bound is 15 and the upper bound is 25). The black dots show examples of metric membership values assigned to different metric values (e.g., if there are 20 total taxa, the metric membership value will be 0.5; if there are 17 total taxa, the membership value will be 0.2; if there are 23 total taxa, the membership value will be 0.8).**

BCG rules for a given level are typically comprised of multiple metrics (which are considered in combination). Together the rules for each BCG level work as a cascade from BCG level 1 to level 6, such that a sample is first tested against the level 1 rules; if the combined rule fails, then the level fails, and the assessment moves down to level 2, and so on. The BCG model evaluates metric membership values for all the metrics included in the rules for a given BCG level and considers the combination rules to derive the membership level for the sample. There are several different types of combination rules. If rules for two metrics are combined with an “AND” operator, then both metrics must meet the thresholds for a given BCG level (as a hypothetical example, let’s say there are two rules for BCG level 3: total taxa richness ≥ 20 AND percent sensitive taxa ≥ 10%; both conditions must be met in order for the sample to be assigned to BCG level 2). If the two rules are combined with an “OR” operator (referred to as an ‘alternate’ rule), then *either* can be true for a sample to meet the requirements (both conditions are not necessary). Another option is having a ‘best xx of xx’ rule, where not all of the metrics in a group need to be met. For example, the PNMR BCG models have ‘best two of three’ rules, where rules for only two of the three metrics need to be met in order to meet the requirements for a given BCG level. Individual metrics that comprise the BCG rules are combined into an output that shows probability of membership in a BCG level. A sample can have full membership in a single BCG level, a tie between two levels or varying memberships among two or more levels (in which case, the level with the highest membership value is taken as the nominal level). We used the following criteria when assigning BCG model ties: the difference between the primary and secondary memberships is less than 0.2 (e.g., membership of 0.54 in BCG level 2 and membership of 0.46 in BCG level 3).

1. <https://www.fs.usda.gov/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml> [↑](#footnote-ref-1)
2. to report problems, please contact Erik Leppo ([Erik.Leppo@tetratech.com](mailto:Erik.Leppo@tetratech.com)) [↑](#footnote-ref-2)