Review of Flow Duration Methods and Indicators of Flow Duration in the Scientific Literature: Hawai'i

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1.0 STATEMENT OF PURPOSE

The purpose of this review is to document methods and indicators that may be used to develop a streamflow duration assessment method (SDAM) for Hawai‘i, with an emphasis on field-based indicators and methods that distinguish ephemeral, perennial, and intermittent streams. It describes indicators proposed for testing at both baseline and validation sites across the state, following the process of Fritz et al. (2020). Additionally, information on potential study sites of known hydrology will be included, as gleaned from the existing literature, and from input from the Regional Steering Committee and other practitioners working in Hawai‘i, where possible. Literature screened for the purpose of identifying possible study sites can be found in Appendix A.

This work is part of a larger effort by the U.S. Environmental Protection Agency (EPA), working cooperatively with the U.S. Army Corps of Engineers (USACE), to develop regional SDAMs for nationwide coverage (https://www.epa.gov/streamflow-duration-assessment).

Although direct measures of flow duration (e.g., long-term records from stream gages) are usually preferred to determine whether a stream is perennial, intermittent, or ephemeral, indirect indicators of hydrology can also be used for this purpose when direct measures are unavailable or impractical to deploy (Fritz et al. 2020). Indirect indicators are generally those which are shaped by the typical hydrology of the channel, such as its geomorphology (e.g., presence of bed and bank, channel depositional features, or riffle-pool sequences), associated biology (e.g., presence and type of macroinvertebrates or presence of wetland plants), and other hydrology indicators aside from the presence of flowing water (e.g., presence of hydric soils or sediment on plants and debris). Indirect flow duration indicators have two major strengths that make them effective tools for those assessing potentially regulated waters and for aquatic resource managers. First, they are substantially less expensive to measure, typically requiring only a single site-visit, whereas stream gages require substantial installation and maintenance costs. Second, many indirect indicators reflect long-term hydrologic characteristics, integrating over space and time; thus, they provide better information about flow duration than instantaneous or short-term observations of hydrology, which may be absent during drier periods that may not reflect typical reach conditions (i.e., drought conditions).

Hawai‘i has a broad range of annual precipitation due to the influence of high elevations exposed to the prevailing northeast trade winds, which capture large amounts of orographic rainfall (Figure 1). This spatial disparity in rainfall generally means that the ‘windward’ sides of islands are usually the wettest and contain the majority of perennial streams (Parham et al. 2008), whereas the ‘leeward’ sides are drier and tend to have few to no perennial streams. At mid-elevations on windward slopes, almost 300 inches of rain on average may fall annually, while on leeward slopes, mean annual rainfall amounts may be as low as 10 to 20 inches. Fog caused by the temperature inversion of the prevailing trade winds also contributes to the water balance through substantial fog drip on forested windward mountain slopes, particularly during periods of low direct rainfall (e.g., Juvik and Perreira 1973, Scholl et al. 2002). The five largest

islands in the Hawai‘i archipelago (Kaua‘’i, O‘ahu, Moloka‘i, Maui, and Hawai‘i) have enough elevation to capture orographic rainfall, while others such as Lāna‘i, Kaho‘olawe, and Ni‘ihau are too low in elevation and have only seeps and/or ephemeral streams (Hawai‘i Cooperative Park Service Unit 1990, Valeros et al. 2020). Due to a lack of persistent freshwater, these smaller islands have small human populations or are largely uninhabited.

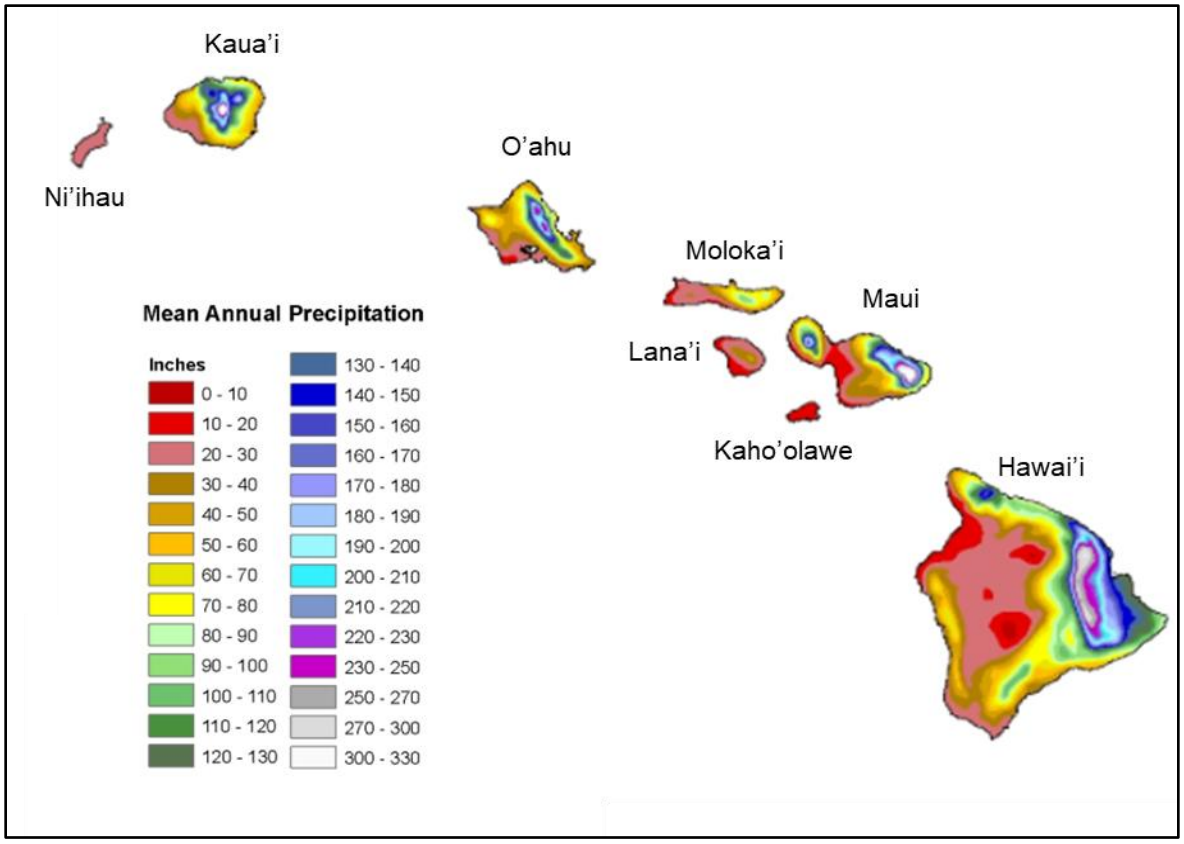


Figure 1. Annual mean precipitation for Hawai‘i, 1971-2000 (adapted from PRISM Climate Group, Oregon State University, 2006; http://prism.oregonstate.edu).

The dichotomy of windward vs. leeward when it comes to rainfall and persistence of perennial streamflow has led to a proliferation of stream diversions to support agriculture. Native Hawaiians began this practice to cultivate taro and other crops in the 15th century; however, with the spread of large sugarcane and pineapple operations in the 19th and 20th centuries came more complex diversion systems consisting of ditches and tunnels that transported water longer distances, usually from windward to leeward areas (Hawai‘i Cooperative Park Service Unit 1990). It is estimated that approximately 50% of all streams throughout Hawai‘i are diverted for agricultural use (Timbol and Maciolek 1978). Diversions can impact flow duration by greatly reducing or stopping flow entirely below the diversion, especially during periods of low flow.

Extreme elevational and rainfall gradients also lead to a broad range of vegetation types on each island, from tropical rainforest to dry grasslands to desert alpine and dry sub-alpine habitats on the highest shield volcanos (Mauna Kea and Mauna Loa on Hawai‘i and Haleakalā on Maui). Figure 2 shows native vegetation zones likely present on the Hawaiian Islands before human occupation; much of the native vegetation, especially in the lower elevations, has been replaced by non-native species.

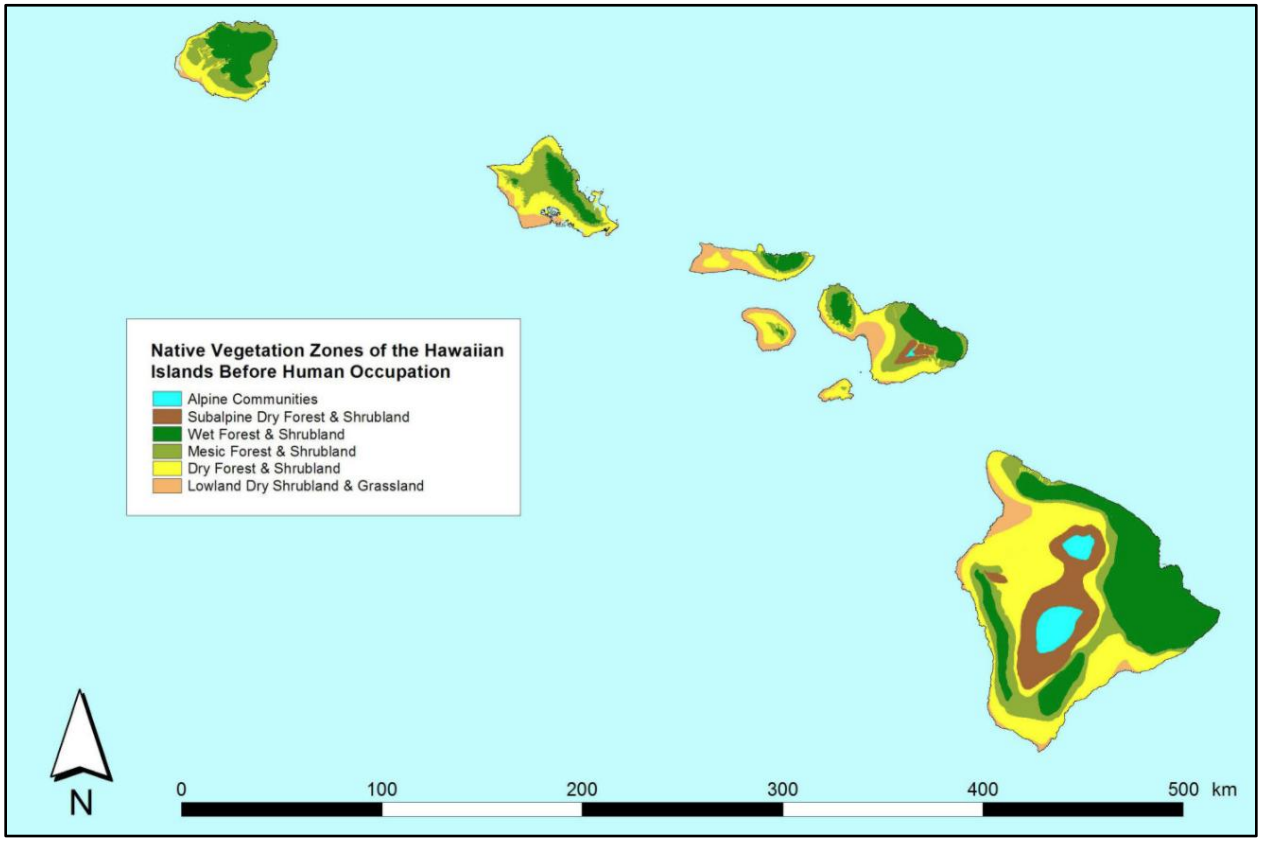


Figure 2. Native vegetation zones of the Hawaiian Islands before human occupation (from An Ecoregional Assessment of Biodiversity Conservation for the Hawaiian High Islands, the Nature Conservancy. Map adapted from Pratt and Gon 1998; http://www.Hawaiiecoregionplan.info/home.html)

2.0 METHODS

2.1 General approach

To date, all regions of the U.S. except Hawai‘i (as shown in Figure 3) have had literature reviews completed in support of the development of regional SDAMs for nationwide coverage by the agencies. These include the Arid West (AW; McCune and Mazor 2019), the Western Mountains (WM; McCune and Mazor 2020), the Great Plains (GP; James et al. 2020a), the Northeast and Southeast (NE/SE; James et al. 2020b), and Alaska (James et al. 2026). For the current literature review, existing flow duration assessment methods, regional references (e.g., primary literature, government reports), and indicators identified in previous literature reviews were reevaluated for their applicability to Hawai‘i. In addition, further queries of literature databases

were conducted to identify and evaluate additional regionally specific flow duration methods, references, and indicators that should be considered. Flow duration assessment methods evaluated for this analysis are generally limited to those with rapid field-based measurements and are not heavily dependent on modeling or streamgage data.

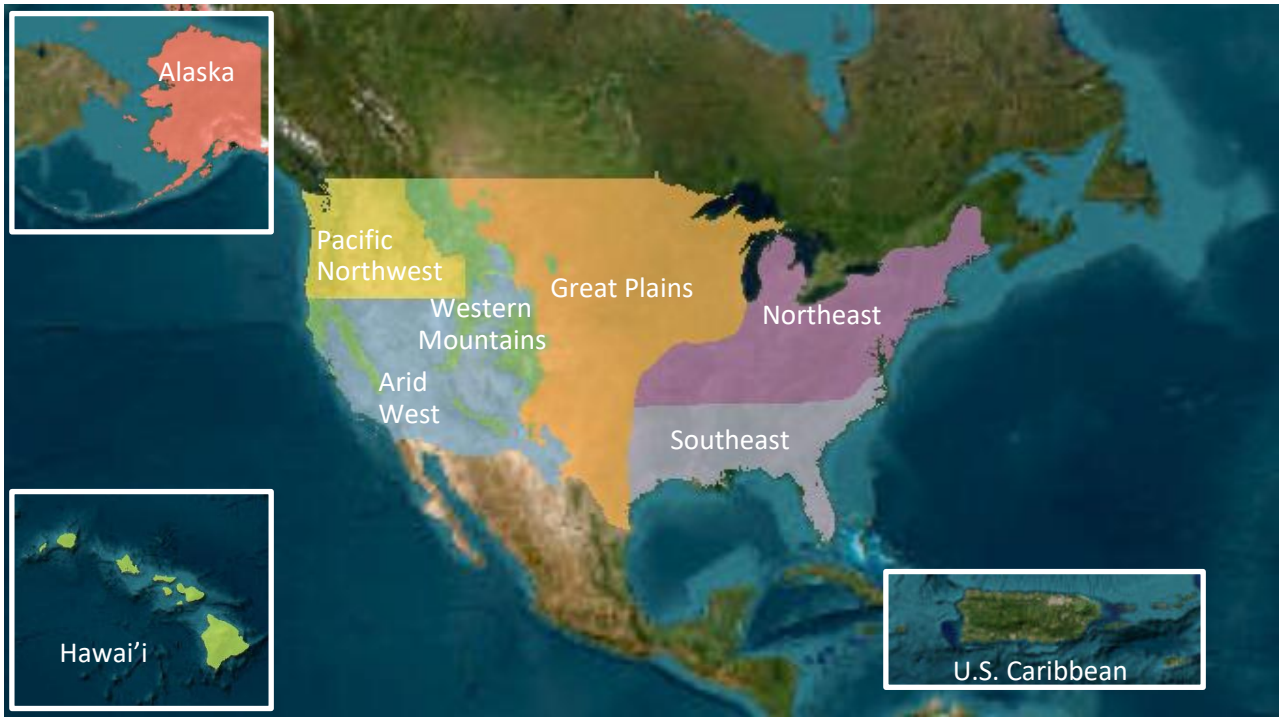


Figure 3. Map of study regions included in the development of SDAMs for use across the U.S.

As with the other regions, candidate field indicators of flow duration for Hawai'i were first identified from established flow duration methods (Figure 4). Indicators were categorized by type (geomorphology, hydrology, or biology) and endpoint used to assess the indicator (e.g., presence of perennial macroinvertebrate indicator taxa, baseflow, or depositional features). This initial set was supplemented with additional indicators whose use was supported by the scientific literature but were not incorporated into established methods. The full list of potential indicators was then evaluated for a number of key criteria:

> *Consistency*: Does it work? Is there evidence from appropriate references (see below) that the indicator can discriminate flow classes across different environmental settings, seasons, etc.? Indicators were consistent if it was used in at least two methods or showed support as a discriminatory tool in the scientific literature.
>
> *Repeatability*: Can different practitioners take similar measurements, with sufficient training and standardization? Is the indicator robust to sampling conditions (e.g., time of day)? Repeatability was assessed based on the authors' personal knowledge of field methods used to determine flow duration.

Defensibility: Does the indicator have a rational or mechanistic relationship (as a control or a response) with flow duration in the region being considered? For example, hydric soils develop in the anoxic conditions created during prolonged inundation and therefore are unlikely to be found in ephemeral streams (Cowardin et al. 1979). In contrast, substrate sorting reflects the magnitude of flow (Hassan et al. 2006), and sorting is evident in ephemeral, as well as perennial and intermittent streams.

Rapidness: Can the indicator be measured during a one-day site-visit (even if subsequent lab analyses are required)? Methods requiring multi-day visits are outside the goals of the present study.

Objectivity: Does the indicator rely on objective (often quantitative) measures? Or does it require extensive subjective interpretation by the practitioner?

For each indicator, it was also noted if there were studies demonstrating efficacy of the indicator in determining flow-duration classes, if available.

The list of potential indicators was shortened to a list of priority indicators for further evaluation if they met most of these criteria. This list was further evaluated for two additional desirable (but not essential) criteria:

Robustness: Does human activity complicate interpretation of the indicator in highly disturbed or managed settings? For example, aquatic vegetation may be purposefully eliminated from streams managed as flood control channels, limiting the value of vegetation indicators in certain environments. Although many indicators can be influenced by human activity, they may still provide value in determining flow class (particularly in undisturbed streams). Therefore, this was considered an important, but non-essential, criterion for selecting indicators for exploration.

Practicality: Can the technical team realistically sample the indicator in the present study? For example, if special permits are required for assessment or conditions too harsh, an indicator may be inappropriate for further investigation.

Based on these criteria, a final list of possible indicators of flow duration were selected as candidate indicators that can be evaluated in an SDAM development study for Hawai‘i.

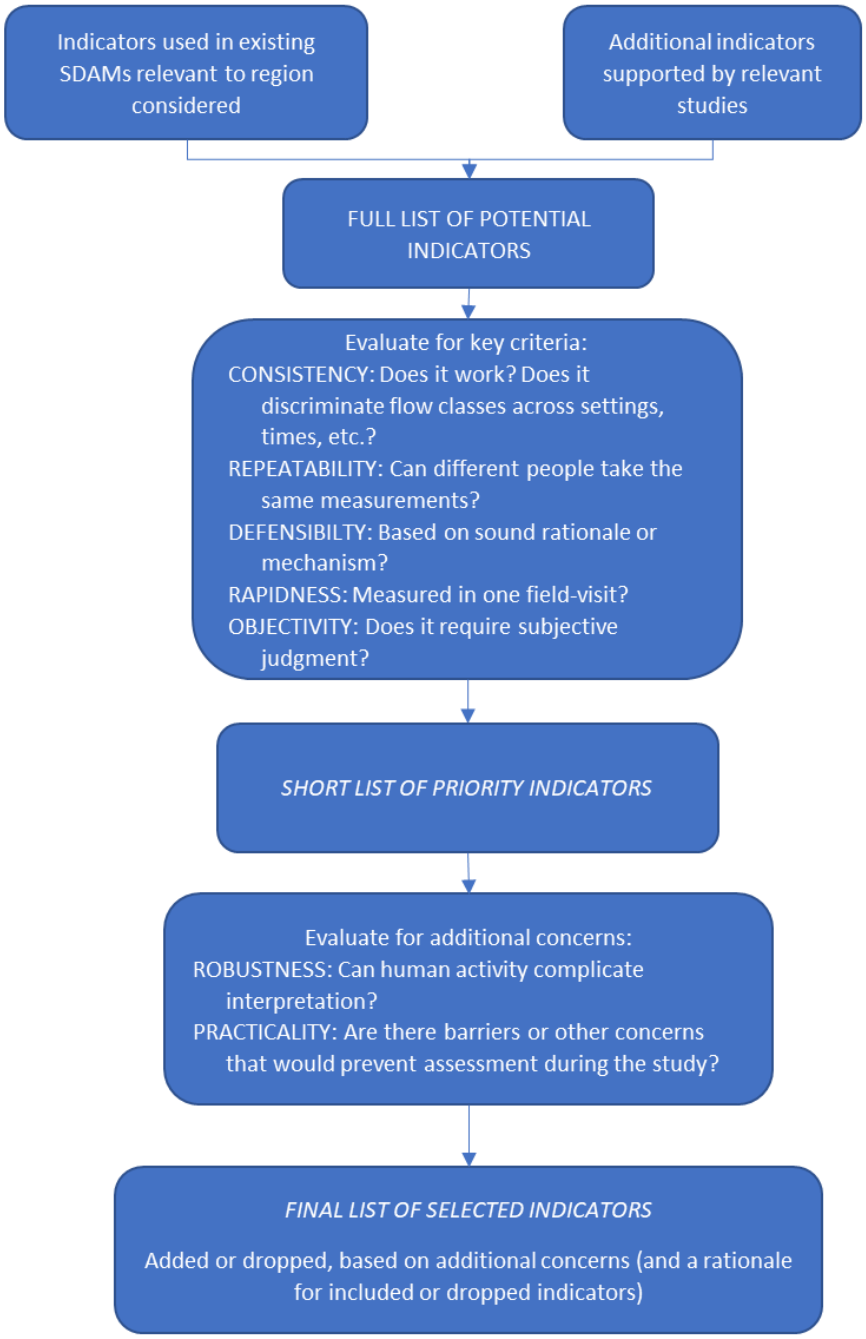


Figure 4. Process for identifying indicators of flow duration.

2.2 Search methods

First, literature identified in the previous reviews were evaluated for their relevance to Hawai‘i. These included flow duration methods from across the U.S. and elsewhere, references that could be more broadly applied across regions, and literature with data specific to Hawai‘i. These references have already been evaluated using the decision tree shown in Figure 5 for the

previous literature reviews. Therefore, no further analysis was performed on these references, unless they had information specific to Hawai‘i.

To compile a more thorough collection of Hawai‘i-specific or relevant flow duration references, additional searches using Google, Google Scholar, and Web of Science (WOS), were completed. Search engines other than WOS were used for comparison, but their results were not appreciably different or did not provide results as comprehensive as WOS. Dates of search, search terms and combinations, and number of hits for each are shown in Table 1. If the number of hits was large, only the titles or abstracts of the first 100 search results were reviewed to determine applicability to subject and Hawai‘i. This compiled library was also supplemented by appropriate sources from the personal libraries of the technical team, and input and source help from members of the Hawai‘i Regional Steering Committee and their partners.

Table 1. Search engines (WOS = Web of Science, GS = Google Scholar, Google = Google), dates, terms, and hits used to assemble literature on indicators of flow duration in Hawai‘i.

Search Source	Search Date	Key Terms	Hits
WOS	12/7/20	"Hawaii" AND ("perennial stream" OR "intermittent stream" OR "ephemeral stream" OR "dry stream" OR " interrupted stream" OR "seasonal stream" OR "temporary stream" OR "episodic stream" OR " flow permanence" OR " intermittency")	13
WOS	3/31/21	"Hawaii" AND ("macroinvertebrates" OR "amphibians") AND "stream"	8
GS	4/8/21	“Flow duration” AND (“Kauai” OR “Oahu” OR “Molokai” OR “Maui” OR “Hawaii”)	885
GS	3/31/21	“Hawaii” AND “stream” AND (“perennial” OR “intermittent” OR “ephemeral”)	42,800
GS	3/11/21	"Hawaii" AND "flow duration" AND ("macrophytes" OR "algae" OR "bryophytes" OR “riparian vegetation”)	172
GS	3/11/21	"Hawaii" AND "flow duration" AND ("macroinvertebrates" OR "fish" OR "amphibians")	237
Google	3/11/21	“Hawaii” AND “flow duration”	77,770
Google	3/11/21	“Hawaii” AND “streamflow duration” AND “indicator”	17,200
GS	3/11/21	“Hawaii” AND “hydrological connectivity” AND “stream”	202
GS	3/11/21	“Hawaii” AND “headwater” AND “intermittent stream”	151

2.3 Analysis of sources

2.3.1 Evaluating References in the Review

Applicability/Utility: Identified references were first reviewed to determine if a reference was ‘applicable’ for this analysis. Applicable sources were those that provided information about the biological, physical (i.e., geomorphological), or hydrologic characteristics of streams, preferably along a flow duration gradient in Hawai‘i. References in regions outside of Hawai‘i

were also considered applicable if other elements of the reference were relevant to the study. Common factors that limited the applicability of a citation include reliance on intensive hydrologic data (e.g., continuous streamgage data), or reliance on other data types that could not be rapidly measured in the field (e.g., model data, remote sensing inputs).

Once a reference was considered applicable, it was evaluated for inclusion in this review following the decision tree in Figure 5 and as described below.

Review: References needed to undergo peer-review, be published by a government agency, or come from a subject-matter expert.

Soundness: References needed to rely on sound scientific principles, and conclusions had to be consistent with data presented.

Clarity/Completeness: References needed to provide underlying data, assumptions, or model parameters, as well as author sponsorship or author affiliations. Several references did not provide a clear basis for determining flow-duration classes for study sites. Where possible, we applied the most appropriate flow-duration class based on available data, sometimes applying ambiguous classifications (e.g., “perennial or intermittent,” or “intermittent or ephemeral”). If data were insufficient to support these designations, the reference was excluded from the review.

Uncertainty/Variability: References needed to identify variability, uncertainties, references of error, or bias, reflecting them in any conclusions drawn. This criterion could generally be satisfied through reported ranges or measures of variability and uncertainty (e.g., standard deviation, statistical significance) associated with each indicator and flow-duration class.

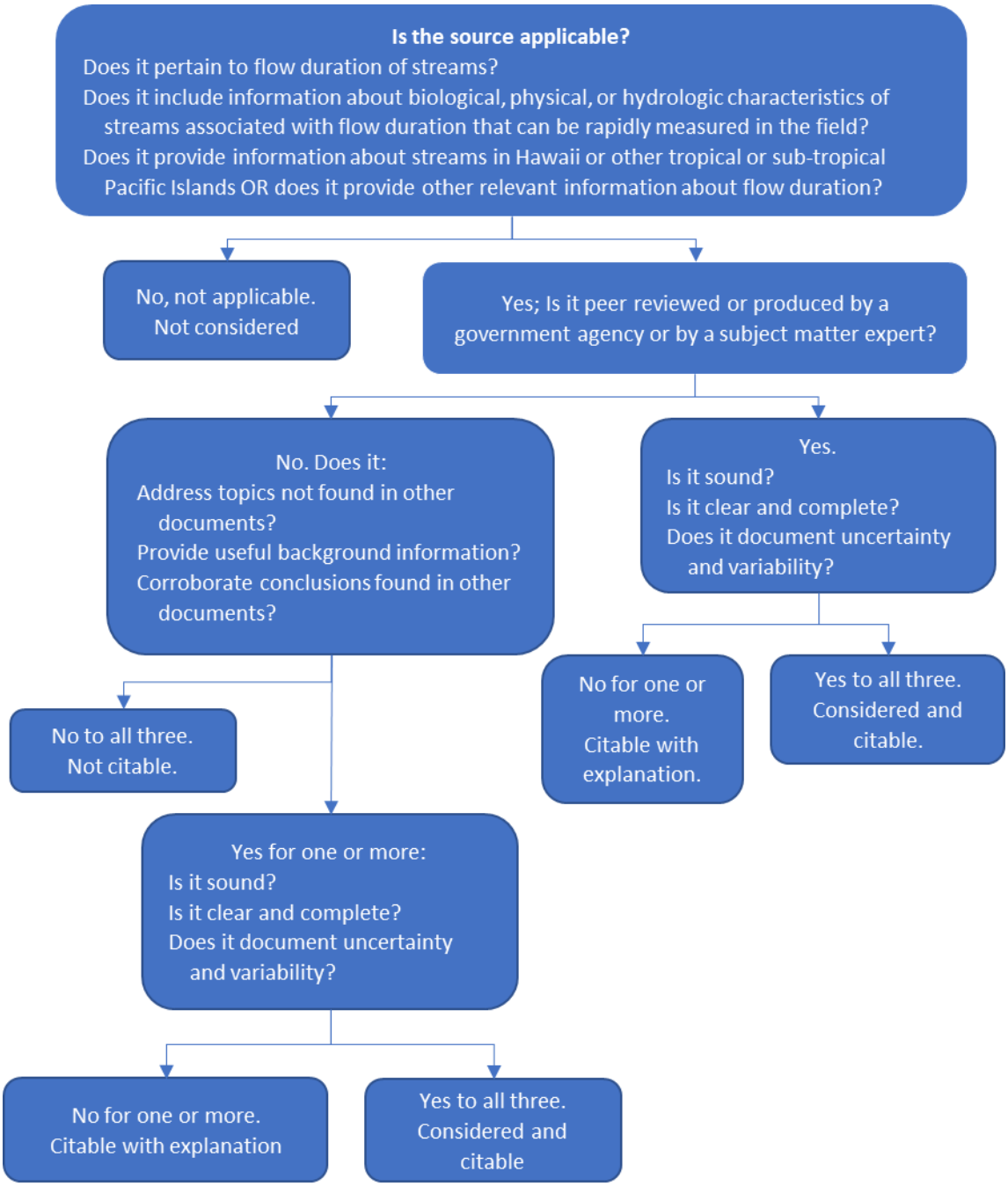


Figure 5. Decision tree for evaluating references.

2.3.2 Evaluating Information About Indicators

Each reference was reviewed to identify information about indicators of flow duration. First, the flow duration classes represented in the study were determined. Classes were either reported by the authors or determined from other data presented in the study. For example, sites were classified as perennial if year-round flow was reported. Where appropriate,

ambiguous classes were applied; for example, if a study reported that a stream dried, but the duration of the dry period was unclear, the site was classified as “ephemeral or intermittent.” Results, including text, figures, and tables, were reviewed for information about indicators associated with different flow classes.

3.0 EXISTING FLOW DURATION ASSESSMENT METHODS

Nineteen methods were considered to be appropriate for evaluating flow duration classes; two of these were developed outside of the U.S. (Table 2). No existing SDAMs appear to have been developed for use in Hawai‘i, as all U.S. SDAMs identified during this effort were developed for conterminous U.S. streams. However, methods developed for use in other parts of the U.S. were considered applicable because they included rapid field approaches for determining streamflow classes. The NC SDAM (NCDWQ 2010) has been used in Hawai‘i (Linda Speerstra, personal communication), though its ability to discern flow duration classes in Hawaiian streams has not been evaluated. Therefore, it is proposed to test NC flow duration indicators for use in Hawai‘i for this study, even if some do not meet the criteria in Section 2.1.

An additional six methods were identified from the AW, WM, or GP literature searches (Kennard et al. 2010, Trubilowicz et al. 2013, Berkowitz et al. 2011, Noble et al. 2010, Berhanu et al. 2015, and Porras and Scoggins 2013), but were excluded because they lacked a rapid field component, focusing instead on long-term records of measured or modeled flow. It is important to note that two included methods from the NE are not field methods, but primarily focus on probability modeling using regression analysis. While methods without a field component are generally outside the scope of this review, these two are included in the discussion because at least one was used to support jurisdictional determinations (though not in Hawai‘i).

Table 3 summarizes which field indicators are used with each method, whereas Table 4 summarizes the evaluation criteria for each indicator. Indicators that met all criteria were designated as priority indicators. All priority indicators are proposed for inclusion in the Hawai‘i study (see Table 4); the rationale for including non-priority indicators is provided in the table.

Table 2. Methods for assessing flow duration and their associated indicators in other regions of the U.S. and in other countries.

Reference	Geographic location	Used in Regulatory Decision-making?	Represented classes	Biological Indicators	Geomorphological Indicators	Hydrological/Other Indicators
Nadeau (2015)	Pacific Northwest (ID, OR, WA)	Yes; used by Corps Districts and EPA as supporting evidence of waters of the U.S. (WOTUS) jurisdiction	Perennial, intermittent, and ephemeral	Benthic macroinvertebrates, wetland plants, fish, amphibians/snakes Ancillary: riparian corridor	Slope Ancillary: evidence of erosion/deposition, floodplain connectivity	
Mazor et al. (2021)	Arid West (parts of AZ, CA, CO, NM, NV, TX, UT, and WY)	Beta tested until 2024; intended to be used by the Corps and EPA to support evidence of WOTUS jurisdiction once final	Perennial, intermittent, and ephemeral	Wetland (hydrophytic) plants, aquatic macroinvertebrates (# and EPT), algae (presence and % cover), fish Supplemental info: amphibians/snakes, perennial indicator macroinvertebrate taxa, iron-oxidizing fungi/bacteria		
Topping et al. (2009)	Oregon Interim SDAM	No; superseded by the OR Final SDAM (Nadeau 2011) and Pacific Northwest method (Nadeau 2015). Was primarily used to test indicators for development of a data-driven SDAM	Perennial, intermittent, and ephemeral	Wetland plants, fibrous roots and rooted plants, streamer mosses or algal mats, iron-oxidizing bacteria, fungi, flocculent material, benthic macroinvertebrates, amphibians/snakes, fish, lichen line, riparian vegetation corridor	Continuous bed and bank, in-channel structure, soil texture or stream substrate sorting, erosional features, depositional features, sinuosity, headcuts and grade controls	Groundwater/hyporheic saturation, springs and seeps, debris piles/wrack lines, evenly disbursed leaf litter/loose debris, redoximorphic features in toe of bank
McCleary et al. (2012)	Alberta, Canada ('Foothills' region)	No, guides forest management	Upland, swale, discontinuous channel, seepage-fed channel, fluvial channel	In-channel vegetation presence; plant community type (to determine soil moisture regime)	Continuous channel, presence of headcuts, pools, and 'organic bridges', bankfull width, undercut width, particle size/substrate sorting, riffle-pool sequence	Water in channel
Savage and Rabe (1979)	Idaho	No	Ephemeral, "spring streams" and permanent	Rooted vascular plants in channel, bryophytes, aquatic invertebrates, amphibians, fish	Gradient, substrate	Water in channel

Reference	Geographic location	Used in Regulatory Decision-making?	Represented classes	Biological Indicators	Geomorphological Indicators	Hydrological/Other Indicators
NC Division of Water Quality (2010; version 4.11)	North Carolina	Yes, to comply with Clean Water Act 401 ('waters of the state') and state-level rules (riparian buffers); used by Corps Wilmington District as supporting evidence of WOTUS jurisdiction	Perennial, intermittent, and ephemeral	Fibrous roots in streambed, rooted upland plants, benthic macroinvertebrates (presence and perennial indicator taxa), aquatic mollusks, fish, crayfish, amphibians, algae, wetland plants in streambed	Continuity of channel bed and bank, sinuosity, in-channel structure, streambed particle size, active/relict floodplain, depositional bars/benches, recent alluvial deposits, headcuts, grade control (natural), natural valley, 2nd or > order channel	Baseflow presence, iron oxidizing bacteria, leaf litter, organic debris drift accumulation, sediment on plants/debris, soil-based evidence of high- water table
Fritz et al. (2006)	Temperate USA (IN, KY, OH, IL, NH, NY, VT, WV, and WA)	No	Perennial, intermittent, and ephemeral	Benthic macroinvertebrates, amphibians, algal cover, algal assemblage, bryophyte assemblage, riparian canopy cover	Sinuosity, slope, depth, wetted width, depth to bedrock/groundwater table, streambed sediment moisture/size distribution	Water chemistry, habitat unit designation, water velocity, continuous hydrologic monitoring
Svec et al. (2005)	Eastern Kentucky	No	Perennial, intermittent, and ephemeral		Bankfull width, width to depth ratio, entrenchment ratio, slope, watershed area	
Ohio EPA (2012)	Ohio	Yes, as an assessment methodology for conducting use attainability analyses of primary headwater habitat streams; does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial (cold water), intermittent/ perennial (warm water), ephemeral	Fish, benthic macroinvertebrates, amphibians (salamander community), riparian zone and floodplain quality	Average bankfull width, sinuosity, stream gradient, max pool depth, number of substrate types (includes leaf litter) and percentages of most predominant types	Water in channel/flow
Fairfax County Public Works and Environmental Services (2003)*	Fairfax County, VA	Yes, to comply with VA Chesapeake Bay Preservation Act (state law enforced by local governments); does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial and intermittent	Rooted aquatic plants in streambed, benthic macroinvertebrates, EPT taxa, bivalves, fish, amphibians, periphyton/green algae, wetland plants in streambed	Continuous bed and bank, sinuosity, riffle-pool sequence, substrate sorting, active/relict floodplain, bankfull bench present, recent alluvial deposits, braided channel, natural levees, 2nd or > order channel	Presence or absence of flowing water (>48 hrs. since last rainfall), leaf litter, organic debris drift lines, sediment on plants/debris, redoximorphic soil features present in sides of channel or headcut, soil chroma

Reference	Geographic location	Used in Regulatory Decision-making?	Represented classes	Biological Indicators	Geomorphological Indicators	Hydrological/Other Indicators
James City County, Chesapeake Bay Board (2009)*	James City County, VA and tested for use in York, Gloucester and New Kent Counties, and the cities of Williamsburg and Newport News, VA	Yes, to comply with VA Chesapeake Bay Preservation Act (state law enforced by local governments); does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial and intermittent	Macrobenthos, gilled amphibians, fish	Continuity of channel bed and bank, sinuosity, in-channel structure, soil texture/depth of channel downcutting, degree of valley development, floodplain/in-channel bench, recent alluvial deposits	Groundwater discharge, leaf litter, flowing water in channel, Yorktown formation
DeBerry and Crayosky (2018)	Virginia	No; in review	Perennial	Macroinvertebrates, vertebrates (includes fish and amphibians)	Channel geometry, in-stream vegetation (indicates presence of stable depositional features)	Streamflow, streambed soils, off-site resources (e.g., interviews with residents or local professionals, county soil surveys, aerials)
Tennessee Department of Environment and Conservation (2011)*	Tennessee	Yes, to comply with TN Water Quality Control Act, as well as Clean Water Act 401 ('waters of the state') and related state-level Aquatic Resource Alteration Permit program; does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial, intermittent, wet-weather conveyance (= ephemeral)	Fibrous roots in channel, rooted upland plants in channel, macroinvertebrates, bivalves/mussels, fish, crayfish in stream, amphibians, filamentous algae and periphyton, wetland plants in channel	Continuous bed and bank, sinuous channel, in-channel structure, sorting of soil textures, active/relict floodplain, depositional bars/benches, braided channel, recent alluvial deposits, natural levees, headcuts, grade control (natural), natural valley, 2nd or > order channel	Sub-surface flow/discharge into channel, water in channel and >48 hrs. since significant rain, leaf litter in channel (January-September), organic debris drift accumulation, sediment on plants/debris, hydric soils in streambed or sides of channel, iron-oxidizing bacteria/fungus
Hansen (2001)	Western GA, NC, and SC (Chattooga River watershed)	No	Perennial, intermittent, and ephemeral	Aquatic insects	Channel definition, material movement, channel materials (includes amount of organic build-up)	Estimated flow duration, bed water level

Reference	Geographic location	Used in Regulatory Decision-making?	Represented classes	Biological Indicators	Geomorphological Indicators	Hydrological/Other Indicators
Surface Water Quality Bureau, NM Environment Department (2011)	New Mexico	Yes, as an assessment methodology for conducting use attainability analyses and to properly classify streams to satisfy NM water quality standards; does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial, intermittent, and ephemeral	**Level 1**: Fish and benthic macroinvertebrates (qualitative), filamentous algae and periphyton, riparian vegetation, rooted upland plants in streambed, iron oxidizing bacteria/fungi. **Level 2**: fish and benthic macroinvertebrates (quantitative), EPT taxa, bivalves, amphibians	**Level 1**: Sinuosity, floodplain and channel dimensions, channel structure, particle size or stream substrate sorting	**Level 1**: Water in channel, hydric soils, sediment on plants or debris, seeps/springs. **Level 2**: water in channel (logged data), hyporheic zone/groundwater table
Gallart et al. (2017)	Mediterranean Europe	No	Intermittent-pools, intermittent-dry, episodic-ephemeral, perennial; Hyperrheic, eurheic, oligorheic, arheic, hyporheic/dry			Hydrologic metrics (based on modeled or recorded flow), citizen observations
Straka et al. (2019)	Czech Republic	No	Intermittent, near-perennial, and perennial	Benthic macroinvertebrates		
Bent and Steeves (2006)	Massachusetts (excluding SE coast)	No	Perennial and intermittent			Not field based — variables in equation: drainage area, areal % of sand and gravel deposits, areal % of forest land, and region (east or west)

Reference	Geographic location	Used in Regulatory Decision-making?	Represented classes	Biological Indicators	Geomorphological Indicators	Hydrological/Other Indicators
Olson and Brouillette (2006)	Vermont	Used as evidence in jurisdictional determinations conducted under Vermont statute that a stream is perennial or intermittent; does not appear to be used by Corps Districts to support WOTUS jurisdiction	Perennial and intermittent			Not field based – variables in equation: drainage area, site elevation, ratio of basin relief to basin perimeter, and areal % of well and moderately well-drained soils in the basin

* Derived from the North Carolina DWQ method (may be from an earlier version than that cited in this document)

Table 3. Summary of indicators included in flow-duration field assessment methods described in Table 2.

Indicator	Pacific Northwest	Arid West	Oregon Interim Method	Alberta (Foothills)	Idaho	North Carolina	Temperate USA	Kentucky	Ohio	Fairfax County, VA	James City County, VA	Virginia	Tennessee	Western GA, NC, SC	New Mexico (Phase 1)	New Mexico (Phase 2)	Mediterranean	Czech Republic
Geomorphology																		
Bankfull width and/or depth				X			X	X	X									
Maximum pool depth							X		X									
Continuous bed and banks presence/consistent in-channel geometry			X	X		X				X	X	X	X	X				
Undercut width				X														
Depositional or erosional features in the channel (e.g., bankfull benches or depositional bars)			X			X				X	X	X	X					
Depositional or erosional features on the floodplain (e.g., recent alluvial deposits, natural levees)						X				X	X		X					
Distinct substrate composition in streambed from adjacent uplands (particle size or substrate sorting/movement)			X	X	X	X	X			X	X		X	X	X			

Indicator	Pacific Northwest	Arid West	Oregon Interim Method	Alberta (Foothills)	Idaho	North Carolina	Temperate USA	Kentucky	Ohio	Fairfax County, VA	James City County, VA	Virginia	Tennessee	Western GA, NC, SC	New Mexico (Phase 1)	New Mexico (Phase 2)	Mediterranean	Czech Republic
Entrenchment ratio (floodplain/channel dimension)							X	X							X			
Evidence of active or relict floodplain						X				X			X					
Presence of natural valley/degree of development						X					X		X					
Presence of headcuts			X	X		X	X						X					
In-channel structure/sequences of erosional and depositional features (e.g., riffle-pool, step-pool)			X	X	X	X	X			X	X		X		X			
Presence of a braided channel										X			X					
Presence of natural grade control						X							X					
Stream order					X	X							X					
Sinuosity			X			X	X		X	X	X		X		X			
Slope/Gradient	X			X	X		X	X	X									
Organic bridge				X														
Hydrology																		
Continuous logged data							X									X		
Groundwater observation			X			X	X		X		X		X		X			
Distribution/presence of leaf litter/packs or other organic debris			X			X	X		X	X	X		X	X				
Soil-based evidence of high-water table—can include hydric soils/soil chroma, redoximorphic features, or organic streaking			X			X				X		X	X		X			
Modeled hydrology																	X	
Observed aquatic state (e.g., presence or level of water in channel)/observation of baseflow				X	X	X	X		X	X	X		X	X	X	X	X	
Reported aquatic state from interviews or off-site resources												X					X	
Observed or reported soil saturation			X				X		X						X		X	
Presence of wrack or drift lines			X			X				X			X					
Sediment deposition on plants or debris						X				X			X		X			
Presence of seeps and springs			X		X										X			

Indicator	Pacific Northwest	Arid West	Oregon Interim Method	Alberta (Foothills)	Idaho	North Carolina	Temperate USA	Kentucky	Ohio	Fairfax County, VA	James City County, VA	Virginia	Tennessee	Western GA, NC, SC	New Mexico (Phase 1)	New Mexico (Phase 2)	Mediterranean	Czech Republic
Iron-oxidizing bacteria or fungi[1]		X	X			X							X		X			
Velocity							X											
Presence of geological formation that contributes to baseflow (Yorktown formation)											X							
Biology																		
Algae (includes alive or dead algal mats)/periphyton		X	X		X	X	X			X			X		X			
Lichen line			X[5]															
Bryophytes (includes streamer mosses)			X		X		X											
Fibrous roots in channel						X							X					
Wetland or aquatic vegetation in channel/immediate vicinity	X	X	X	X	X	X				X			X					
Upland vegetation in channel			X	X		X							X		X			
Distinct riparian corridor/differences in vegetation			X[5]												X			
Aquatic macroinvertebrates[2] – Presence/Ease of Detection and/or Abundance and/or Diversity[3]	X	X	X			X	X		X	X	X			X	X	X		
Aquatic macroinvertebrates[4] - Indicator taxa (e.g., EPT taxa)	X	X	X		X	X			X	X		X	X			X		X
Aquatic macroinvertebrates – Traits																		X
Crayfish/Crustacean – Presence and/or Abundance[3]						X							X					
Amphibians – Presence and/or Abundance and/or Diversity[3]	X		X		X	X	X		X	X	X	X	X			X		
Amphibians – Indicator Taxa	X	X					X		X									
Reptiles – Presence or Indicator Taxa	X	X	X															
Aquatic Mollusks/Bivalves – Presence/Ease of Detection and/or Abundance[3]						X				X			X			X		
Fish – Presence/Ease of Detection and/or Abundance and/or Diversity (of life stages, generally)[3]	X	X	X			X			X	X	X	X	X		X	X		
Fish –Indicator taxa					X				X									

[1] This indicator is included in the biological category in the Oregon Interim and Tennessee methods but is considered a hydrology indicator in the North Carolina method (non-categorized supplemental indicator in NM and AW methods). The presence of iron-oxidizing bacteria or fungi generally reflects the presence of groundwater inputs, so it has been included in the hydrology category for this literature review.

[2] Other aquatic invertebrate taxa are evaluated separately in the NC and TN methods (crayfish and mollusks/bivalves) and the Fairfax County method (bivalves)
[3] Indicator scoring or evaluation is often a composite of presence/absence, abundance, and/or diversity depending on the method; therefore, these metrics were combined for this table.
[4] Includes aquatic insects and worms as well as aquatic mollusks (snails and mussels)
[5] Only used in arid and/or alpine areas for this method

Table 4. Evaluation criteria (see Section 2.1) for indicators identified in the literature review.

Indicator	Consistency	Repeatability	Defensibility	Rapidness	Objectivity	**Priority Indicator**	Robustness	Practicality	**Proposed**
Geomorphology									
Bankfull width and/or depth	X	X		X	X	No	X	X	**Yes[2]**
Maximum pool depth	X	X		X	X	No	X	X	**Yes[2]**
Continuous bed and banks presence/consistent in-channel geometry	X	X		X		No	X	X	**Yes[1]**
Undercut width		X		X	X	No	X	X	**No**
Depositional or erosional features in the channel (e.g., bankfull benches or depositional bars)	X	X		X		No		X	**Yes[1]**
Depositional or erosional features on the floodplain (e.g., recent alluvial deposits, natural levees)	X	X		X		No		X	**Yes[1]**
Distinct substrate composition in streambed from adjacent uplands (particle size or substrate sorting/movement)	X	X		X		No	X	X	**Yes[1]**
Entrenchment ratio (floodplain/channel dimension)	X	X		X	X	No		X	**Yes[2]**
Evidence of active or relict floodplain		X		X		No	X	X	**Yes[1]**
Presence of natural valley/degree of development	X	X		X		No		X	**No**
Presence of headcuts	X	X		X	X	No	X	X	**Yes[1]**
In-channel structure/sequences of erosional and depositional features (e.g., riffle-pool, step-pool)	X	X		X		No	X	X	**Yes[1]**
Presence of a braided channel	X			X		No		X	**No**
Presence of natural grade control	X	X		X		No		X	**Yes[1]**
Stream order	X	X		X	X	No		X	**No**
Sinuosity	X	X		X	X	No	X	X	**Yes[1]**
Slope/Gradient	X	X	X	X	X	Yes	X	X	**Yes**
Organic bridge		X		X		No		X	**No**
Hydrology									
Continuous logged data	X	X	X		X	No	X		**No**
Groundwater observation	X	X	X		X	No	X		**No**
Distribution/presence of leaf litter/packs or other organic debris	X	X		X		No		X	**Yes[1]**
Soil-based evidence of high-water table—can include hydric soils/soil chroma, redoximorphic features, or organic streaking	X	X	X	X	X	Yes	X	X	**Yes**
Modeled hydrology	X	X	X		X	No	X		**No**
Observed aquatic state (e.g., presence or level of water in channel)/observation of baseflow	X	X	X	X	X	Yes		X	**Yes**
Reported aquatic state from interviews or off-site resources		X	X		X	No	X		**No**
Observed or reported soil saturation		X	X	X	X	No		X	**No**
Presence of wrack or drift lines	X	X		X		No		X	**Yes[1]**
Sediment deposition on plants or debris	X	X		X	X	No	X	X	**Yes[1]**
Presence of seeps and springs	X	X	X	X	X	Yes	X	X	**Yes**
Iron-oxidizing bacteria or fungi[1]	X	X	X	X	X	Yes	X	X	**Yes**

Indicator	Consistency	Repeatability	Defensibility	Rapidness	Objectivity	**Priority Indicator**	Robustness	Practicality	**Proposed**
Velocity		X		X	X	No	X	X	**No**
Presence of geological formation that contributes to baseflow (Yorktown formation)	X		X	X		No		X	**No**
Biology									
Algae (includes live or dead algal mats)/periphyton	X	X	X	X	X	Yes		X	**Yes**
Lichen line		X	X	X	X	No		X	**No**
Bryophytes (includes streamer mosses)	X	X	X	X	X	Yes		X	**Yes**
Fibrous roots in channel	X	X		X		No		X	**Yes[1]**
Wetland or aquatic vegetation in channel	X	X	X	X	X	Yes		X	**Yes**
Upland vegetation in channel	X	X	X	X	X	Yes		X	**Yes**
Distinct riparian corridor/differences in vegetation	X	X	X	X	X	Yes		X	**Yes**
Aquatic macroinvertebrates – Presence/Ease of Detection and/or Abundance and/or Diversity	X	X	X	X	X	Yes	X	X	**Yes**
Aquatic macroinvertebrates - Indicator taxa (e.g., EPT taxa)	X	X	X	X	X	Yes		X	**Yes**
Aquatic macroinvertebrates – Traits	X	X			X	No	X	X	**No**
Crayfish/Crustaceans – Presence and/or Abundance	X	X	X	X	X	Yes	X	X	**Yes**
Amphibians – Presence and/or Abundance and/or Diversity	X	X	X	X	X	Yes	X	X	**Yes**
Amphibians – Indicator Taxa	X	X	X	X	X	Yes		X	**Yes**
Reptiles – Presence	X	X	X	X	X	Yes	X	X	**Yes[3]**
Aquatic Mollusks/Bivalves – Presence/Ease of Detection and/or Abundance	X	X	X	X	X	Yes	X	X	**Yes**
Fish – Presence/Ease of Detection and/or Abundance and/or Diversity (of life stages, generally)	X	X	X	X	X	Yes		X	**Yes**
Fish – Indicator taxa		X	X		X	No			**No**
Additional indicators from primary literature									
Hydrology									
Dissolved O_2 *		X		X	X	No		X	**No**
Water column organic C[+]		X		X	X	No		X	**No**
Woody jams[§]		X	X	X	X	No	X	X	**No**
Windward vs. leeward	X	X	X	X	X	Yes		X	**Yes**
Biology									
Diatom abundance[+]		X			X	No			**No**
Bird abundance[+]		X			X	No			**No**
Terrestrial arthropods[+]		X	X	X	X	No			**No**
Canopy cover[+]	X	X		X	X	No		X	**No**
Riparian vegetation – diversity[+]	X	X	X		X	No			**No**
Microbial diversity[+]		X	X		X	No			**No**

1: Non-priority indicator proposed for inclusion because it is used by the North Carolina Method (NCDWQ 2010)

2: Non-priority indicator proposed for inclusion because studies identified in Section 3 or 4 suggest a potential relationship with flow duration

3: Freshwater reptiles are limited to introduced turtles on the Hawaiian Islands

* Identified in both AW and WM literature reviews

+ Identified in AW literature review

§ Identified in WM literature review

3.1 Pacific Northwest (PNW)

For purposes of classifying perennial, intermittent and ephemeral streams in the Pacific Northwest (PNW), Nadeau (2015) developed a method that uses five biological and physical indicators: 1) presence of aquatic macroinvertebrates; 2) number of mayflies (order Ephemeroptera); 3) presence of perennial aquatic macroinvertebrate indicator taxa from Mazzacano and Black (2008) or Blackburn and Mazzacano (2012); 4) presence of wetland indicator plants (specifically, SAV, FACW, or OBL) as determined from regionally appropriate wetland plant lists; and 5) reach slope. Single indicators such as the presence of fish and aquatic stages of amphibians may result in an "at least intermittent" classification. Ancillary indicators, such as evidence of sediment erosion or deposition, are also considered as contextual support for the flow duration determination. Indicators are measured objectively, without requiring subjective or qualitative visual assessments by practitioners. This data-driven method resulted from a three-state study (Idaho, Oregon, and Washington; Nadeau et al. 2015) of the Oregon Interim Method (Topping et al. 2009; see 3.2).

Indicators are evaluated with a simple branching flow-chart (Figure 6), and not all indicators are needed to make a flow duration determination at every site. Consequently, it is among the simplest tools to implement. This method strongly emphasizes biological indicators, including only one geomorphological indicator (slope) and no hydrological indicators.

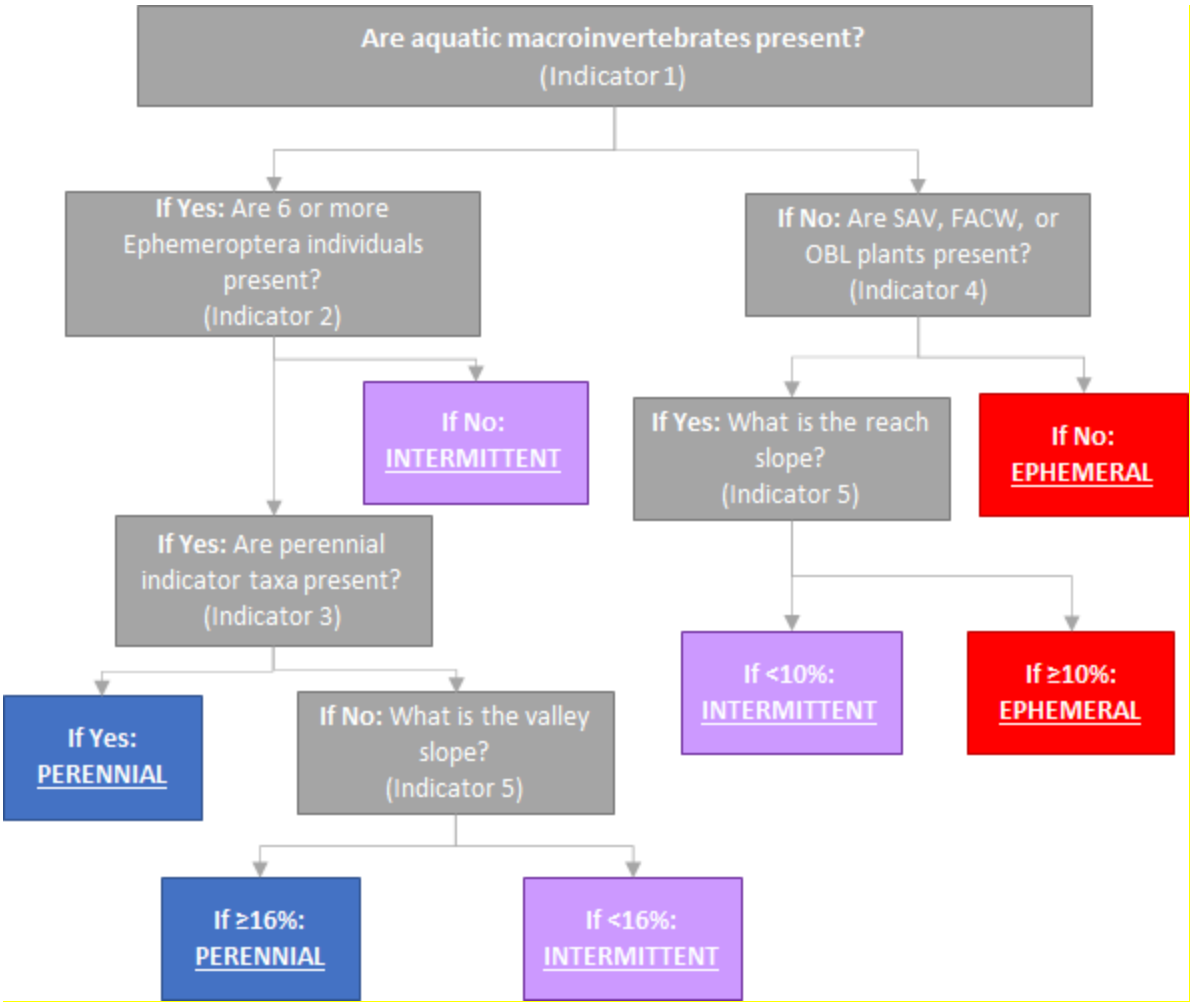


Figure 6. Decision tree used to determine streamflow duration class in the Pacific Northwest method (adapted from Nadeau 2015).

3.2 Arid West (Beta)

This method (Mazor et al. 2021) is the first produced as part of the regional SDAM expansion effort described in Section 1, developed cooperatively by the EPA and USACE and using the process outlined in Fritz et al. (2020). Based on the statistical results of field sampling, five biological indicators were found to support a determination of a stream's flow duration in the Arid West:

1) How many hydrophytic plant species are growing in the channel, or within one half-channel width of the channel?
2) How many aquatic macroinvertebrate individuals are found?
3) Is there evidence of aquatic stages of EPT taxa?
4) Are algae found on the streambed?

5) Are single indicators (i.e., the presence of fish or ≥10% algal cover) of intermittent or perennial streamflow duration observed?

The first four indicators are evaluated together to assign a preliminary flow duration class; the presence of single indicators as shown in #5 above determine that a reach is at least intermittent, either supporting or superseding the preliminary flow class from indicators 1-4. Field-measured indicator data is fed through the decision matrix shown in Figure 7, going from left to right, to determine a classification (Note, figure updated to show 2023 version which corrects classification errors found in the original analysis).

Table 5. Streamflow classifications based on field-measured indicator data in the Arid West SDAM (Mazor et al. 2023)

1. Hydrophytic plant species	2. Aquatic invertebrates	3. EPT taxa	4. Algae	5. Single indicators • fish present • algae cover ≥ 10%	Classification
None	None	Absent	Absent	Absent	**Ephemeral**
				Present	**At least intermittent**
			Present		**Intermittent**
	Few (1-19)	Absent	Absent	Absent	**Less than Perennial**
				Present	**At least intermittent**
			Present		**At least intermittent**
		Present	Absent		**Intermittent**
			Present		**Perennial**
	Many (20+)	Absent	Absent	Absent	**Ephemeral**
				Present	**At least intermittent**
			Present	Absent	**Ephemeral**
				Present	**At least intermittent**
		Present			**Intermittent**
Few (1-2)	None				**Intermittent**
	Few (1-19)	Absent			**Intermittent**
		Present	Absent		**Intermittent**
			Present		**Perennial**
	Many (20+)	Absent			**Intermittent**
		Present	Absent		**Perennial**
			Present		**Intermittent**
Many (3+)	None				**Intermittent**
	Few (1-19)	Absent	Absent		**Intermittent**
			Present		**Perennial**
		Present			**Perennial**
	Many (20+)				**Perennial**

As with Nadeau (2015), not all indicators are needed to make a classification at every site, as the blanks in Figure 7 show. An outcome of 'less than perennial' is also possible, which usually occurs when classifications of ephemeral and intermittent cannot be distinguished with confidence based on the five primary indicators. However, supplemental information can also be collected as part of the AW SDAM field protocol and used as evidence of longer-duration flows, including the presence of the following: 1) aquatic life stages of amphibians or reptiles; 2) aquatic invertebrates that prefer perennial streams (requires family-level identification); and 3) iron-oxidizing bacteria/fungi.

3.3 Interim Oregon Method

Prior to the development of the method of Nadeau (2015) for the Pacific Northwest, Topping et al. (2009) developed an Interim SDAM for Oregon similar to the NC method that evaluates a series of geomorphological, hydrological, and biological indicators as absent, weak, moderate, or strong. In general, the strength of the indicator is considered evidence of longer flow durations. Each indicator is scored and summed; if the total score is below 13, the stream is considered ephemeral, and if the total score is above 25, the stream is considered perennial. Single indicators (e.g., presence of fish, amphibians, or aquatic macroinvertebrates) may override an "ephemeral" classification. In contrast to Nadeau (2011, 2015), assessing the strength of the indicators requires subjective visual assessments by practitioners.

Note that the release of the data-driven Final Streamflow Duration Assessment Method for Oregon (Nadeau 2011) superseded the use of the Interim Method in Oregon; the Final Oregon Method was, in turn, superseded by the substantively similar Streamflow Duration Assessment Method for the Pacific Northwest (Nadeau 2015) as a result of a three-state validation study (Nadeau et al. 2015).

3.4 Alberta, Canada (Foothills)

This method was developed for use in the forested Foothills region of Alberta to assign erosion-based stream classifications to headwater streams to better inform forest management decisions (McCleary et al. 2012). These classifications are largely based on dominant surface erosion processes, which are often driven by degree of flow permanence. The classes align with traditional flow duration categories as shown in Table 6.

Table 6. Erosion-based stream classes and corresponding flow duration class (adapted from McCleary et al. 2012).

Class	Best corresponding flow duration class	Class Description
Upland	Upland (none)	Surface erosion driven by overland flow and tree root throw; no depression or surface water present; usually vegetated, with non-hydrophytic species.
Swale	Ephemeral	Historic channel migration removed material and created a depression. Feature is vegetated, with hydrophytic species.
Discontinuous channel	Intermittent	Includes alternating sections of channel and vegetated ground. Channel may be actively migrating upstream or in recovery with encroaching vegetation, but vegetation will usually be limited or absent in the channel itself.
Seepage-fed channel	Intermittent, transitional, or small permanent	Channel with a continuous bed but insufficient stream power to transport larger streambed material; therefore, these channels generally lack typical bed features (e.g., regular riffle-pool sequence).
Fluvial channel	Small or large permanent	Channel with a continuous bed and sufficient amount of power to transport most material endemic to the area.

Simple observations (type, presence/absence of vegetation, continuity of channel) are used to distinguish the first two stream classes (not including upland) from each other and seepage-fed and fluvial channels. For seepage and fluvial channels, the indicators shown in Figure 7 are used to determine the class. This method is a simple way to distinguish ephemeral and discontinuous intermittent streams; however, for continuous channels, it is not able to distinguish intermittent from perennial streams.

Feature number	Seepage-fed channel features	Fluvial channel features
1	Fine bed material collected from deepest part of channel is mostly silt and organic matter. If required, use a hand texturing procedure to confirm[a].	Fine bed material collected from deepest part of channel is mostly well-sorted sand. If required, use a hand texturing procedure to confirm[a].
2	Unconsolidated bed along the deepest part of channel. Indicated if when standing on one foot, the surveyor's boot sinks to a depth > 10 cm.	Consolidated channel bed. Indicated if the surveyor's boot does not sink to a depth of > 10 cm.
3	No steps / riffles created by mobile gravel or cobbles[b].	Steps / riffles with regular spacing created by mobile gravel or cobbles[b].
4	No pools present[b].	Pools present with regular spacing[b].
5	Organic bridges present[b].	No organic bridges present[b].
6	Head cuts present[b and c].	No head cuts present[b and c].
7	Maximum bankfull width[d] >3x the minimum width.	Maximum bankfull width[d] <3x the minimum width.
8	Total undercut width[e] > bankfull width.	Total undercut width[e] < bankfull width.
Total	**See Section 3.1 for interpreting tally**	**See Section 3.1 for interpreting tally**

Figure 7. Characteristics of seepage-fed and fluvial channels in McCleary et al. (2012). Subscripts in original and provide details on the field methods.

3.5 Idaho

Savage and Rabe (1979) classified lower order (1°-4°) streams in Idaho (and applicable to other Rocky Mountain states) based on physical, chemical, and biological differences. The five stream classes include ephemeral, spring-fed, and three types of permanent streams (categorized as '1', '2', and '3'). Ephemeral streams are described as only containing water during high runoff, though this characteristic appears to be the only one used to distinguish it from the other classes. Spring-fed streams have a major spring source, with little seasonal variation in discharge (likely perennial). The different types of permanent streams are largely distinguished by gradient (expressed as bedform pattern, e.g., riffle-pool vs. meandering-glide) and type of substrate. 'Permanent' streams, as described by the authors, have high seasonal variation in flow volume and intermittency, especially in the summer months, which appears to indicate that truly 'intermittent' streams are likely included in this category with non-spring-fed perennial streams. The biological community of the three types of permanent streams is also characterized, including vascular plants, algae, liverworts, benthic macroinvertebrates, amphibians, and fish. However, because intermittent streams are not separated from perennial streams in the permanent stream class, this system has low utility as a flow duration method.

3.6 North Carolina

This method, developed by the North Carolina Division of Water Quality (2010), includes 9 biological, 11 geomorphic, and 6 hydrologic indicators to determine if a stream is perennial, intermittent, or ephemeral, as well as to designate locations in the landscape as origins of streamflow, or sinks where flow ceases. Indicators are scored to yield an index, with more indicators (or more robustly evident indicators) yielding a higher score. Scores for each indicator range from 0 to 3 or 0 to 1.5 depending on whether it is primary or secondary and are generally allocated using the descriptors in Figure 8, though some indicators have 'yes' or 'no' answers instead of a range. To be considered at least intermittent, a stream reach must score at least a 19 or above, with scores at 30 or above indicative of a perennial channel. Scores less than 19 indicate the channel is ephemeral. However, the presence of specific taxa (fish, crayfish, amphibians, or clams) or more than one benthic macroinvertebrate that requires water for their entire life cycle (later instars of certain aquatic insect and mollusca families) can also result in a perennial designation, even if scores are low.

Category	Description
Absent	The character is not observed
Weak	The character is present but you have to search intensely (i.e., ten or more minutes) to find and evaluate it
Moderate	The character is present and observable with brief (i.e., one or two minutes) searching and evaluation
Strong	The character is easily observable and quickly evaluated

Figure 8. NC SDAM general scoring guidance (from NC DWQ 2010).

This method applies within a state that is included in both the NE and SE study regions and has been used as the basis for active SDAMs in both Virginia and Tennessee (see below). Fritz et al. (2013) evaluated the method's ability to correctly classify streams of differing flow permanence in forested catchments of the Piedmont and Southeastern Plains ecoregions of South Carolina, in both the wet and dry seasons. In addition to the NC method indicators, the authors also measured bankfull width and depth for each reach, and calculated drainage area, elevation, channel and valley slope, and relief ratio. The authors found the NC method tended to overestimate the flow permanence class of intermittent reaches, though the method itself was generally seasonally stable. Presence of baseflow was the most important predictor variable of streamflow duration in the classification model that used attribute scores from both the wet and dry seasons. When only dry season scores were used, other variables important for distinguishing between flow classes included presence of macrobenthos, presence of rooted upland plants in the streambed, and presence of fibrous roots in the streambed, in addition to the added variables of bankfull width, drainage area, and ecoregion.

Lampo (2014) tested the use of the NC method in agricultural watersheds in southern Illinois. The author found that the ability of the NC method to distinguish ephemeral from intermittent and perennial streams was successful 100% of the time, based on comparisons to direct measurement or observation of flow. However, when compared to the flow duration derived from direct measurements or observations of flow, the NC method incorrectly categorized intermittent and perennial streams 28% and 17% of the time, respectively. The author also found that watershed area and bankfull depth and width had a significant positive correlation with flow duration as determined by the NC stream score, similar to Fritz et al. (2013).

3.7 Temperate US (IN, KY, OH, IL, NH, NY, VT, WV, and WA)

Fritz et al. (2006) described a comprehensive suite of protocols for measuring potential flow permanence indicators in headwater streams, which, due to their position in the landscape, are more prone to drying. The suite of indicators and description of collection methods is more comprehensive than the other listed methods, but no conclusive flow duration classification is drawn upon at the end of the analysis. Indicators are physical or biological and include channel slope, basic channel geomorphology (bankfull width and depth, entrenchment ratio), water depth (maximum pool depth, thalweg depth), macroinvertebrates, and algae, among others. Publications following this report (Fritz et al. 2008; Johnson et al. 2009; Fritz et al. 2009; Roy et al. 2009) assess the effectiveness of some indicators separately. For instance, Fritz et al. 2008 found that mean entrenchment ratio was the best discriminatory 'dry' variable for distinguishing between intermittent and perennial sites in IN, KY, and OH. In these same states, Johnston et al. (2009) found that during the wet season (spring), maximum pool depth was the best at separating ephemeral sites from other flow types but was somewhat less so in the dry season (summer).

3.8 Eastern Kentucky

This method by Svec et al. (2005) was developed to determine the flow duration of a stream (ephemeral, intermittent, or perennial) in the context of determining required silvicultural best management practices in the eastern coalfield region of Kentucky. The authors measured a suite of channel geometry characteristics to determine their power to predict flow duration, including bankfull width, mean bankfull depth, width to depth ratio, flood prone width, streambed slope, depth to bedrock, entrenchment ratio, and cross-sectional area. The most predictive measurements of flow duration were found to be watershed area, stream slope, bankfull width, width to depth ratio, and entrenchment ratio. However, it is important to note that none of the streams sampled in this study were truly ephemeral (defined in this study as having measurable discharge <10% of the time), with no streams having <50% flow duration. Therefore, predictive models developed from data collection in this study may not apply as robustly to ephemeral or near-ephemeral intermittent streams as they do to perennial streams or near-perennial intermittent streams.

3.9 Ohio

Ohio EPA (2012) has developed an assessment and classification method for Primary Headwater Habitat (PHWH; generally, drainage areas less than 1.0 mi^2 and deep pools less than 40 cm) to better evaluate water quality in small headwater stream ecosystems. This method determines different stream classes (Class I, II, and III) based on the type of biological community the stream can support. These classes are partially based on flow duration, where Class I streams are considered ephemeral, Class II streams are considered intermittent to perennial (warmwater), and Class III streams are considered perennial streams influenced by groundwater (coldwater). There are three levels of assessment, where the first two levels are considered 'rapid': Level 1 is a physical assessment of habitat using the headwater habitat evaluation index (HHEI), Level 2 incorporates qualitative biological sampling, and Level 3 is a quantitative biological assessment of vertebrate and macroinvertebrate communities (taxa evaluated to lowest practicable taxonomic level). Level I metrics include substrate (including habitat such as leaf packs and fine detritus), maximum pool depth, and average bankfull width. Scores from these metrics determine the HHEI, which is then fed into the flowchart in Figure 9. Generally, Level I, combined with Level II, is enough to determine the PHWH stream class; however, the use of Level III is the final arbiter of stream class.

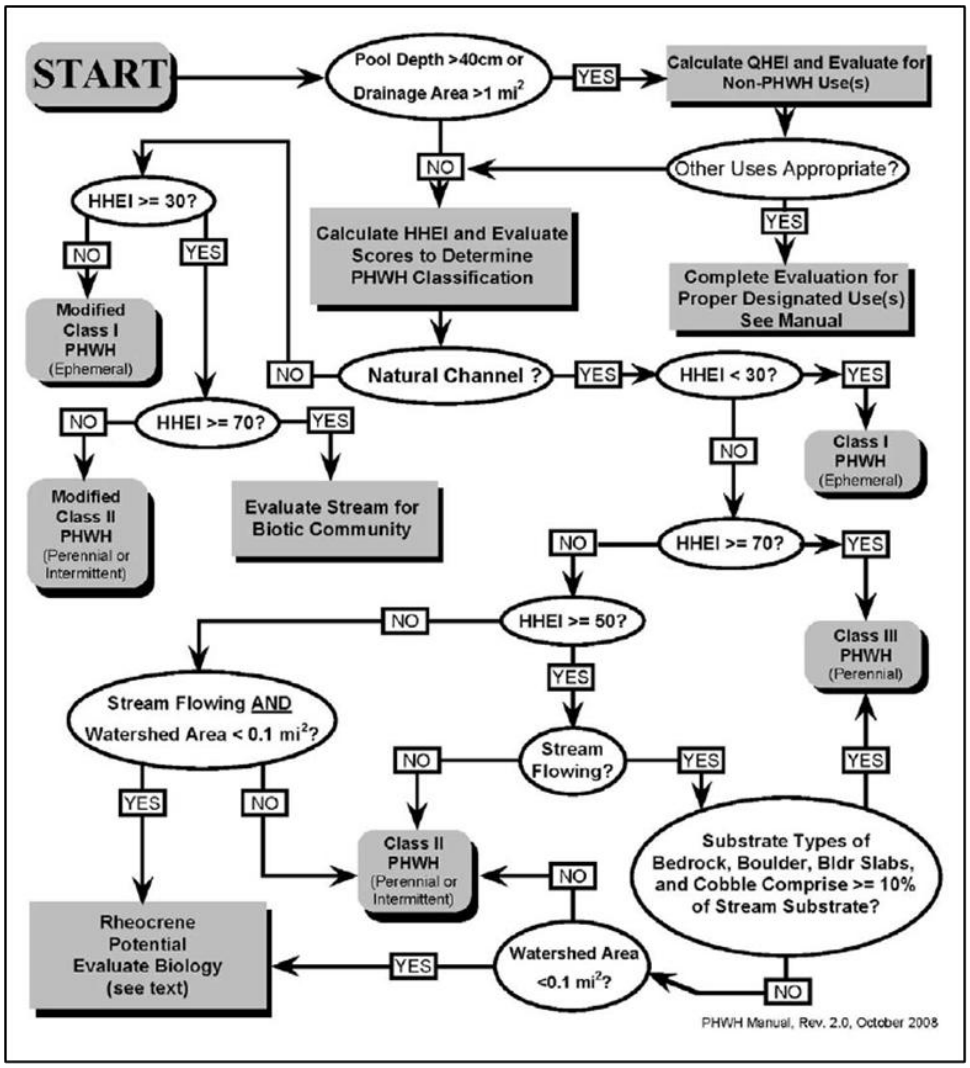


Figure 9. PHWH stream classification flow chart based on HHEI scoring (from Ohio EPA 2012).

Fritz et al. (2008) found that the OH HHEI correctly classified perennial sites 98% of the time, though the success rate for intermittent and ephemeral sites was more modest (34% and 46%, respectively). Two geomorphological indicators, maximum pool depth and bankfull width, best distinguished ephemeral from the two other flow classes and vice versa, respectively.

3.10 Fairfax County and James City County, Virginia

These VA counties have developed separate methods to determine whether a stream is perennial to facilitate compliance with the VA Chesapeake Bay Preservation Act; however, both are largely derived from earlier versions of the NC SDAM and are scored in the same way (see Figure 4), though the types and total number of indicators and the perennial/intermittent thresholds are different from the NC method, and from each other. In addition, the Fairfax County method (2003) also used an unpublished manuscript of the 'Qualitative Field Procedures for Perennial Stream Determinations', later published by DeBerry and Crayosky

(2018; see below), to develop its protocol. Fairfax County's method has 26 total indicators, including 10 for geomorphology, 7 for streamflow, hydrology, and streambed soils, and 9 for biology. The minimum threshold for a perennial rating is 25; however, streams with lower scores can be classified perennial if additional information supports this classification (e.g., presence of EPT or other taxa with an extended aquatic life stage, long-term observations by a resident or local professional).

James City County's method (2009) has 14 total indicators, including 7 for geomorphology, 4 for hydrology, and 3 for biology. Generally, streams scoring 18 points or more are classified as perennial and streams scoring 10 points or less are classified as intermittent. For those streams scoring between 10 and 18, the perennial flow threshold is 14 points with a range of +/- 2. This range allows for classifications not strictly based on the threshold value, as long as the preponderance of the evidence and professional judgement support the flow determination (e.g., an intermittent stream can have a score up to 16 and a perennial stream can have a score as low as 12). Additional factors specified to support a determination include soil mottling, periphyton, grade control, and offsite stormflow inputs, but not specific biological indicator taxa. This method has been tested in surrounding counties (Gloucester, New Kent, and York) and cities (Williamsburg and Newport News) in the upper coastal plain of VA and found to be an accurate tool for identifying perennial water bodies in these areas as well (VA DCR 2010).

3.11 Virginia (state-wide)

DeBerry and Crayosky (2018) identified a set of 7 qualitative indicators (6 field, 1 off-site) that could be used to determine if a stream has a perennial flow duration in Virginia. Unlike the two other SDAMs developed in the state, this method is not based on a point system or a numerical index, but instead builds on positive corroborative evidence that a stream is perennial. Therefore, if a majority of the indicators (4 or more) are present (e.g., dry season flow) or suggest perennial streamflow (e.g., presence of macroinvertebrates having an aquatic life cycle greater than a year) than the stream is considered perennial. This method is not currently being used in an official capacity but is under review by regulatory agencies in VA for use as an approved perennial stream determination approach.

3.12 Tennessee

This method is also derived from the NC method, though it differs in that the primary goal is not necessarily to determine flow duration, but to determine if a channel is a jurisdictional stream (intermittent or perennial) or a 'wet-weather conveyance' that is not subject to regulatory jurisdiction as a water of the state (WWC; generally ephemeral). To that end, there is a set of 9 'yes' or 'no' questions that, if at least one is answered in the affirmative, determine whether the channel is a stream or a WWC (Figure 10). If no primary indicator is present, an evaluator completes the secondary indicator score sheet, which is largely a replica of the North Carolina method (2010 version, with slight modifications), to determine if the channel is subject to state regulatory jurisdiction. If a channel scores less than a 19 (intermittent threshold), it is considered a WWC; anything above is considered a stream.

Primary Indicators	NO	YES
1. Hydrologic feature exists solely due to a process discharge		WWC
2. Defined bed and bank absent, dominated by upland vegetation / grass		WWC
3. Watercourse dry anytime during February through April 15th, under normal precipitation / groundwater conditions		WWC
4. Daily flow and precipitation records showing feature only flows in direct response to rainfall		WWC
5. Presence of multiple populations of obligate lotic organisms with ≥ 2 month aquatic phase		Stream
6. Presence of fish (except *Gambusia*)		Stream
7. Presence of naturally occurring ground water table connection		Stream
8. Flowing water in channel and 7 days since last precipitation in local watershed		Stream
9. Evidence watercourse has been used as a supply of drinking water		Stream

Figure 10. Primary indicators to determine if a channel is a stream or a WWC (from TDEQ 2011).

3.13 Chattooga River Watershed (western GA, NC, and SC)

Using stream networks identified and digitized for the Chattooga River watershed in mountainous western GA, NC, and SC, Hansen (2001) presents a set of physical and biological indicators that can be used to distinguish between perennial, intermittent, and ephemeral streams (Figure 11). It is important to note that these criteria are based on the author's stream observations over many years and have not been formally tested or verified for their reliability. This work was completed primarily to better estimate flow type extent throughout the Chattooga River watershed and relationships to stream order.

Criteria	Stream type		
	Perennial	Intermittent	Ephemeral[a]
Channel	Defined	Defined	Not defined
Flow duration (estimated)	Almost always	Extended, but interrupted	Stormflow only
Bed water level	Above channel	Near channel surface	Below channel
Aquatic insects	Present	Few, if any	None
Material movement	Present	Present, less obvious	Lacking or limited
Channel materials	Scoured, flow sorted	Scoured or flow sorted	Mostly soil materials
	No organic buildup	Lacks organic buildup	Organic buildup

[a] Healed gully channels were classed as ephemerals when there were no recent signs of flow or scour. When forested, there is evidence of organic accumulations and decomposition.

Figure 11. Physical and biological criteria used to delineate flow types in Hansen (2001).

3.14 New Mexico

The New Mexico Environment Department (NMED) developed a two-phase method for assessing flow duration (NMED 2011) for streams throughout the state. The first phase is more rapid and is sometimes sufficient to classify a stream as perennial, intermittent, or ephemeral. This first phase is very similar to the NC method and relies on qualitative sampling of benthic macroinvertebrates, fish, filamentous algae, and other organisms, plus field observation of

channel morphology and soils. In some cases, a second phase consisting of quantitative fish and benthic macroinvertebrate samples may be necessary. This second phase also requires the use of continuous loggers or stream gages to measure water presence. In this method, 14 indicators of flow duration ("attributes") are scored, yielding a quantitative index that forms the basis of the classification (Table 7). Notably, this method may result in ambiguous situations (gray rows in Table 7), which may be resolved by more intensive "level 2" analysis, and by investigation of adjacent reaches. Certain indicators (specifically, fish and aquatic macroinvertebrates) may result in a perennial designation, even if scores are low.

Table 7. Score interpretation for the New Mexico method.

Waterbody type	Level 1 total score	Determination
Ephemeral	Less than 9.0	Stream is ephemeral
	≥ 9.0 and < 12.0	Stream is recognized as intermittent until further analysis indicates that the stream is ephemeral.
Intermittent	≥ 12 and ≤ 19.0 ***or*** score is lower but aquatic macroinvertebrates and/or fish are present	Stream is intermittent
	> 19.0 and ≤ 22.0	Stream is recognized as perennial until further analysis indicates that the stream is intermittent
Perennial	Greater than 22.0	Stream is perennial

3.15 Mediterranean Europe

Prat et al. (2014) developed an assessment framework known as Mediterranean Intermittent River ManAGEment (MIRAGE) to identify the flow status of streams in order to guide selection of appropriate condition assessment tools based on biology, water chemistry, habitat, or other condition indicators. The first step in analysis is determining the flow duration of a stream using the Temporary Stream Regime Tool (TRS-Tool; Gallart et al. 2012, Gallart et al. 2017). The TRS-Tool uses three potential sources of flow estimation/observation to determine stream flow classification: 1) interviews, 2) interpretation of high-resolution aerial photographs and rapid field observation, and 3) outputs from hydrologic rainfall-runoff models.

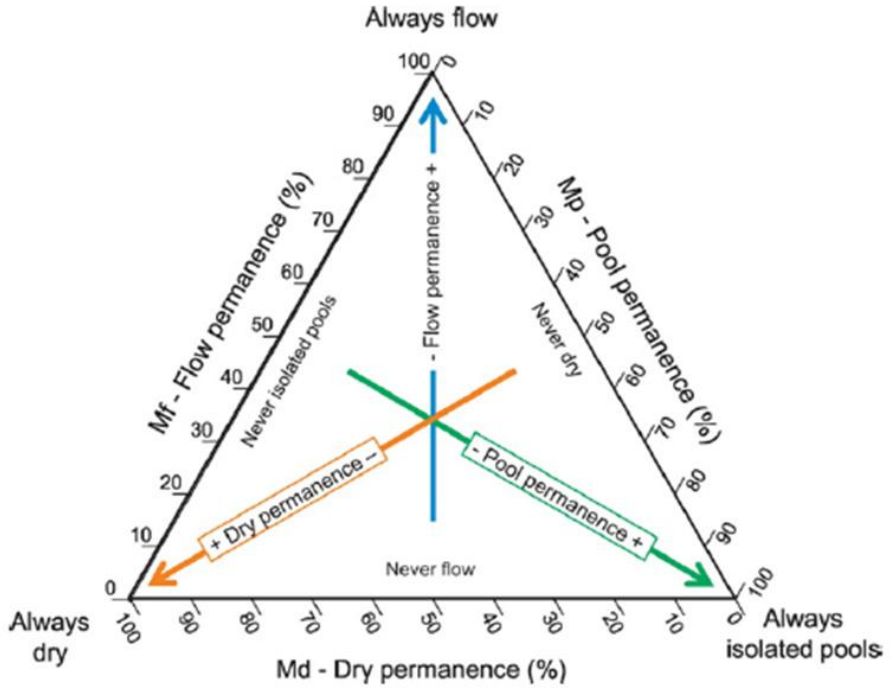
In contrast with other methods, this assessment method classifies streams into more than three flow-duration classes, reflecting the predominant aquatic states, such as intermittent-pool, intermittent-dry, episodic-ephemeral or perennial.

Methodology for interviews is documented in Gallart et al. (2016). Interviews target locals encountered in the vicinity of a stream in question, who either live or tend land along the stream. The core interview consists of five key questions:

1. How often does flow cease?
2. During non-flowing months, are there pools and for how long?
3. When there is no surface water, is there water in the alluvium?

4. How frequently are flow/pools/dry riverbeds observed during each season?
5. Have any changes in flow regime been observed recently?

Rapid field observations and photographic interpretation focuses strictly on hydrologic indicators, such as presence of pools, riffles, or dry streambed over several visits. Interviews and observations allow for a finer categorization of different aquatic states that involve flow as well as disconnected pools and dry riverbed. These are represented by flow permanence (Mf), pool permanence (Mp), and dry-period permanence in Figure 12.



Arrangement of the three main metrics that correspond to the three aquatic phases; flow permanence (*Mf*), Isolated pools permanence (*Mp*) and dry river permanence (*Md*), in the FPD (Flow – Pools – Dry) graph. The arrows show the progression of every one of the three metrics whereas the axes show the values of every one of them. The central point represents a river that undergoes the three aquatic phases with the same frequency.

Figure 12. Relationship of aquatic phases to flow duration in Gallart et al. (2017).

3.16 Czech Republic

Straka et al. (2019) recently developed a "biodrought" index to classify streams as perennial or intermittent based strictly on the composition of benthic macroinvertebrate communities (Figure 13). Based on a data set of 23 streams in the Czech Republic (mostly in the Carpathian Mountains and Central Highlands) consisting mostly of paired perennial and non-perennial sites (both "intermittent" and "near perennial"), they identified indicator species associated with different flow regimes, and developed a seasonally-adjusted index consisting of three metrics that could discriminate between the three flow-regime classes (Table 8).

Table 8. Metrics in the Biodrought index developed by Straka et al. (2019).

Metric	Flow state indicated by high values
Proportion of indicator taxa (perennial indicators/ perennial + intermittent indicators)	Perennial
Proportion of taxa with high body flexibility	Intermittent
Preference for organic substrate (Autumn samples only)	Intermittent
Total abundance (Spring samples only)	Perennial

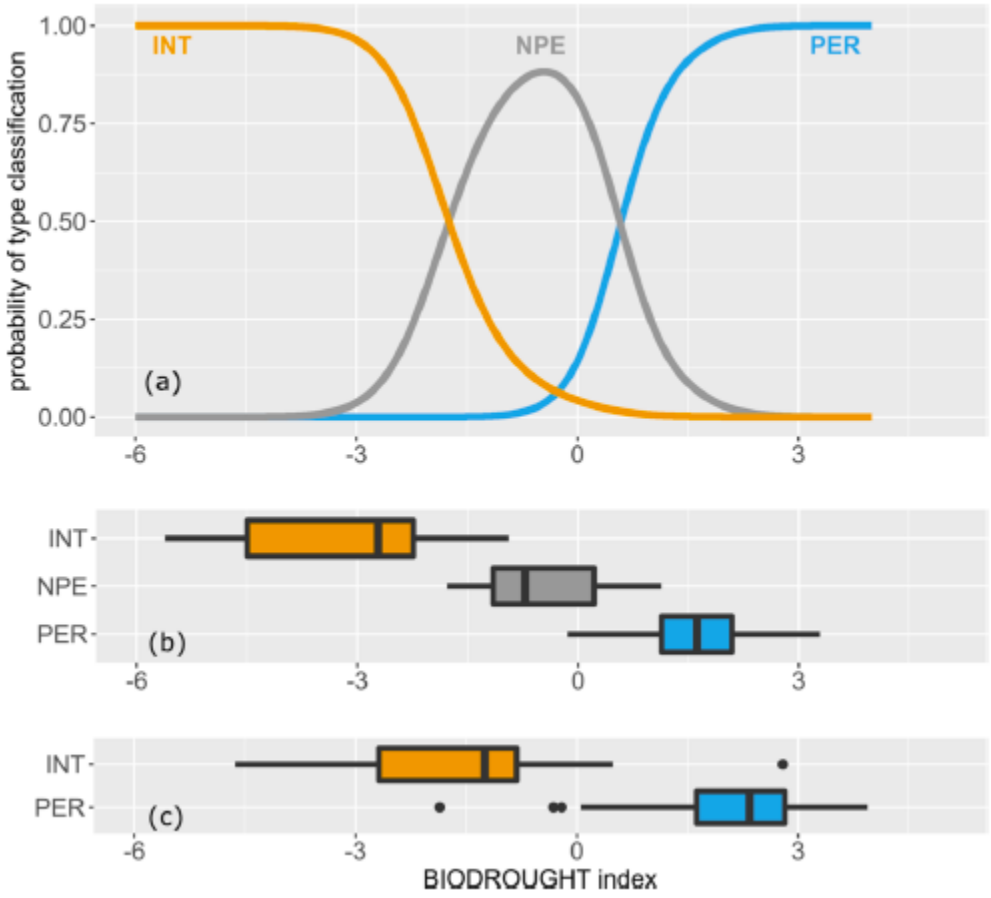


Figure 13. Relationship between biodrought index scores and flow classes, from Straka et al. (2019).Top panel shows the probability of classification as the index score increases. The second panel shows scores associated with calibration data. The bottom panel shows scores associated with independent validation data. INT: Intermittent. NPE: Near-perennial. PER: Perennial.

As with Nadeau (2015), the index of Straka et al. (2019) uses aquatic invertebrates to discriminate between perennial and intermittent streams, but not to discriminate ephemeral streams. But the two indices differ in a few important aspects. First, indicator taxa were identified at the species or genus level, which reduces the rapidness of this method if lab-based identifications are required. Second, indicator taxa were identified through an empirical

method (i.e., indicator species analysis), whereas the indicators of Nadeau (2015) were derived from life history information and experience of stream ecologists in the Pacific Northwest (Blackburn and Mazzacano 2012) and through analysis of field collected data (Nadeau et al. 2015). Third, the biodrought index takes into account the presence of intermittent indicator taxa, whereas the method of Nadeau (2015) found superior performance when only perennial indicator taxa are considered. It is important to note that this index has not yet been validated.

3.17 Massachusetts and Vermont

Logistic regression equations were developed to determine the probability of a stream reach in Massachusetts and Vermont being perennial or intermittent. These are not field based methods but could be complementary to field surveys if developed for other states or regions, and at least in Vermont's case, are already being used as supporting evidence for state jurisdictional determinations. The Massachusetts regression model (Bent and Steeves 2006) is applicable for stream sites with drainage areas between 0.04 and 2.0 sq. miles (above 2.0 sq. miles, the streams became reliably perennial), excluding the southeastern coastal region of the state. Factors in the equation include drainage area, areal percent of sand and gravel deposits (influenced by glaciation), areal percentage of forest land, and whether the stream was in the eastern or western portion of MA. A logistic regression equation using these variables was found to be about 75% accurate; in other words, there is about a 75% chance that a stream site is correctly classified as perennial using the equation. The authors developed an automated procedure to map stream types using the equation and did so in the Shawsheen River basin in northeast MA as a case study. It is unknown whether other basins have been mapped since the equation was developed. The procedure requires a National Hydrography Dataset (NHD) of at least a 1:24,000 scale, elevation derived datasets (flow direction, flow accumulation and catchment grids) and data layers of equation variables.

The state of Vermont has developed a hydrography dataset (VHD) at a 1:5,000 scale, which is much finer scaled than what is available nationally (finest scale NHD is generally 1:24,000). Olson and Brouillette (2006) developed a logistic regression equation to determine the probability a stream was intermittent in Vermont and used it to assign streamflow characteristics to channels shown on the VHD. Factors in the equation include drainage area, elevation of the site, ratio of basin relief to basin perimeter, and areal percentage of well and moderately well-drained soils. A logistic regression equation using these variables was found to be about 85% accurate; in other words, there is about an 85% chance that a stream site is correctly classified as intermittent using the equation. The VHD dataset with regression derived streamflow classifications is cited by the Vermont Department of Environmental Conservation (VDEC) as an evaluative parameter when conducting jurisdictional determinations under the Vermont Stream Alteration Permit Program (VDEC 2018).

4.0 INDICATORS IN HAWAIʻI

A review of literature describing possible indicators of streamflow duration class in Hawaiʻi shows some support for those used in current flow duration assessment methods, though

studies exploring flow duration and existing indicators in Hawai‘i were scarce, especially for geomorphological and hydrological indicators. We discuss each class of indicators and determine whether specific indicators should be included in the development of flow duration assessment methods in Hawai‘i, with particular attention to the indicators included in Nadeau (2015) and NCDWQ (2010) where possible. All applicable references met the evaluation criteria outlined in Section 2.3.1.

4.1 Geomorphological and Hydrological Indicators

No studies pertaining to geomorphological flow duration indicators in Hawai‘i were found during this review; however, it is important to note that the volcanic nature of Hawai‘i has an important bearing on island geomorphology. Basalt is highly permeable, and streams are unable to develop for a period of time after volcanic activity has ceased because rapid transmission loss typically prevents sufficient surface runoff for fluvial erosion and deposition. For example, the Kīlauea area in the southern part of Hawai‘i Island is an area with little to rarely occuring surface runoff (Craddock et al. 2012). Once less porous soils form due to weathering, rates of stream erosion may be different between windward and leeward sides of the island due to great differences in rainfall (see Section 1.0; Stearns 1946).

The porosity of volcanic rock also plays a large part in the hydrology of Hawai‘i. Volcano rift zones contain dikes (generally vertical layers of impermeable rock) that impede the movement of groundwater, leading to areas of dike-impounded groundwater at relatively high elevations (Oki and Brasher 2003, Trettin et al. 1995). Both Hirashima (1971) and Oki and Brasher (2003) found that streams on O‘ahu had perennial flow in the interior parts of the island where they intercept water from dike-impounded groundwater and persistent rainfall, and near the coast where they intercept the basal water table (about 20 to 30m elevation). However, in between the interior and the coast, many perennially flowing streams lose water to infiltration through highly permeable rock (see above), making them more likely to be intermittent or ephemeral in these reaches. Given the volcanic origins of the Hawaiian Islands, this phenomenon is not restricted to O‘ahu, demonstrated by the definition of a perennial stream in the state of Hawai‘i’s water quality standards (Hawai‘i Dept. of Health 2014; see also Polhemus et al. 1992). This definition stipulates perennial streams may be either ‘continuous’ or ‘interrupted’. Interrupted perennial streams ‘usually flow perennially in their upper reaches but only seasonally in parts of their middle and lower reaches, due to either downward seepage of surface flow (naturally interrupted) or to man-made water diversions (artificially interrupted). Streams may also flow perennially where dikes are not present; for example, in eastern Kaua‘i, groundwater discharges to streams from a vertically extensive freshwater lens system found in low permeability rocks at several hundred feet of altitude (Oki 2003).

Streams in Hawai‘i are prone to flash floods, mainly due to the intensity of rainfall, small and steep drainage basins, steep channel profiles, and limited channel storage (Oki 2003). The NC SDAM (NCDWQ 2010), which has been used in the past to determine stream flow duration in Hawai‘i (L. Speerstra, personal communication), uses the presence of ‘organic debris lines or piles’ (woody or non-woody material) as an indicator of perennial flow. In Hawai‘i, frequent

high flows may shorten the residence time of organic debris (woody or non-woody material) in streams, as Larned (2000) observed with coarse particulate matter. The WM region has similar stream types in high elevation headwaters, though the occurrence of spates in these systems is typically less frequent than in Hawai‘i. In the WM literature review (McCune and Mazor 2020), large woody jams (or debris jams) were identified as an important component of streams, with several studies investigating the impacts of large woody jams on stream ecology, stream channel morphology, water velocity, and to a lesser extent, flow duration. In the WM, there were conflicting reports of effect (Gippel 1995, Mason Jr. et al. 1990, Faustini & Jones 2003, Shields & Gippel 1995) versus no effect (Matheson et al. 2017, Lester & Wright 2009) on the influence of organic jams (flow obstructing large woody debris) on flow duration. However, several studies did consistently support the direct influence of jams on modifications of other stream flow duration indicators, particularly geomorphological indicators – e.g., Abbe and Montgomery (1996), Faustini and Jones (2003) and Smith et al. (1993) showed significant differences in gradient, bank morphology and pool frequency along stream reaches pre- and post-jam removal. In a review of hydrologic effects of large woody jams, Gippel (1995) reports that organic jam presence can have an indirect, slowing effect on flow conveyance via increases in channel roughness and increases in channel stage height, though no studies in the WM found a direct hydrologic influence of debris jams. The usefulness of organic debris or large woody jams in determining streamflow duration in Hawai‘i may be limited due to the flashiness of these systems.

The NC SDAM also uses the presence of leaf litter as an indicator of less than perennial flow, as dry conditions hinder decomposition (by microbes or macroinvertebrates) and do not transport leaves that have collected in channels or accumulate leaves into packs on flow obstructions. Hawai‘i, as with many other remote tropical islands, generally lacks shredding stream invertebrates like stoneflies (Howarth and Polhemus 1991, Larned 2000, Benstead et al. 2009, MacKenzie et al. 2013). Therefore, stream flow is the primary mechanism by which leaf litter is fragmented into finer particulate material (Benstead et al. 2009, MacKenzie et al. 2013). However, due to the flashiness of Hawaiian streams, litter residence time is usually less than 20 days (Larned 2000). Roberts et al. (2016) found that leaf decay rates for certain common tree species in Hawai‘i (one native, three non-native) were generally lower in streams with low flow, though this finding was dependent on the chemical and physical properties of each species’ leaves.

4.2 Biological Indicators

In contrast to geomorphological and hydrological indicators, biological indicators are often directly related to flow duration. Consequently, many studies in other regions have corroborated relationships between these indicators and flow duration, particularly aquatic macroinvertebrates and vertebrates. Also included here are discussions of studies from the AW, WM, GP, and NE/SE since biological indicators can be widespread; if a study is specific to Hawai‘i or similar environments, it is indicated as such.

4.2.1 Aquatic macroinvertebrates

In general, SDAMs from other regions provide strong support for the use of aquatic invertebrates as indicators of flow duration, either as simple abundances (Mazor et al. 2021) or using indicator orders or specific families (e.g., Nadeau 2015). When considering the use of indicator taxa, it is important to note that there is evidence that taxa occurrence occurs along a gradient of flow permanence and the presence of certain taxa may not be an indicator of flow duration by itself (Beugley and Pyron 2010, Feminella 1996, Chadwick et al. 2012, Collins et al. 2007, Grubbs 2011). Although training is required, field-based family level identifications are practical for aquatic macroinvertebrates, further underscoring their suitability as indicators. The Pacific Northwest SDAM (Nadeau 2015) uses a list of macroinvertebrate flow duration indicators developed by the Xerces society (i.e., Mazzacano and Black 2008, Blackburn and Mazzacano 2012) as an integral part of its flow duration decision tree. Similarly, the NC SDAM (NCDWQ 2010) uses a list of perennial indicator taxa (PIT; NCDWQ 2005) as support for perennial stream determinations even when the stream score is lower than the perennial threshold. The Interim Oregon Method (Topping et al. 2009) also uses a list of perennial and intermittent indicator taxa as support for a stream being at least intermittent even if the stream score is lower than the intermittent threshold. The indicator taxa across these three SDAMs have extensive overlap (Table 9). As remote tropical islands, Hawai'i has a depauperate native aquatic macroinvertebrate community compared with the mainland; therefore, the indicator taxa identified in the PNW, NC, and Oregon SDAMs have limited applicability, though some families are represented in the Hawaiian Islands either as native (indigenous/endemic) species or as introductions (Table 8).

During the literature search, very few studies of the effects of flow duration on the macroinvertebrate community in Hawai'i were found. In a few cases, the studies explored the macroinvertebrate taxa above and below stream diversions (Gingerich and Wolff 2005). Diverted sections often had little to no flow and functioned more like intermittent or ephemeral stream reaches. Results from these studies are summarized in Table 10 and mostly deal with aquatic insects, mollusks, and crustaceans (shrimp). These studies present their results at different taxonomic resolutions, ranging from genus and species to family level or higher.

Table 9. Perennial and intermittent indicator taxa used in the Pacific Northwest, North Carolina, and Interim Oregon SDAMS (Nadeau 2015; NCDWQ 2010; Topping et al. 2009) and status of these taxa in Hawai'i. Note: larval indicators are for late-instar stages only.

Taxa	PNW Method Perennial Indicator Families	NC Method Perennial Indicator Families	Interim Oregon Method Perennial (P) or Intermittent (I) Indicator Families	Status of Indicator Families in Hawai'i
Ephemeroptera (larvae)	No indicator families; uses abundance of Ephemeroptera (6 or more individuals)	Baetidae, Caenidae, Ephemerellidae, Ephemeridae, Heptageniidae, Leptophlebiidae, Siphlonuridae	None	No Ephemeroptera are native to Hawai'i (Howarth and Polhemus 1991); however, *Caenis nigropunctata* has been successfully introduced on O'ahu and has been collected occasionally on that island since its introduction in the 1950's (Zimmerman 1957, Smith 2000)
Plecoptera (larvae)	Pternarcyidae, Perlidae	Peltoperlidae, Perlidae, Perlodidae	Same as PNW (P); Capniidae, Nemouridae (I)	No Plecoptera are native to Hawai'i (Howarth and Polhemus 1991) and no genera appear to have been successfully introduced.
Trichoptera (larvae)	Philopotamidae, Hydropsychidae, Rhyacophilidae, Glossosomatidae	Philopotamidae, Hydropsychidae, Ryacophilidae, Lepidostomatidae, Limnephilidae, Molannidae, Odontoceridae, Polycentropidae, Psychomyiidae	Same as PNW (P); Limnephilidae (I)	No Trichoptera are native to Hawai'i (Howarth and Polhemus 1991); however, *Cheumatopsyche pettiti* (or *analis*, Hydropsychidae) is established on the five main Hawaiian Islands (Polhemus 1995).
Coleoptera (larvae)	Elmidae, Psephenidae	Elmidae, Psephenidae, Dryopidae (*Helichus* adults only)	Same as PNW (P); larvae or adults of Dytiscidae, Hydrophilidae (I)	Members of Dytiscidae and Hydrophilidae (both native and non-native) are found in Hawai'i (Howarth and Polhemus 1991).
Odonata (larvae)	Gomphidae, Cordulegastridae, Calopterygidae	Gomphidae, Cordulegastridae, Calopterygidae, Aeshnidae, Libellulidae	Same as PNW (P); Lestidae (I)	Stream-dwelling members of the Aeshnidae and Libellulidae (both native and non-native) are relatively widespread on most of the larger Hawaiian Islands (Polhemus 1995).
Megaloptera (larvae)	Corydalidae	Corydalidae, Sialidae	None	No Megaloptera are native to Hawai'i (Howarth and Polhemus 1991) and no genera appear to have been successfully introduced.
Mollusca (any life stage)	Any life stage of Unionidae, Ancylidae, Pleuroceridae, Hydrobiidae, Margaritiferidae	Unionidae, Ancylidae, Planorbidae, Pleuroceridae; presence of Sphaeriidae only requires at least an 18 on geomorphology section of NCDWQ stream form	Adults of Juga spp. (Pleurocerid snail), Unionidae, Margaritiferidae (P); none (I)	Freshwater species of Ancylidae, Hydrobiidae, Planorbidae, Sphaeriidae (mostly introduced), and Neritidae have been found on the Hawaiian Islands (Cowie 1997, Christensen 2016, Christensen et al 2021).

Diptera	None	Ptychopteridae, Tipulidae (*Tipula* sp. only)	None	While numerous species in the Tipulidae are endemic to Hawai'i, none are *Tipula* sp. (all are *Limonia* sp. and *Gonomyia* sp.; Howarth and Polhemus 1991).
Crustaceans (any life stage)	None	Crayfish in channel; if only crayfish are present, require at least an 18 on geomorphology section of NCDWQ stream form	None	The introduced crayfish *Procambarus clarkii* is established throughout Hawai'i (Englund et al. 2000).

Table 10: Studies from Hawai'i of aquatic macroinvertebrates in different flow duration classes or with or without stream diversions.

Reference	Island(s)	Notes	Perennial/Permanent	Intermittent/ Ephemeral/Diverted
Brasher (1997)	Moloka'i	Reaches of Waikolu Stream that dry during the year due to water diversions upstream.		Substantially fewer of the native Hawaiian snail *Neritona granosa* (hīhīwai) were found in and above areas of stream diversion, even when these reaches had water. Dewatered sections inhibit downstream dispersal of larvae and upstream migration of individuals returning from the ocean (amphidromous).
Brasher et al. (2004)	O'ahu	One intermittent stream (Kaluanui Stream) is sampled as part of a land use/habitat study (remaining sampled streams are perennial).		Annelids made up a higher proportion of the fauna at Kaluanui Stream than the sampled perennial streams (77%). 82% of the insect fauna (22% of sample) were dipterans. Kaluanui Stream was only forested site with mollusks (*Ferrissia sharpi*, Ancylidae)
Englund et al. 2002	Hawai'i	Sampled the intermittent sections of 2 streams with permanent flow upstream (Keanu'i'omanō and Waikoloa Streams), though sampling was conducted during periods of flow.		No crustaceans or mollusks were collected; insect species collected included *Anax strenuus, A. junius, Pantala flavescens, Enallagma civile, Rhantus gutticollis*, and a variety of dipterans.
Hau (2007)	Maui	Sampled 2 streams (Īao and Honomanū) below diversions that remove most of the stream flow.		Hīhīwai (*N. granosa*) cannot survive for long in totally de-watered stream sections, at first being restricted to pools and then damp pockets under gravel/cobble.

McIntosh et al. (2002)	Maui	Sampled Īao stream above and below uppermost flow diversion; this diversion decreases flow by 92-97% of upstream levels.	Stream never went totally dry below the diversion; however, fast-flowing riffle habitat was largely absent due to decrease in flow. Three taxa, *Procanace* sp. (either *acuminata* or *constricta*), *Atyoida bisulcata* (ʻŌpae kalaʻole), and amphipods were only documented from above the diversion.	*Hydroptila arctia, Cheumatopsyche pettiti* (synonymous with *C. analis*), and Chironomids were found both above and below the diversion.
McIntosh et al. (2008)	Maui	Sampled Waiheʻe River above and below uppermost flow diversion, which diverts all surface flow to the Waihee Ditch.	Similar to McIntosh et al. (2002), *Atyoida bisulcata* found only above the diversion.	*Cheumatopsyche analis/pettiti, Hydroptila potosina* (nee *Hydroptila arctia*; see Flint et al. 2003), and *Procance* sp. found both above and below diversion.
Polhemus and Asquith (1996)	All islands	Guide to identification and ecology of native and non-native Coenagrionid damselflies in Hawaiʻi (mostly *Megalagrion* sp.).	Larvae of *M. blackburni, M. heterogamias* (Kauaʻi only), and *M. oceanicum* (Oʻahu only) live in swift stream waters of perennial streams; *M. nigrohamatum* breed in pools along headwater sections of perennial streams	*M. calliphya* can be found breeding in intermittent headwaters or upland rain-fed pools; *M. hawaiiense* and *M. xanthomelas* appear to be able to exploit a variety of temporary aquatic habitats; *M. leptodemas* (Oʻahu only) can be found along intermittent streams and slow sections of perennial streams

Below, major groups of aquatic macroinvertebrates are considered in relation to flow duration; cited references may also draw from the AW, WM, GP, and NE/SE where applicable.

Mollusks

In the AW and WM regions, there was generally strong support for the perennial indicator status of mollusks (e.g., Lusardi et al. 2016), particularly for the New Zealand mudsnail (*Potamopyrgus antipodarum*; Hydrobiidae), a non-native invader in streams throughout the West (e.g., Herbst et al. 2008, Bogan et al. 2013), though this species is not yet found in Hawai‘i. There are only two families of gastropods native to Hawai‘i that inhabit freshwater or brackish stream habitats: the Neritidae and Lymnaeidae (Christensen et al. 2021). These include two culturally important species, *Neritona granosa* (hīhīwai), and *Neripteron vespertina* (hapawai; both Neritidae), though *N. vespertina* is generally confined to more brackish areas in lower stream reaches (these may be more likely to be perennial) and estuaries while *N. granosa* is a better climber and able to migrate farther upstream. Both neritid species are amphidromous, meaning that larvae disperse to the ocean, where they spend up to six months before migrating back to the estuary or streams to mature to adulthood (Parham et al. 2009). Hau (2007) and Brasher (1997) found that de-watered sections of streams due to diversions limit the number and survival of *N. granosa* in these reaches and inhibit their migration upstream. No flow duration studies found for this review observed lymnaeid snails (native or non-native), though members of this family were observed only in perennial streams in the NE and SE (Eaton and Vander Vorste 2012) and were indicators of intermittent or nearly perennial Czech streams (Straka et al. 2019).

There are representatives of gastropod families used as perennial indicators in other SDAMs (see Table 8) that have been introduced to Hawai‘i, including members of the Ancylidae, Hydrobiidae, and Planorbidae, though the number of genera is limited (Cowie 1997). *Ferrissia californica* (originally identified as *F. sharpi*) is an ancylid, which is considered a perennial indicator family in the PNW and NC SDAMs; however, Brasher et al. (2004) found this species in both intermittent and perennial streams on O‘ahu.

Although they are less widespread than many gastropods, freshwater bivalves are also likely to be good indicators of perennial flow; however, there are only four freshwater bivalves currently found in the Hawaiian Islands, all introduced (Christensen 2016). These include *Corbicula fluminea* (Asian clam) and three species in the Sphaeriidae (*Musculium lacustre, M. partumeium*, and *Pisidium casertanum*). There were no studies found on bivalves and streamflow duration specific to Hawai‘i or similar areas during this review. In the SE, Golladay et al. (2004) and Haag and Warren (2008) found that a prolonged drought event along the Gulf Coastal Plain, where normally perennial streams dried or flow was substantially reduced, resulted in significant declines in *Corbicula fluminea* (Asian clam) abundance and survival. Sphaeriidae are not generally treated as a perennial indicator taxon, at least without other evidence the stream is perennial (NCDWQ 2010), though some support for this classification is found in Lusardi et al. (2016), Kelso (2012), and Kelso and Entrenkin (2018). However, Straka

(2019) identified *Pisidium* sp. (pea clams) as an indicator of intermittent flow, and Davis et al. (2003) found this taxon in intermittent streams in Georgia.

Ephemeroptera (mayflies) and Plecoptera (stoneflies)

No Ephemeroptera or Plecoptera are native to the Hawaiian Islands. One mayfly introduced as prey for stocked fish, *Caenis nigropunctata*, has been collected intermittently on O‘ahu since its introduction in the 1950’s (Zimmerman 1957, Smith 2000). The rarity of this order across the islands limits the use of Ephemeroptera abundance or families as perennial indicators in Hawai‘i.

Trichoptera (caddisflies)

There are no Trichoptera native to the Hawaiian Islands; however, introduced members of the families Hydropsychidae and Hydroptilidae have become established on islands with flowing water (generally the five largest islands; Flint et al. 2003, Howarth and Polhemus 1991, Kondratieff et al. 1997, and Polhemus 1995). Hydropsychidae is used as a perennial indicator family in the PNW, NC, and Interim Oregon SDAMs. However, McIntosh et al. (2002, 2008) found the hydropsychid *Cheumatopsyche analis* (synonym *pettiti*) both above and below stream diversions that diverted much of the streamflow (>90%), greatly reducing riffle habitat. In the continental U.S., six studies in the NE/SE, WM, and GP support the use of this family as a perennial indicator (Bramblett and Fausch 1991, Burk and Kennedy 2013, Fritz and Dodds 2002, Miller and Brasher 2011, Smith et al. 2017, and Stagliano 2005). Though Price et al. (2003) found this family only in intermittent streams on Vancouver Island, Canada.

There is no evidence from other regions to suggest that Hydroptilidae is a flow duration indicator taxon. Consistent with this finding, McIntosh (2002, 2008) found *Hydroptila potosina* (formerly identified as *H. arctia*, see Flint et al. 2003) in both diverted and undiverted stream reaches.

Coleoptera (beetles)

Both Elmidae and Psephenidae, which are considered perennial indicator taxa in all three of the SDAMs in Table 8, do not appear to occur in Hawai‘i. In addition, information on Coleopteran families and flow duration in Hawai‘i and similar environments was scarce to absent. The families Dysticidae and Hydrophilidae are considered indicators of intermittent flow in the Interim Oregon method (Topping et al. 2009), both of which are represented in Hawai‘i (Howarth and Polhemus 1991, Polhemus 1995). There are five species of Hydrophilidae (*Omicrus brevipes, Limnoxenus nesiticus*, and *L. semicylindricus*) and Dysticidae (*Hydrovatus confertus* and *Rhantus pacificus*) endemic to Hawai‘i and are known to be aquatic in all life stages (Howarth and Polhemus 1991). However, Englund et al. (2002) found the non-native dysticid *Rhantus gutticollis* in intermittent stream reaches on Hawai‘i.

In the AW and WM, studies supported the use of Hydrophilidae as indicators of intermittent flow (Bonada et al. 2006, Bogan and Lytle 2007). Straka et al. (2019) identified Hydrophilidae as indicators of intermittent flow, while Dytiscidae were found as indicators of both intermittent and perennial streams.

Odonata (dragonflies and damselflies)

The Odonata are one of the most diverse native aquatic insect orders in Hawai'i, likely due to their strong dispersal ability (Howarth and Polhemus 1991). Of the families identified as perennial indicator taxa in other regions (
Table 9), only representatives of the Aeshnidae and Libellulidae are found in Hawai'i. However, Englund et al. (2002) found *Anax strenuus, A. junius* (both Aeshnidae), and *Pantala flavescens* (Libellulidae) in intermittent reaches of streams with permanent flow upstream on Hawai'i island. In the NE/SE, Chadwick et al. (2012) observed *Erthrodiplax* (Libellulidae) in perennial streams only, though Eaton and Vander Vorste (2012) observed other members of this family in both perennial and intermittent streams (e.g., *Pachydiplax, Libellula*).

The damselfly genus *Megalagrion* (Coenagrionidae) is endemic to the Hawaiian Islands and is especially diverse, with 23 species and sub-species recognized (Polhemus and Asquith 1996). Some of these species have restricted distributions (occurring on one or two islands), and a few have life histories that do not involve streams during the larval stage. For instance, the immatures of *M. koelense* and *M. kauaiense* live in water-filled leaf axils, whereas others use damp leaf litter (*M. oahuense*) or wet seeping rock faces (*M. eudytum*). Of those that use stream habitats for breeding, the suite of species present is often highly dependent on elevation (Polhemus and Asquith 1996), which can often be associated with flow duration in Hawai'i (see Section 4.1). Those species that might be expected to inhabit perennially flowing stream reaches include riffle specialists like *M. blackburni, M. heterogamias*, and *M. oceanicum*, as well as pool breeders like *M. nigrohamatum*. Species that might be expected to inhabit less permanent stream reaches include those that utilize high headwater areas (e.g., *M. calliphya*) as well as those who have been observed to exploit a variety of temporary aquatic habitats (e.g., *M. hawaiiense* and *M. xanthomelas*). Straka et al. (2019) identified a Coenagrionidae species to be indicative of intermittent flows in Czech streams, though Kelso (2012) and Fritz and Dodds (2002) found *Argia* sp. to be associated with perennial streams.

Diptera (true flies, craneflies)

The Diptera contains the majority of the Hawaiian aquatic insect fauna (Howarth and Polhemus 1991). The NC SDAM considers Ptychopteridae and *Tipula* sp. as perennial indicator taxa; however, no Ptychopteridae have been recorded to inhabit Hawai'i and while there are Tipulidae in Hawai'i, *Tipula* sp. do not occur there (Howarth and Polhemus 1991, Englund et al. 2002). There is scant regional evidence of relationships between specific dipteran families and flow duration. McIntosh et al. (2002) found freshwater species of the beach fly *Procanace* sp. (Canacidae) only above a stream diversion that decreased streamflow 92-97% on Maui, while

McIntosh et al. (2008) found *Procanace* sp. both above and below a similar diversion on the same island.

Cañedo-Argüelles et al. (2016) suggest that the diverse genera within Chironomidae may have strong preferences for certain flow duration conditions, which is supported by several studies from the AW and WM (e.g., Bonada et al. 2006, Miller and Brasher 2011). Herbst et al. (2019) found numerous midge taxa associated with perennial flows, while other taxa were associated with intermittent flows. In the NE/SE, Chironomidae were usually associated with intermittent or drier flow regimes (Delucchi 1988, Smith et al. 2017, Williams and Taylor 2003) and were one of the most abundant and cosmopolitan taxa in both perennial and intermittent streams in the GP (Miller and Golladay 1996, Vander Vorste et al. 2008, Vander Vorste 2010). Fritz and Dodds (2002) also found that families in the Brachycera suborder (Phoridae, Sepsidae, and Scathophagidae) were generally associated with intermittent streams. However, challenges with taxonomically identifying genera and families within this group in the field may make them impractical for use in a field-based flow duration assessment method.

Other aquatic invertebrates

Hawai‘i has two native freshwater crustaceans, the shrimps *Macrobrachium grandimanus* (ōpae‘oeha‘a) and *Atyoida bisulcata* (ōpae kala‘le), both of which are amphidromous (see Mollusks). Based on climbing ability, these two species are distributed by elevation; *A. bisulcata* is able to disperse to the upper reaches of streams, while *M. grandimanus* is limited to the lower stream reaches. McIntosh et al. (2002 and 2008) found *A. bisulcata* only above stream diversions that reduced downstream flow substantially. However, it should be noted that due to their amphidromous nature, the individuals above the diversion would have needed to migrate through the diverted section, likely during high flow periods, on their upstream migration from the ocean.

The non-native crayfish *Procambarus clarkii* is established throughout Hawai‘i (Englund et al. 2000). The NC SDAM utilizes crayfish as a perennial indicator taxon, though its use must be supported by other evidence the stream is perennial (
Table 9). Studies involving this taxon in the NE/SE mostly show that crayfish density is generally higher in intermittent versus perennial streams, which appears mainly due to a decrease in predatory fish due to drying (Adams et al. 2018, Flinders and Magoulick 2003, Yarra and Magoulick 2018). DiStefano et al. (2009) observed that crayfish species in southwest Missouri were able to persist in these streams through numerous bouts of seasonal drying, which appeared to be promoted by their use of the hyporheic zone.

Hawai‘i is unique in the U.S. in that it harbors endemic moths in the genus *Hyposmocoma* (Cosmopterigidae) that can survive for extended periods in flowing water as caterpillars (Howarth and Polhemus 1991, Rubinoff and Schmitz 2010, Schmitz and Rubinoff 2011). These species are amphibious in that they can remain submerged for weeks (generally in faster flowing water for oxygen exchange, as they are without gills) or live on dry rocks far from water (Rubinoff and Schmitz 2010). They are a relatively common resident of Hawaiian streams

(Polhemus 1995), and their silk cases are easily mistaken for those made by caddisflies (Howarth and Polhemus 1991).

4.2.2 Algae

Algal biofilm, mats and other macroalgal forms are evident in most streams within a week of the onset of flow (even 1 day, in the case of biofilms), and thus their presence may not always be a good indicator of perennial or intermittent flow (Benenati et al. 1998, Robson et al. 2008, Corcoll et al. 2015). However, most studies suggest that macroalgal growth in the first two weeks may be limited, particularly in hydrologically isolated systems without access to perennial refugia (Robson et al. 2008). Thus, the abundance, rather than the presence of macroalgae may be an effective indicator of flow duration, which has been found to be the case in development of a beta SDAM for the Arid West (Mazor et al. 2021).

Taxonomic identity for most algal species is difficult to ascertain in the field, and they are therefore ill suited for use as a field-based flow duration indicator. However, several studies suggest that there are flow-duration affinities for several groups. For example, Benenati et al. (1998) showed that the macroalga *Cladophora* tend to dominate in perennial streams, while diatoms and the filamentous cyanobacterium *Oscillatoria* dominate in intermittent streams. Certain macroalgae groups are readily identifiable in the field (Entwisle et al. 1997), potentially providing sufficient information to inform flow duration assessment. Sherwood (2006) completed a floristic survey of freshwater algae in Hawai‘i, though surveys were not based on flow duration and focused on perennial streams on the windward sides of islands.

Dormant algal propagules may accumulate in the dry streambed and be resuscitated in lab conditions. This approach has been proposed as a way to assess ecological conditions of dry lakes and streambeds (Carvalho et al. 2002, Robson et al. 2008) and could be used to assess flow duration. But because of the intensive nature of this approach, it is not well suited for a rapid flow duration assessment method.

4.2.3 Bryophytes

The presence of “streamer mosses” is an indicator of intermittent or perennial flow duration in the Interim Oregon method (Topping et al. 2009). Several studies support this use (Fritz et al. 2009, Cole et al. 2010), and a number of moss and liverwort taxa have been designated in terms of moisture preferences (e.g., Appendix A in Fritz et al. 2009); at least some of the moss genera are also found in Hawai‘i (Staples et al. 2004). Vieira et al. (2012, 2016) identified bryophyte community types characteristic of intermittent and perennial rivers in Mediterranean Europe. They found that least-submerged habitats were dominated by certain species (e.g., the liverwort *Lunularia cruciata*, also found in Hawai‘i; Staples and Imada 2006) and upright acrocarpous annual forms, while perennial streams had more prostrate pleurocarpic perennial mats.

On Kaua‘i, Shevock et al. (2019) observe that almost 10% of moss species are found in riparian habitats where they are either in the ‘splash’ zone, occasionally inundated, or seasonally submerged. Some are almost exclusively rheophytic (living in fast-moving water currents) and include *Bryum baldwinii, Donrichardsia bartramii, Glossadelphus limnobioides,* and *Phyllodon lingulatus*, among others.

4.2.4 Wetland and Riparian Vascular plants

The presence of wetland indicator plants (see USACE 2018) is an important indicator of flow duration in several methods (e.g., NCDWQ 2010) but is particularly so in the PNW and Arid West methods (Nadeau 2015, Mazor et al. 2021), where it may be the most important indicator in a dry stream reach. An advantage of plants over other biological indicators of flow duration is that they are non-motile organisms, some of which have very long lifespans (i.e., decades). Therefore, they are well suited to reflect local, long-term conditions in a way that fish or invertebrates might not be. Thus, the taxonomic composition of plants found in the channel and immediate riparian zone may be an effective indicator of flow duration. There were no regionally specific studies on relationships between vascular plants and flow duration found during this literature review.

4.2.5 Vertebrates

<u>Amphibians and Reptiles</u>

Several SDAMs use vertebrates (fish, amphibians) as flow duration indicators, usually through measures of presence/ease of detection, abundance, and/or diversity. There are no amphibians or freshwater reptile species native to Hawai‘i; however, several freshwater turtles and amphibians have been introduced to Hawai‘i and a few have become relatively established across most or all of the main islands (Englund et al. 2000, Englund et al. 2007, USGS 2021). These include the pond and red-eared sliders (*Trachemys scripta* and *T. s. elegans*), Chinese softshell (*Pelodiscus sinensis*), the American bullfrog (*Rana catesbeiana*), cane toad (*Bufo marinus*), and the wrinkled frog (*R. rugosa*). NCDWQ (2010) indicates that certain species of frogs require very long larval stages (>1 year; includes *R. catesbeiana*) and that presence of very large tadpoles of these species may indicate the presence of water over several seasons. To that end, NCDWQ uses the presence of large, multi-year tadpoles to determine if a stream is perennial, even if the stream scores less than the perennial threshold.

<u>Fish</u>

NCDWQ (2010), Nadeau (2015), and Topping et al. (2009) allow the presence of fish (except *Gambusia*, if only species present) to determine if a stream is perennial (NC) or at least intermittent (PNW, OR), respectively. In the case of NCDWQ, the presence of fish can supersede a stream score less than the perennial threshold. There are only five freshwater fishes native to Hawai‘i, though many others have been introduced (Englund et al. 2002) including guppies (e.g., *Poecilia mexicana*), *Gambusia affinis*, chiclids (e.g., *Chichlasoma nigrofasciatum*), and

armored catfish (*Hypostomus watwata*). The five native species are gobioid fishes derived from marine ancestors and all are amphidromous: *Awaous stamineus* (ʻoʻopu nākea), *Eleotris sandwicensis* (oʻopu ʻakupa), *Lentipes concolor* (ʻoʻopu ʻalamoʻo), *Sicyopterus stimpsoni* (ʻoʻopu nōpili), and *Stenogobius hawaiiensis* (oʻopu naniha). These species display a longitudinal distribution pattern along streams based on climbing ability, though they may co-occur in the lower elevations, especially where gentle gradients extend farther inland. The general pattern is that *E. sandwicensis* and *S. hawaiiensis* inhabit lower stream reaches and upper estuaries; *A. stamineus* and *S. stimpsoni* inhabit lower to middle stream reaches; and *L. concolor* inhabits middle to upper stream reaches on the windward sides of islands (to about 500m) and is a very good climber, to where individuals have been found above ʻAkaka Falls, with a free-falling drop of 130m (Kinzie 1990, Parham et al. 2009, Radtke and Kinzie 1996).

Brasher (1996) found that the densities of *S. stimpsoni, A. stamineus* (synonym *guamensis*), and *L. concolor* were all lower in and above a periodically dewatered section of stream compared to similar elevations along a nearby, free-flowing stream with similar characteristics on Molokaʻi. The author posits that temporary dewatering of the diverted stream is inhibiting the upstream migration of these species. Radtke and Kinzie (1996) found that *L. concolor* could occur in perennially flowing upper reaches of streams that naturally have temporary flow in their lower elevations (see Section 4.1) on Molokaʻi and Hawaiʻi. Collected specimens showed physiological evidence of spending time in a saline environment, meaning they migrated up the periodically flowing stream reaches from the ocean during periods of flow. Even when there is flow below a diversion, the reduction in flow may lead to water depths less than 15 cm, which are generally unsuitable for native adult fishes (Parham et al. 2009).

5.0 PROPOSED INDICATORS

Should a Hawaiian Island SDAM be developed, we propose evaluating applicable indicators included in the Pacific Northwest (Nadeau 2015) and NC methods (NCDWQ 2010), including some additional indicators with positive evidence for determining flow duration in the primary literature, as well as any priority indicators from Table 4 (see Section 3) not already included.

Geomorphological indicators

- Slope (Nadeau 2015)
- Continuity of channel bed and bank (NCDWQ 2010)
- Sinuosity of channel along thalweg (NCDWQ 2010)
- In-channel structure (NCDWQ 2010)
- Particle size of stream substrate (NCDWQ 2010)
- Active/relict floodplain (NCDWQ 2010)
- Depositional bars or benches (NCDWQ 2010)
- Recent alluvial deposits (NCDWQ 2010)
- Headcuts (NCDWQ 2010)
- Grade control (NCDWQ 2010)

- Natural valley (NCDWQ 2010)
- Second or greater order channel (NCDWQ 2010)
- Entrenchment ratio (Fritz et al. 2008; Johnson et al. 2009)
- Bankfull width and depth (Fritz et al. 2008; Johnson et al. 2009)
- Maximum pool depth (Fritz et al. 2008; Johnson et al. 2009)

Hydrologic indicators

- Presence of baseflow (NCDWQ 2010)
- Iron oxidizing bacteria (NCDWQ 2010)
- Leaf litter (NCDWQ 2010)
- Sediment on plants or debris (NCDWQ 2010)
- Organic debris lines or piles (NCDWQ 2010)
- Soil-based evidence of high-water table (NCDWQ 2010)
- Seeps and springs (NMED 2011)
- Number of woody jams within 10 m of the reach (Mersel and Lichvar 2014)
- Windward vs. leeward (Parham et al. 2008)

Biological indicators

<u>Aquatic macroinvertebrates</u>

- Presence of aquatic macroinvertebrates (Nadeau 2015; NCDWQ 2010; Topping et al. 2009). Early instars, partial terrestrial taxa, and aerially dispersing life stages will be noted separately, if encountered. Includes aquatic mollusks and crustaceans.
- Presence of perennial and intermittent indicator taxa (Nadeau 2015, NCDWQ 2010, Topping et al. 2009); includes only those taxa found in Hawai‘i. To facilitate this indicator, benthic macroinvertebrates will be identified to the following taxonomic levels:
    - Family: Aquatic Insects, Mollusks, and Crustaceans; it may be decided that species level is practicable for some families
    - Superorder or Order: Aquatic Mites
    - Phylum or Class (if possible): Aquatic Annelida and others

  Every taxon that requires identification to the family level (i.e., aquatic insects and mollusks) will be collected for laboratory confirmation of field identifications. Additionally, whenever the identity of a specimen that requires family level ID is unknown or uncertain, vouchers will be collected to determine identification in the laboratory.

<u>Algae and Bryophytes</u>

- Algae, including general cover % (NCDWQ 2010, Mazor et al. 2021)
- Presence of live or dead algal mats (Topping et al. 2009)

- Presence of streamer mosses (Topping et al. 2009)
- Presence of liverworts (Fritz et al. 2009, Vieira et al. 2016)
- Presence of pleurocarp and acrocarp bryophytes in the channel and banks (Fritz et al. 2009, Vieira et al. 2016)

Wetland and riparian plants

- Fibrous roots in streambed (NCDWQ 2010)
- Presence of wetland plants (includes FACW and OBL; Nadeau 2015, NCDWQ 2010, Topping et al. 2009); Hawai‘i regional plant list shall be used (USACE 2018)
- Distinct riparian vegetation corridor (Topping et al. 2009, NMED 2011)

Vertebrates

- Presence of aquatic reptiles (Nadeau 2015) and aquatic stage amphibians (Nadeau 2015; NCDWQ 2010); identify to genus
- Presence of fish (Nadeau 2015, NCDWQ 2010)

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Note, references gathered, evaluated and used in 2021.

6.1 Flow duration assessment methods

Here we present the references reviewed for methodology or methodology validation in determining flow duration classes. Methods that were excluded based on the criteria in Figure 5 are presented separately; rationale for exclusion is provided in "*Notes*" for each entry. Where applicable, validation studies or studies associated with the development of a method are listed under "*Related References*".

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APPENDIX A:

LITERATURE SCREENING FOR POTENTIAL FLOW DURATION TESTING SITES

This appendix catalogs screening results of literature reviewed for potential leads on baseline or validation sampling sites, with particular focus on intermittent and ephemeral sites. Screening questions included: 1) flow duration classes identified and how/if they were defined; 2) how/if flow duration classes were determined; 3) year(s) work conducted; and 4) locality information provided by the author(s). Reviewed literature was the result of searches shown in Table 1 in the main document.

Table A-1 contains the screening information for literature with potential to provide baseline or validation sites. Included are sites that may dry due to stream diversions. **NOTE**: Indicator and method references are found in Section 6.0; all others (*) are at the end of this Appendix.

Table A-1. Literature Screening for Potential Hawai'i Baseline and Validation Sampling Site Selection. Note: Indicator and method references are found in Section 6.0; all others (*) are at the end of this Appendix.

Reference	Flow Classes and Definition (where available)	How is Flow Class Determined?	Year Work Conducted	Provided Locality Information
Brasher (1997)	Perennial stream with diversion; no definition	Observation of drying in diverted reaches	1992-1994	No coordinates; reaches of Waikolu stream observed to be dry during certain times of the year are identified by station number. Map of stream showing stations is included.
Brasher et al. (2004)	Perennial (8) and intermittent (1)—intermittent stream has 'intermittent flow and occasionally dries completely'	Gage records	1999-2001	No coordinates; maps of watershed locations on island are shown and stream names given.
Cheng (2014)*	Ephemeral (modeled using index sites)—dry more than 50% of the time	Flow duration curves of natural low-flow conditions based on similarly situated index sites with continuous gage records; observations during work period	2012-2013	Gage lat/longs; map of dry reaches
Cheng (2016)*	Ephemeral (modeled using index sites)—dry more than 50% of the time	Flow duration curves of natural low-flow conditions based on similarly situated index sites with continuous gage records	N/A; gage record years differ based on location	Map of sites (index and augmented) with estimated low flow discharge; sites that are estimated to be dry more than 50% of the time are denoted.
Clilverd et al. (2018)*	Intermittent flow during low flow conditions—periodic drying (1 or more days)	Gage records of undiverted streams	N/A; gage record years differ based on location	Streams experiencing flow intermittence are identified by name; USGS gage ID numbers are given for all streams (not just intermittent ones)

Reference	Flow Classes and Definition (where available)	How is Flow Class Determined?	Year Work Conducted	Provided Locality Information
Englund et al. (2002)	Intermittent reaches of 'perennial' streams (both streams have permanently flowing upper reaches)—do not have long enough stretches of flowing water to maintain a diverse aquatic insect population	Lack of algae and less developed aquatic insect fauna	2001	Stream names are given, elevations of sampling are provided
Gingerich (2004)	Intermittent and perennial; no specific definitions provided but describe streams “going dry due to infiltration losses” or going “dry at low flow” or being dry some percentage of time.	Continuous-record stream-gaging station data	1932-2004	Gaging station numbers, station names, and maps of locations. Can use station numbers to determine coordinates in USGS database.
Gingerich and Wolff (2005)	Perennial stated but not defined. Some reaches were described as going dry. The percent of diverted flow is used to characterize habitat conditions.	Discrete measurements (water depth, velocity) and some sites coincided with continous-record stream-gaging stations.	2003-2003	Study reaches named and identified on map. Coordinates can be determined based on stream sites and dates in USGS field measurement database.
Hau (2007)	No flow classes given; flow is ‘absent most of the time’ in reaches studied	Assumed to be observation	1999-2004	Lower reaches of 'Iao and Honomanu Streams have no flow due to water diversions upstream; map of where streams are located on the island are shown, but locations of water diversions are not given

Reference	Flow Classes and Definition (where available)	How is Flow Class Determined?	Year Work Conducted	Provided Locality Information
Hawaii Cooperative Park Service Unit (1990)	Perennial--continuous or interrupted (see Timbol and Maciolek, 1978). Approximately two-thirds of cataloged perennial streams are continuous, the rest are interrupted.	Primary sources (e.g., Timbol and Maciolek 1978), resource experts	N/A	All perennial streams on 5 larger islands are cataloged and indicated as continuous or interrupted, though no coordinates for interrupted reaches are given; maps of perennial streams are provided for each island. Whether these streams have diversions is also indicated, as well as if they have been channelized and lined (usually with concrete), though this info is incomplete.
Hirashima (1971)	Perennial and intermittent; no definition given	Gage records	N/A; gage record years differ based on location	Middle reaches of streams draining to Pearl Harbor are non-perennial, though upper and lower reaches may also be less than perennial; map of streams shown, demarcation of upper and middle reaches not given (approximate altitude given for generally perennial lower reach start).
Kinzie et al. (2006)	Normally perennial stream with water diversion (dam)—no flow over dam 45-55% of the time	Gage records upstream of diversion	1994-1996	Wainiha River; approximate map of dam location is provided
Mink (1962)*	Perennial and ephemeral; ephemeral reaches flow only in response to rainfall	Observation/gage	1957-1959	Kipapa Stream and tributaries; upper third of basin subject of study. Map of study area/tributaries shown, with corresponding elevations. No coordinates

Reference	Flow Classes and Definition (where available)	How is Flow Class Determined?	Year Work Conducted	Provided Locality Information
Presley et al. (2008)*	Ephemeral; no definition given	Gage records	2003-2005	USGS gage ID's are given
Radtke and Kinzie (1996)	Intermittent reaches below perennial ones; definition based on how many days streams flowed to the ocean uninterrupted	Historic flow info from DLNR	1991, 1994	Names of streams and very general map location--Kawela, Papio (Moloka'i) and Kolekole (Hawai'i). Elevational extent of intermittent flow given (measured from stream mouth).
Spengler et al. (2018)*	Perennial and ephemeral; stream described as ephemeral is 'normally dry and only flows during heavy rainfall events or when water is released from the Waiāhole ditch system'	Observations	2018	Names of streams and map locations of watersheds
Stock et al. (2003)*	Ephemeral—flow only in response to rain	Observations	N/A	Area of study is described as having no non-ephemeral water sources (Kahikinui, SE Maui). Map is shown of area in relation to island (leeward).
Strauch et al. (2015)*	Perennial and intermittent—intermittent streams have periods of zero flow	Two gages (1 USGS gage and 1 researcher placed)	2012-2013	Stream names are given, streams with periods of zero flow are denoted separately
Timbol and Maciolek (1978)	Continuous and interrupted, though all are called 'perennial'--Continuous = naturally flowing to sea year-round; Interrupted = intermittent flow in a portion of channel, discharges to sea in wet season (generally May to September)	N/A	1975-1976	Summarizes named perennial streams by island. Provides coordinates for these streams and whether they are continuous or interrupted. Maps are included for altered streams. Describes one 'intermittent stream' (Kawa tributary; O'ahu) that flows intermittently above 180m elevation.

Reference	Flow Classes and Definition (where available)	How is Flow Class Determined?	Year Work Conducted	Provided Locality Information
Trettin et al. (1995)	Perennial and intermittent/ephemeral; the latter are the ‘result of high rainfall’.	N/A	N/A	Maps of Maui and Hawai‘i show areas with perennial streams vs. intermittent/ephemeral. Streams in Waimānalo region of O‘ahu are described as 'short and intermittent'.

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