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REVIEW

Foundational Elements for Developing a US Caribbean Streamflow Duration Assessment Method

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ABSTRACT

Water resource managers need Streamflow Duration Assessment Methods (SDAMs) to predict if streams are ephemeral, intermittent or perennial. Although SDAMs exist for some regions of the United States, no validated SDAM has been developed for Puerto Rico and the US Virgin Islands. This review lays the foundation for a US Caribbean SDAM that will be accurate and practical by characterizing trends in stream research and identifying flow class documentation, candidate indicators of streamflow duration and a hydrogeographic framework. We screened 2081 titles and abstracts and 750 full-text documents. Despite many Caribbean islands having only non-perennial streams or a mixture of perennial and non-perennial streams, our review identified only 10 studies that evaluated stream characteristics between reaches with different flow duration. Candidate indicators include drainage area, riparian herbaceous cover, two fish metrics and 19 aquatic invertebrate metrics. A total of 235 documents provided localities for 2282 stream reaches, 94.7% in Puerto Rico and 5.3% in the US Virgin Islands. Eighty-two documents classified streamflow duration, but only 45 provided flow class and locality. From these, we identified 425 candidate SDAM study reaches, of which 308, 103 and 14 were perennial, intermittent and ephemeral, respectively. Hydrology, chemistry and geomorphology topics dominated the stream research literature. The ecological life zones framework is the most suitable of 13 hydrogeographic frameworks for a US Caribbean SDAM. The subtropical dry forest zone contained most of the documented intermittent reaches, whereas documented perennial reaches dominated the subtropical moist forest and subtropical wet forest zones.

1 | Introduction

Many classification terms have been used to describe streamflow duration, but perennial, intermittent and ephemeral are among the most used terms in water resource management and hydrography (Busch et al. 2020; Fritz et al. 2013). Perennial reaches have continuous surface flow that does not stop outside of drought periods. Intermittent reaches have continuous surface flow for part of the year that is maintained by groundwater or another stable water source. Ephemeral reaches have surface flow only during and immediately after precipitation events (Nadeau 2015; Fritz et al. 2020).

Hydrologic data and models that accurately describe flow duration for entire river networks are limited and are often disproportionately focused on large rivers in densely populated regions (Krabbenhoft et al. 2022). Remote sensing surveys may not capture the spatial extent and flow conditions of headwater streams due to technical limitations in many regions (Christensen et al. 2022). Streamflow Duration Assessment Methods (SDAMs) are rapid, single-visit, field-based methods that can accurately predict flow duration classes in support of reach-scale (i.e., stream length ~40× channel width) management decisions (e.g., water quality standards, riparian buffer widths and regulatory jurisdiction [Fritz et al. 2020]). SDAMs have been developed for the Pacific Northwest (Nadeau 2015), Arid West and Western Mountains (Mazor et al. 2024), Great Plains (James et al. 2024) and the Northeast and Southeast United States (James et al. 2023), but there are no validated SDAMs for the US Caribbean or other Caribbean islands. Despite this, streamflow duration classification of stream reaches is used in the application of Puerto Rico (PR) and the US Virgin Island (USVI) Water Quality Standards Regulations (water quality standard variance [DPNR 2019; PRDNER 2022]) and best management practices for erosion and sediment control (Puerto Rico Environmental Quality Board and U.S. Department of Agriculture Natural Resources Conservation Service 2005; Horsley Witten Group 2022). Under USVI law there are also several relevant provisions that recognize conservation of non-perennial streams (e.g., USVI Code title 12 § 187(b), title 29 § 3–226(p); Reiblich and Ankersen 2016).

The key components of SDAMs are hydrologic data, study reaches and physical and biological indicators (Fritz et al. 2020). Hydrologic data represent the direct measurement for the assignment of stream reaches to a flow duration class. The relationship between hydrologic data and indicators reflects the cause-and-effect relationship between stream drying and inferential physical and biological variables. Such variables may be environmental characteristics that control streamflow duration or those that respond to streamflow duration. Study reaches used in SDAM development need to represent the range of streamflow duration and other covariate conditions (e.g., physiographic region, land use and stream size) for which the SDAM will be implemented. Distributing study reaches across expected strata or gradients will help produce a robust SDAM that captures variability in how indicators distinguish flow duration classes across the target region. A hydrogeographic framework that describes dominant controls of streamflow duration should guide the spatially balanced distribution of study reaches. This ensures the SDAM can be applied adequately for the region, even in areas with contrasting hydrologic conditions.

The development of SDAMs involves a multistep process to integrate the key SDAM components into implementable methods (Fritz et al. 2020). The first step, preparation, involves conducting a literature review, engaging stakeholders and identifying candidate indicators (single-visit, field-measurable geomorphic, hydrologic or biotic factors) and study reaches (stream segments with a documented streamflow duration class) to develop a protocol for data collection. In step one (preparation) and step two (data collection) of the Southeastern US SDAM development, both PR and the USVI were included (James et al. 2023). However, step three (data analysis) revealed that indicators collected from study reaches in PR and the USVI differed from those collected from the rest of the southeastern United States (Gross et al. 2023). This is consistent with the region's unique geology (volcanic origin and tectonic uplift), tropical climate, high biodiversity, steep and short stream channels and intense human pressures on freshwater resources (Boulton et al. 2008; Smith et al. 2003; Heartsill Scalley 2012). The US Caribbean was excluded from the SDAM effort in the Northeastern and Southeastern regions because there were insufficient data collected from PR and the USVI to develop a US Caribbean-specific SDAM. Additionally, the beta SDAM developed for the Southeast was only 42% accurate at classifying perennial, intermittent and ephemeral reaches in PR and the USVI (Gross et al. 2023). The literature review for the Northeastern and Southeastern United States (James et al. 2022) also neglected to include any references for stream studies in PR or the USVI. Therefore, a US Caribbean-specific SDAM is still needed, and a systematic review of the Caribbean stream literature is needed to provide a foundation for its development.

The overarching objective of the systematic literature review is to gather foundational information for the development of a US Caribbean-specific SDAM. This literature review addresses four questions aimed at informing and improving the understanding of streamflow duration and the state of knowledge in the US Caribbean.

1. What are candidate indicators for predicting flow duration class of insular Caribbean streams?
2. Where are study reaches with documented streamflow duration class in the US Caribbean?
3. What are the existing hydrogeographic frameworks that capture important gradients (i.e., strata) related to streamflow duration in the US Caribbean?
4. What are the geographic and temporal distributions of published stream research by topic in the US Caribbean?

2 | Methods

A detailed protocol was prepared to support consistency, repeatability, and objectivity of the systematic literature review (Supporting Information S1). A summary of the protocol is described here.

2.1 | Stakeholder Engagement

As a first step towards developing our systematic review, a group of collaborators and stakeholders was assembled as a US Caribbean Regional Steering Committee (RSC) to guide SDAM development and implementation. The purpose of the RSC to SDAM development is to share knowledge and connections to the network of resource practitioners and organizations in the region. RSC involvement from the onset is important for their technical vetting of the regional SDAM development, enabling representation from diverse perspectives and building ownership that can improve subsequent adoption and implementation of the SDAM. The contributions of the RSC to the systematic review included sharing relevant documents that were overlooked in the systematic searches and providing feedback on the organization and synthesis of information gathered.

2.2 | Systematic Searches for Documents

The literature databases used were Web of Science, ProQuest, the Environmental Protection Agency's National Service Center for Environmental Publications, the US Geological Survey's Publication Warehouse, the National Oceanic and Atmospheric Administration's Institutional Repository, the US Army Corps of Engineers' Digital Library, the US Department of Agriculture Forest Service's Treesearch, and the US Fish & Wildlife Service's Publication Library to search for relevant articles, theses, dissertations, book chapters, and governmental reports (Table S-1). No restriction for inclusion in the literature review was placed on the year of publication.

Two systematic searches were made within each of the eight databases on 17 November 2023, one using an indicator and reach search string (to address Questions 1, 2 and 4) and another using a hydrogeographic framework search string (to address Question 3), resulting in 16 separate search corpora. Up to the first 100 documents (excluding any duplicates) identified in each search corpus were compiled for screening. The search terms (Table S-2) were selected to target location, hydrology and types of indicators used in existing SDAMs or factors used in hydrogeographic frameworks. Location, hydrology and indicator sets of terms were combined into an indicator and study reach Boolean search string and used to retrieve documents to address Questions 1, 2 and 4. The location and framework sets of terms were combined into a Boolean search string and used to retrieve documents to identify hydrogeographic frameworks (Question 3) (Table S-3). Most terms used were in English; however, some hydrology terms in Spanish (*quebrada*, *río*, *riachuelo* and *ribereño*) and the English-speaking Caribbean region vernacular terms, gut and ghut (=stream), were added based on RSC recommendations. Only sources in Spanish and English were reviewed.

Our search strategy was designed to cover a broad scope of documents to address our review questions. However, to identify additional documents for screening, we manually searched the reference sections of documents identified through the systematic searches (SSDs) and relevant review articles and documents provided by the RSC. These additional documents were collectively referred to as non-systematic documents (NSDs). The comprehensiveness of our SSD corpora was assessed relative to our NSD corpora.

2.3 | Article Screening and Data Extraction

Documents were screened in two stages, a title and abstract stage followed by a full-text stage (Figure S1.1). Documents without an abstract, preface or executive summary (e.g., chapters of relevant books) were screened only at the title level. Documents were eligible for the indicator criterion (Question 1) at the title and abstract stage if the documents described the study of physical, chemical or biological characteristics of streams or rivers from any Caribbean island. Documents were eligible for the study reaches criterion (Questions 2 and 4) if they included stream or river study reaches in PR or the USVI. Documents were eligible for the hydrogeographic frameworks (Question 3) if the titles and abstracts described a Caribbean framework for organizing geographical units based on climate, geology, hydrology, landform, ecology or other pertinent variables. The documents were screened by the study's authors as follows: The document screening was divided between K.G.-R. and K.M.F., whereas A.C.E., T.H.-S., S.P.K. and C.E.R.-S. screened a random subset of documents (160 documents) to confirm screening consistency with KGR and KMF was at least 90%.

At the full-text screening stage, the eligibility criterion for candidate indicators was the assessment of one or more relationships between an indicator metric and streamflow duration (or drying). Eligible documents for candidate study reaches in PR or the USVI included precise locality (latitude and longitude coordinates, ≥ 5 decimal places) or locality could be estimated from a detailed study map. Documents were ineligible if no coordinates for study reaches were provided or could not be estimated. Eligible documents for hydrogeographic frameworks described a Caribbean framework in the title and abstract for identifying landscape units with similar hydrologic characteristics and biophysical associations. Such eligible documents could extend beyond but must have included PR and/or the USVI and described variation in landscape-scale characteristics such as climate, geology, hydrology, landform, ecology or other pertinent variables. The eligibility criterion at the full-text screening was having a map or geodatabase that explicitly delineated the location of the hydrogeographic framework. Lastly, review or editorial articles that did not provide original data were considered ineligible for data extraction to avoid duplication with cited original studies.

Because ephemeral and intermittent streams have been understudied globally compared to perennial streams (Leigh et al. 2016; Allen et al. 2020), our literature review for candidate indicators of streamflow duration broadly included Caribbean studies that characterized indicator metrics for flow duration, desiccation (lab experiments), drought or water diversions. The data extracted from each eligible document about candidate indicators included the indicator type for a specific metric, stream drying treatment (i.e., flow duration, desiccation, drought or diversion) and the reported relationship (i.e., directional, neutral, or mixed) (Table S-4). Directional relationships could be positive or negative, representing increases or decreases, respectively, of an indicator metric with increasing flow duration or less exposure to stream drying (e.g., non-drought). Neutral relationships were identified for metrics having no reported relationship. Mixed relationships were identified for metrics having sometimes positive, negative or no relationships with stream drying.

Data extracted from the full-text screening were used to address five criteria for identifying candidate indicator metrics: (1) Discernable: Does the document report that an indicator metric can discriminate between stream drying treatments? (2) Repeatability: Can the indicator metric be consistently measured by different trained practitioners and across sampling conditions? (3) Defensibility: Does the indicator metric have a rational or mechanistic relationship with flow duration? (4) Rapidness: Can the indicator metric be modified to be measured during a 1-day site visit? (5) Objectivity: Does the indicator rely on objective or quantitative measurement? Candidate indicators for developing a US Caribbean SDAM were those identified to satisfy the five criteria. We further distinguished candidate indicator metrics that met the discernable criterion based on statistical analysis from those based on a non-statistically supported interpretation of study data.

Among the documents identified in the review was a Puerto Rico Department of Natural and Environmental Resources technical report (hereafter called the PR Protocol) that described the development of an SDAM for PR (PRDNER 2007). The PR Protocol includes 26 indicator metrics that are scored either ordinally (five levels) or as binary (present or absent) and represent hydrology, geomorphology and biological indicator metrics (Table S-5). Among the indicator metrics used, 24 were adapted from indicators used in an SDAM developed for North Carolina, USA (NCDWQ 2005), and two were novel indicator metrics characterizing the presence of natural flow connectivity and the presence of skeletonized leaves on the streambed. The purpose of the PR Protocol was to develop a rapid method for classifying whether a topographic feature is an ephemeral/intermittent (non-perennial) or perennial stream or not a stream. However, the SDAM classes developed were based on the combined indicator values rather than association with the actual duration of channelized surface flow, nor has the method yet been validated across stream reaches with varying flow duration (PRDNER 2007; Francisco A. Catalá Míguez, personal communication).

Although the PR Protocol did not describe the performance of different indicator metrics (independently or jointly) for discerning flow duration classes, it contains information that can be used to address Question 1 of our review. First, the document includes scoring the importance of indicator metrics for discriminating flow classes by a panel of 27 experts to derive weighting factors used in the PR Protocol. Second, although the actual streamflow duration classes of study reaches are unknown, the 83 study reaches of the PR Protocol were selected to represent a range of flow duration. Given this, metrics with mostly uniform scoring across study reaches would be expected to be less useful in distinguishing among streamflow duration classes than metrics with varying scores. Lastly, we used contingency tables (Fisher's exact test with Benjamini–Hochberg procedure) to compare associations between ordinal scoring of the observed base flow conditions recorded during one-time, dry season (12/26/07 to 2/22/08) reach visits and the recorded scores of the other 25 PR Protocol metrics. Somers' delta (*DescTools* 0.99.55 package in R v4.4.0) was used to measure strength and direction between the ordinal base flow condition scores and each of the scores of the other PR Protocol metrics across the 83 study reaches. Although the observed base flow conditions represent an instantaneous measure rather than streamflow duration, exploring the associations between observed flow conditions at the time of assessment provides insight on relative responsiveness to stream drying among the PR Protocol metrics.

Data extracted from documents identified as eligible for candidate study reaches included territory and municipality (for PR) or island district (for the USVI); certainty of study locality (provided coordinates, coordinates estimated from detailed study maps or coordinates unknown); reported streamflow duration class (perennial, non-perennial, intermittent or ephemeral) and associated definitions; and study data used to support streamflow duration class (e.g., observation, streamgage, camera or other types of data loggers). To address literature review Question 4, we coded candidate study reaches identified in eligible documents based on the data reported for different research topics: hydrology, geomorphology, chemistry, microbiology (bacteria, fungi and algae), vegetation (plants and organic matter), invertebrates and vertebrates (fish, amphibians and reptiles).

Data extracted from eligible documents for candidate hydrogeographic frameworks for use in SDAM development (Question 3) included the geographic scope, the factor categories (climate, geology, hydrology, landform, ecology or other), factor type (categorical or continuous), specific factor(s) used in the framework, the number of regions identified in the framework and the regionalization approach (qualitative or quantitative) used to define regions. The extraction and coding of information from eligible documents at the full-text stage was evaluated by applying the double-screening and consistency process to 12 randomly chosen documents and resulted in 88% consistency in the coding of extracted information.

The data extracted were synthesized to best inform the foundational elements for the development of a US Caribbean-specific SDAM. All maps were created using ArcGIS Pro 3.3 and graphs were created in R v4.4.0 or SigmaPlot v15.0. To display the distribution of study locations, we intersected each unique study reach with a boundary layer of PR municipalities and USVI districts and aggregated them accordingly. We measured the total stream kilometres (km) for each municipality and USVI district using the National Hydrogeography Dataset (NHD) (USGS 2023) flowline layer (f-codes 33400, 33600, 46003, 46006 and 55800) and described variation in the density of documented study reaches relative to the total kilometres of NHD flowlines across the US Caribbean.

3 | Results

The systematic searches to address questions for candidate indicators, study reaches and research topics identified a corpus of 14,358 documents, and the systematic searches for candidate hydrogeographic frameworks identified a corpus of 11,867 documents. Of the identified documents, we screened the titles and abstracts of 1270 SSDs and an additional 811 NSDs. Of those documents, 139 SSDs and 611 NSDs were eligible for full-text screening (Figure S2.1). All eligible SSDs for full-text screening were in English, whereas 582 and 29 of NSDs were in English and Spanish, respectively.

3.1 | What Are Candidate Indicators for Predicting Flow Duration Class of Caribbean Streams?

We completed full-text screening of 677 documents for candidate indicators (Table S-6). We identified and excluded nine documents from data extraction because they had redundant content already extracted from other documents. We identified 25 documents that compared indicator metrics across drying

TABLE 1 | Candidate indicator metrics identified in literature review by indicator type, stream drying treatment and source document.

Indicator type	Indicator metric	Dry treatment	Document
Catchment	Drainage area (+)	Flow duration	Larsen and Santiago Román (2001)
	Drainage area (+)	Flow duration	Pike (2006)
Riparian vegetation	Riparian herb cover (+)	Flow duration	Scatena (1990)
Aquatic invertebrates	Mollusc presence (+)	Flow duration	Harrison and Rankin (1978)
	Juvenile Thiaridae survival* (+)	Flow duration	Facon et al. (2004)
	Tarebia granifera survival (−)	Desiccation	Chaniotis et al. (1980)
	T. granifera density (+)	Drought	Yong et al. (1987)
	T. granifera presence* (+)	Flow duration	Facon et al. (2004)
	Biomphalaria glabrata abundance (+)	Flow duration	Pimentel and White (1957)
	B. glabrata presence (+)	Flow duration	Pimentel and White (1959a)
	B. glabrata survival (+)	Desiccation	Pimentel and White (1959b)
	B. glabrata and *Tropicorbis* abundance (−)	Diversion	Ritchie et al. (1962)
	B. glabrata survival* (−)	Desiccation	Sturrock (1970)
	Medium *B. glabrata* survival* (−)	Desiccation	Sturrock (1970)
	Large *B. glabrata* survival* (−)	Desiccation	Sturrock (1970)
	Macrobrachium presence (−)	Diversion	Sutton et al. (1997)
	Atya density (+)	Drought	Covich et al. (1998)
	Atya density* (+)	Drought	Covich et al. (2003)
	Xiphocaris density* (+)	Drought	Covich et al. (2003)
	Percent gravid *Atya* females* (−)	Drought	Covich et al. (2003)
	Macrobrachium abundance* (−)	Drought	Covich et al. (2006)
	Macroinvertebrate density in riffles (+)	Drought	Gutiérrez-Fonseca et al. (2020)
	Macroinvertebrate density in pools (+)	Drought	Gutiérrez-Fonseca et al. (2020)
Fish	Fish presence (+)	Flow duration	Loftus (2003)
	Agonostomus monticola presence (−)	Diversion	Sutton et al. (1997)

Note: + = positive relationship with dry treatment; − = negative relationship with dry treatment. Metrics with asterisk (*) identify statistical analysis supported relationships; otherwise, relationships were based only on statements in documents.

treatments (only 1.6% of the 1521 total documents screened for indicator metrics) through our full-text reviews. Among those documents, metric responses were measured between flow duration classes in 10 documents, between drought and non-drought conditions in nine documents, between desiccation exposures in four documents and between water diversion and non-diversion treatments in two documents. Stream drying has been most studied in PR relative to other Caribbean islands (19 of the 25 identified documents). The other six identified documents are studies in Cuba, Curaçao, Martinique, St Lucia, St Vincent and the USVI.

The number of indicator metrics evaluated in the 25 documents ranged from 1 to 26. The most studied metric type we identified was invertebrates, with 45 different indicator metrics across 18 identified documents (Table 1 and Table S-7). The other 24 metrics evaluated organic matter (8 unique metrics), riparian vegetation (6), algae (3), hydrology (3), fish (2), physicochemistry (1) and catchment (1) measures between stream drying treatments. Four metrics (drainage area, *Biomphalaria glabrata* snail survival, *Atya* shrimp density and *Xiphocaris elongata* shrimp density) were each evaluated in two identified documents, resulting in a total of 73 metrics to evaluate across the 25 documents (Table 1 and Table S-7). Based on relationships reported in the identified documents, we scored 59% of the 73 metrics as meeting the discernable criterion (Table 1 and Table S-7). Most metrics meeting the discernable criterion decreased with stream drying duration, but there were density-based metrics for invertebrates, algae and organic matter that were higher during drought than non-drought conditions. The discernable criterion for 46.6% of the identified indicator metrics was based on results supported by statistical analyses reported in the documents (Table 1 and Table S-7). Fifteen of the identified metrics that met the discernable criterion were determined to not be easily modified for 1-day field assessments (Table S-7).

There were 23 candidate metrics that satisfied the five evaluation criteria for candidate indicator metrics (Table 1). The candidate metrics included drainage area, cover of riparian herbaceous vegetation, two fish metrics, and 19 aquatic invertebrate metrics. Fish metrics included presence of mountain mullet (*Agonostomus monticola*) and presence of fish. Aquatic invertebrate metrics included 12 for molluscs, five for shrimp and two for overall macroinvertebrate density.

The PR Protocol metrics identified by the panel of experts as being the most important in differentiating flow classes were presence of fish, aquatic crustaceans, aquatic molluscs, aquatic insects, filamentous green algae, red algae and skeletonized leaves (Figure 1a). Presence of soil redox, soil chroma, histosol soils, wetland plants, fibrous roots and terrestrial plants in the channel were identified as being the least important

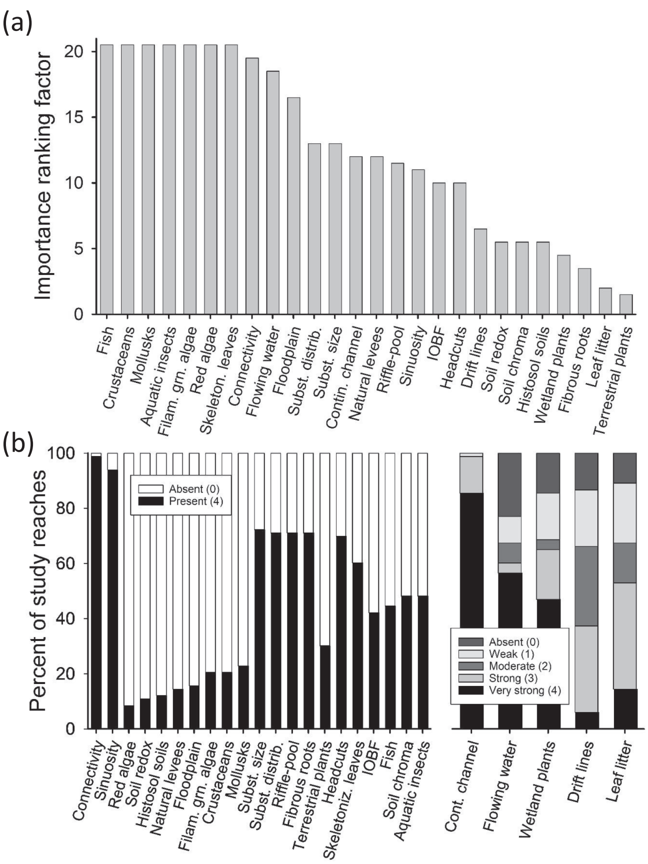

FIGURE 1 | Indicator metrics proposed for streamflow duration classification in a Puerto Rico Department of Natural and Environmental Resources technical report (PDNER 2007). (a) Importance ranking factors for 26 indicator metrics for discriminating among flow classes as scored by a panel of 27 experts, where higher values represent indicator metrics considered more important in streamflow duration classification. (b) Indicator metric scores across 83 study reaches of varying streamflow duration in Puerto Rico. Metrics scored as presence/absence are shown on left and metrics scored ordinally (five levels) are shown on right. Metrics are ordered by degree of uniformity across study reaches, where high uniformity infers low discriminatory ability among streamflow classes. IOBF = iron-oxidizing bacteria and fungi.

indicators for flow classification of PR streams. Based on the scoring of 83 study reaches, the PR protocol metrics that were most uniformly scored (≥ 90%) were presence/absence of connectivity to downstream water, channel sinuosity and red algae (Figure 1b). These three metrics are expected to be ineffective at distinguishing perennial, intermittent and ephemeral reaches in PR. Ordinal scoring of observed flow conditions at the time of assessment varied significantly with scoring of prevalence of leaf litter, degree of continuity of channel, wetland plant categories, presence/absence of riffle-pool sequences, within-channel differences in substrate distribution, in-channel versus out-of-channel substrate sizes, aquatic molluscs, aquatic insects, fish, iron oxidizing bacteria and skeletonized leaves across the 83 PR protocol study reaches (Fisher exact text $p < 0.05$; Table S-5). The presence-absence of aquatic insects, riffle-pool sequence, and fish, and the degree of continuity of channel, were the most strongly associated metrics with the observed flow condition score (Somer's delta > 0.5; Table S-5). Presence/absence of soil chroma indicative of redox, histosol soils, natural levees, head cuts and skeletonized leaves had the lowest correlation with observed flow condition scores and/or the direction of the relationship was opposite of expected direction for the metrics.

3.2 | Where Are Study Reaches With Documented Streamflow Duration Class in the US Caribbean?

Across the 529 eligible documents for full-text review (Table S-6), we identified 235 documents with detailed locality for study reaches (2282 unique reaches) and 82 documents with streamflow classifications for study reaches, but only 45 documents provided study reaches with flow class and detailed locality. Among those 45 documents, we identified 425 unique candidate SDAM development reaches (Table S-8). Most (72.5%) of the candidate study reaches we identified were documented as perennial, with only 24.2% and 3.3% documented as intermittent and ephemeral, respectively. Only four perennial reaches were in the USVI (all in St Thomas), where most of the documented intermittent (72 of 103) and ephemeral reaches (8 of 14) were identified. We only identified one candidate study reach that had different classifications across documents: the reach in St Thomas (the Dorothea Gut—USGS station 50252000) was classified as intermittent in two documents (Reid 1991; Gardner 2008) and perennial in three other documents (Jordan and Cosner 1973; Ajayi and Smith 1983; Benoit and Nemeth 2011). The methods used to classify the 425 candidate study reaches among the 45 documents varied, with 48.7% of the reaches classified based on the National Hydrography Dataset (NHD) and all being perennial reaches. Candidate study reaches classified using streamgage data accounted for 16.5%, whereas 12.5% of reaches were classified based on periodic observations or measurements. Most of the reaches classified based on streamgage data and periodic data (59 of 70 and 32 of 53, respectively) were perennial. No basis for the flow classification was documented for 22.4% of the candidate study reaches identified, and most (79 of 95) represented intermittent reaches. Overall, 84% of the candidate study reaches had coordinates provided in the reviewed documents, whereas 17% required locality estimation from detailed maps.

3.3 | What Are the Existing Hydrogeographic Frameworks That Capture Important Gradients (Strata) Related to Streamflow Duration in the US Caribbean?

Full-text screening of 119 documents was completed for existing hydrogeographic frameworks for the US Caribbean, but only 29 documents included existing frameworks (Table S-6). Among those 29 documents, 13 unique candidate frameworks were identified (Table 2). Of these 13 frameworks, three were statistically derived and based on continuous measures such as elevation, topographic relief, seasonal precipitation and temperature. The number of regions included in frameworks ranged from 3 to 14, spanning part or all of the US Caribbean (Table 2).

All 13 candidate hydrogeography frameworks were presented in the hybrid workshop with RSC members, and the Ewel and Whitmore (1973) 'ecological life zones' framework emerged as the most suitable existing framework for capturing important gradients related to streamflow duration in the US Caribbean. This choice was validated by the consensus that the chosen framework for which an SDAM be developed should include PR and the USVI. Ten of the 13 identified frameworks did not include the USVI. The physiographic province and climate regions frameworks included PR and the USVI, and each divided the US Caribbean into four regions (Table 2). However, compared to the ecological life zones framework, these other two frameworks did not integrate several characteristics that the RSC discussed as strongly influencing streamflow duration in the US Caribbean; instead, they mainly draw four boundaries based on generalized topography and annual precipitation. For this reason, the ecological life zones framework, which considers mean annual precipitation, mean annual biotemperature and potential evapotranspiration, was deemed the best existing framework for designing a US Caribbean SDAM development study. The ecological life zones framework includes six zones with the subtropical moist forest (SMF), subtropical dry forest (SDF) and subtropical wet forest (SWF) representing 73.2%, 22.0% and 3.0% of the US Caribbean, respectively. The SDF and SMF are the only zones represented in the USVI and the outlying PR islands of Vieques and Culebra. The subtropical rain forest (SRF), low montane wet forest (LMWF) and low montane rain forest (LMRF) zones together represent 1.8% of the US Caribbean and are restricted to the main island of PR.

3.4 | What Are the Geographic and Temporal Distributions of Published Stream Research by Topic in the US Caribbean?

We identified 230 documents with detailed locality for study reaches where reported stream data were collected. Across the 230 documents, we identified 2282 unique study reaches (three reaches were excluded because the reported coordinates placed them in the Atlantic Ocean). About 5% of the reaches were in the USVI and 95% were in PR. Within PR, study reaches were heavily concentrated in the northeastern (San Juan and Río Grande) and central (Utuado) municipalities of the main island (Figure 2a and Figure S2.2); these areas also had among the highest total length of NHD flowlines (Figure 2b). The geographic distribution of study reaches relative to the total length of NHD flowlines within municipalities further shows a geographic emphasis of stream research in northeastern PR (San Juan, Río Grande, Luquillo) and the islands of Culebra, St Thomas and St John (Figure 2c). No or few study reaches were identified in several smaller coastal PR municipalities (e.g., Arroyo, Florida and Rincón) with shorter NHD flowline extents. Some areas, such as the municipalities in western PR (Cabo Rojo, Lajas, Las Marías and San Sebastián), central PR (Orocovis) and southeastern PR (Guayama and Salinas), have been understudied relative to the extent of NHD flowlines.

The geographic distribution of data collection reveals that some research topics are widely represented across the US Caribbean, whereas others are primarily clustered in specific areas and completely absent on some islands. Most identified documents reported data across multiple topics, with 55% reporting data collected for more than one topic and 45% reporting data for only one topic. Among individual topics, hydrology had the highest percentage of documents in both PR (53.1%) and the USVI (63.6%) (Figure 3a), and hydrological data collection exhibited widespread distribution across the US Caribbean (Figure S2.3a). Chemistry and geomorphology data were also reported in high percentages of documents in PR (40.2% and 28.1%, respectively) and the USVI (45.5% and 27.3%, respectively). Chemistry and geomorphology data collection were geographically clustered in northeastern PR (Figure S2.3b,c). Chemistry data had a comparable geographic range as geomorphology data, although we identified chemistry data from only one location in Culebra and no locations in Vieques. Biological data were more sparsely collected in the US Caribbean than hydrology, chemistry and geomorphology data (Figures 3a and S2.3). Among biological topics, invertebrate data collection was the most prevalent studied in PR (33.5% of documents), clustered mainly in northeastern PR (Figure S2.3f). In the USVI, invertebrate data collection was only reported in 13.6% of the identified documents and was restricted to reaches on St Thomas. Reported data on riparian vegetation and organic matter were from 21.7% of the identified PR studies and only 9.1% of identified USVI studies. Stream microbiology (bacteria, fungi and algae) was the most sparsely (4.5%) reported type of data from the USVI. Aquatic vertebrate (fish, amphibian and reptile) data were reported only from 12.6% of the PR studies but from 27.3% of the USVI studies identified in our review.

Beyond geographic patterns, the temporal distribution of documents provides insight into changing research focus. The oldest reported data we identified were from 1930 and reported mainly data on fish and invertebrates (Figure 3b). We identified few documents published during the 1930s–1950s, and the reported data from those documents were mainly on aquatic invertebrates, vertebrates and algae. From the 1960s through 1980s, there was a gradual increase in reporting chemistry, geomorphology, hydrology and microbiology data. In contrast, the reporting of riparian vegetation, organic matter, aquatic vertebrate and invertebrate data continued to average less than one document per year during this period. From the 1990s onwards, US Caribbean stream publications across all topics experienced an increase in the mean number of documents published per year (Figure 3b). Hydrology, chemistry

TABLE 2 | The candidate hydrogeography frameworks for the US Caribbean identified in full-text screening. The geographic extent identifies if the frameworks apply to Puerto Rico (PR), US Virgin Islands (USVI) or both. The factors are the characteristics that are spatially described by the number of regions in the hydrogeographic frameworks. The regionalization approach provides a general description of how regions were defined (qualitative = descriptive, subjective judgement; quantitative = numerical, statistical analysis).

Candidate framework	Geographic extent	Factors	Number of regions	Regionalization approach	References
Ecological life zones	PR, USVI	Mean annual precipitation and mean annual biotemperature, potential evapotranspiration	6	Qualitative	Ewel and Whitmore (1973); Clark (1998); Miller and Lugo (2009); Erickson et al. (2014); Ramírez and Gutiérrez-Fonseca (2014)
Climate regions	PR, USVI	Major mountain ranges and annual precipitation	4	Quantitative	Van Beusekom et al. (2014); Van Beusekom et al. (2016)
Physiographic provinces	PR, USVI	Generalized topographic	4	Qualitative	Monroe (1976); Monroe (1977); Monroe (1980); Veve and Taggart (1996); Miller et al. (1999); Williams-Sether (2021)
Groundwater provinces	PR	Geologic units and physiographic features	8	Qualitative	Gómez-Gómez and Heisel (1980); Gómez-Gómez (1987); Veve and Taggart 1996; Renken et al. (2002); Gómez-Gómez et al. (2014)
Geographic regions	PR	Soil, topography, climate, natural vegetation, and economic activities	11	Qualitative	Picó 1974; Gómez-Gómez et al. (2014)
Satellite image mapping zones	PR	Mean annual precipitation, mean annual biotemperature, potential evapotranspiration, rocks grouped by soil-producing characteristics	9	Qualitative	Helmer et al. (2002)
Hydrographic zones	PR	Generalized trade winds and geography	4	Qualitative	Colón-Dieppa (1986); Colón-Dieppa and Torres-Sierra 1991; Lugo et al. (2011)
Climatic zones	PR	Seasonal precipitation, mean, max and min temperature	4	Quantitative	Malmgren and Winter (1999)
Climax forests	PR	Original vegetation	8	Qualitative	Picó (1974)
Natural landscape units	PR	Elevation, surface, roughness, rock type, life zones	14	Quantitative	Soto and Pintó (2010)
Climate divisions	PR	Mean monthly precipitation	6 or 7	Qualitative	Harmsen et al. (2002); Gómez-Gómez et al. (2014); Torres-Valcárcel (2018)
Biomes	PR	Generalized biome distribution	3	Qualitative	Yu et al. (2019)
Physiographic provinces	PR	Generalized topography	6	Qualitative	Van der Schalie (1948)

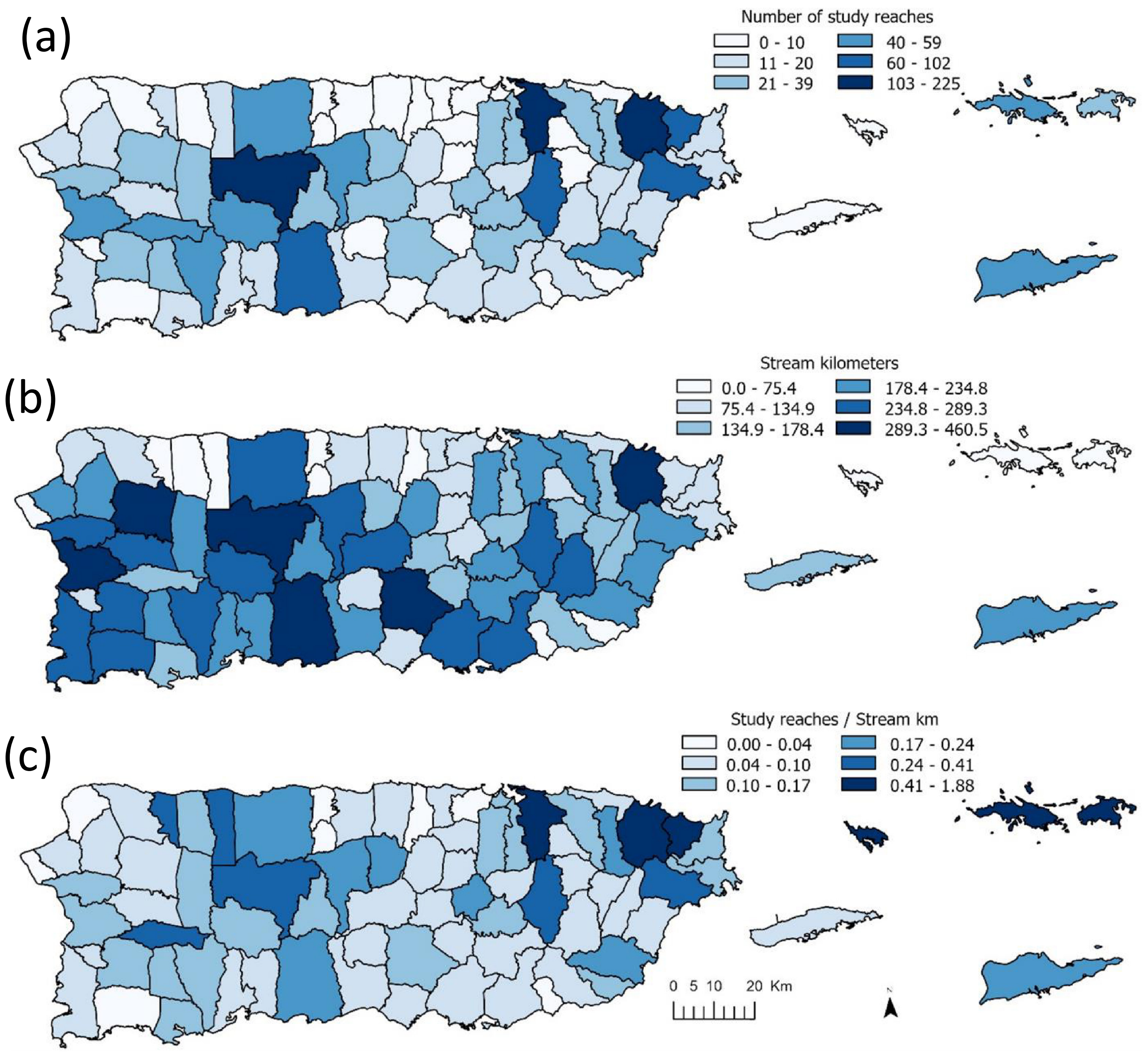

FIGURE 2 | (a) Number of study reaches by Puerto Rico municipality or US Virgin Island district. (b) Total length of National Hydrographic Dataset (NHD) flowlines within municipality or district. (c) Number of study reaches by municipality and district relative to the total length of NHD flowlines within municipalities or district.

and geomorphology emerged as the most frequently published data from US Caribbean streams.

4 | Discussion

This systematic review assembled and synthesized baseline information on candidate indicators, candidate study reaches and a hydrogeographic framework as foundational elements for the development of an SDAM specific to the US Caribbean. Consultation with the RSC ensured that the SDAM would be informed by existing regional knowledge to its fullest extent and enhanced engagement of local stakeholders for successful implementation. Although the questions were specifically asked to provide a foundation for developing a US Caribbean SDAM, the information synthesized provides a state of knowledge for stream drying in the Caribbean and an overview of the geographic and temporal patterns of stream and river research in PR and the USVI.

4.1 | Candidate SDAM Indicators

Based on our literature review, flow duration in Caribbean streams has been infrequently studied. Despite many Caribbean islands having only non-perennial streams or a mixture of perennial and non-perennial streams (Matalas and Grossling 2002; Heartsill Scalley 2012), our review identified only 10 studies that evaluated stream characteristics between reaches with different flow duration. Additionally, we supplemented our review

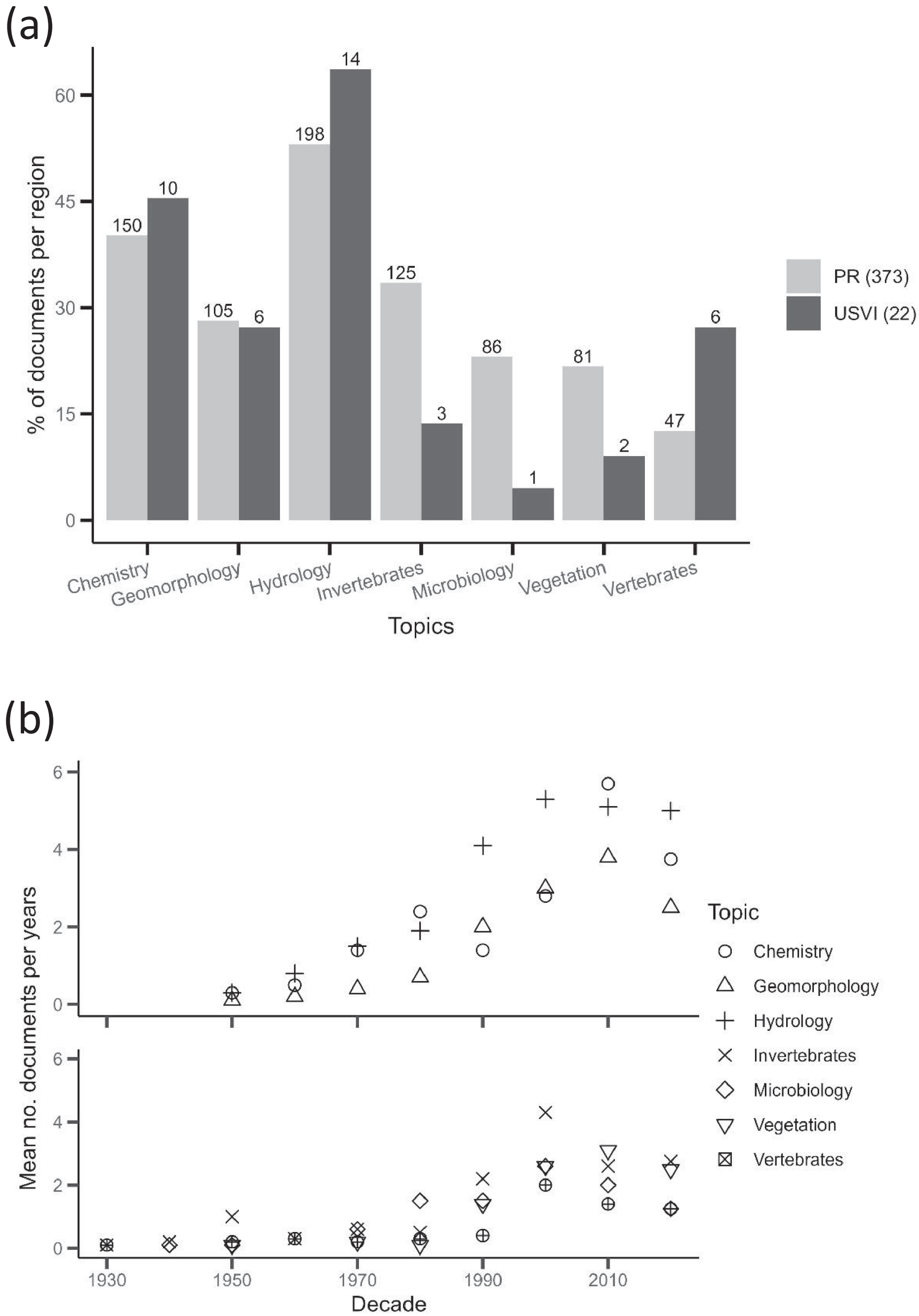

FIGURE 3 | Geographic and temporal distributions of published stream and river research by topic. (a) The percent of documents for each topic in Puerto Rico and the US Virgin Islands. The number above each bar is the total number of documents. (b) The mean number of documents per years by decade regarding seven different topics.

of candidate indicators of flow duration by including studies investigating the effects of drying associated with drought in perennial streams, control of disease vectors and water diversions. The indicator metrics identified in our review as candidates to evaluate in a US Caribbean SDAM study include mainly aquatic macroinvertebrate and fish metrics. Aquatic macroinvertebrates and fish are commonly included and considered among the most important indicators in SDAMs developed for other regions (e.g., Fritz et al. 2013; Nadeau 2015; Mazor et al. 2021) and so would be expected to be among candidate indicators to evaluate for a US Caribbean-specific SDAM. Some candidate invertebrate metrics are tailored to the US Caribbean fauna, namely, the presence or abundance of some aquatic snails (Thiaridae and *B. glabrata*) and amphidromous shrimp (Atyidae and Palaemonidae). Including aquatic macroinvertebrates and fish among candidate metrics is further supported by their relative importance in the PR Protocol (PRDNER 2007) and by their strong association with observed base flow conditions.

Our review also identified some support for drainage area and cover of riparian herbaceous vegetation as candidate indicators of streamflow duration class. Pike (2006) used a 6-ha drainage area threshold to define the extent of the perennial stream network in a Luquillo Mountain basin in northeast PR. For a southeast PR basin draining the Cayey Mountains, the extent of the perennial stream network was defined by a 0.72-ha drainage area threshold (Larsen and Santiago Román 2001). Drainage area has been commonly identified as an important geospatial predictor of streamflow duration class (e.g., González-Ferreras and Barquín 2017; Sando et al. 2022) and regional flow-duration and low-flow frequency statistics (e.g., Williams-Sether 2021). Scatena (1990) reported that riparian herbaceous vegetation cover was 100% along perennial reaches draining headwater watersheds in the Luquillo Mountains but was $< 50\%$ along upstream intermittent reaches.

In addition to aquatic invertebrate and fish metrics, our analysis of the PR Protocol metrics supports some rapid measures of geomorphology, iron-oxidizing bacteria and fungi and organic matter metrics that were modified from an SDAM developed for North Carolina (NCDWQ 2005). Reaches with well-defined channel continuity, no or very patchy leaf litter, presence of riffle-pool sequences, iron-oxidizing bacteria and fungi and differences of channel substrate texture and distribution tended to be associated with reaches having some observed base flow, whereas reaches observed to lack these features tended to be dry reaches or reaches with surface water restricted to isolated pools. Future research should assess the utility of the metrics used in the PR Protocol across stream reaches of known flow duration.

4.2 | Candidate SDAM Study Reaches

A sufficient sample size of reaches of each flow class with a spatially balanced distribution is needed to develop a robust regional SDAM. Stream reaches with documented flow class in the US Caribbean are dominated by perennial reaches in PR and intermittent reaches in the USVI. Additionally, the reliability of streamflow classifications in this systematic literature review was challenged by inconsistent reporting methods for classification across most studies. Our results indicate that most of the documented perennial reaches were classified using the NHD or streamgage data. In contrast, intermittent and ephemeral reaches were under-represented and frequently lacked classification details, causing more uncertainty of the flow classification of the non-perennial candidate study reaches. USGS streamflow gages on the USVI and outlying PR islands of Culebra and Vieques, which were primarily on non-perennial reaches, have been inactive since at least 2006 (Lancellotti and Hensley 2024; USGS 2016).

Identifying reaches based on existing hydrological data or documented flow duration is an initial step for selecting SDAM study reaches. Identifying more candidate study reaches through discussions with the RSC and local management agencies, including those focused on publicly accessible stream reaches, will be necessary. Interviews with managers and neighbours of streams and use of crowdsourced information and street view and aerial imagery where the channel is visible (Gallart et al. 2016; Scheller et al. 2024) are options to add study reaches of expected flow classes that are needed to balance geographic coverage. Incorporating local knowledge through collaboration with stakeholders, regional organizations and targeted field visits may help improve the identification of intermittent and ephemeral study reaches. Data from active streamgages or low-cost data loggers (e.g., Chapin et al. 2014; Noto et al. 2022) should be used to classify streamflow duration of study reaches, whereas candidate indicators are measured for developing the regional SDAM. Additional study reaches may need to be added once the actual streamflow duration classes have been determined to further balance study reaches spatially among flow classes so the training dataset for SDAM model development is sufficiently robust for flow class prediction throughout the region.

We used the NHD flowline data to gauge the geographic distribution of documented study reaches across the US Caribbean, and some of the candidate sites identified in the review used the NHD to specify perennial reaches. The NHD includes f-codes for intermittent and perennial but not ephemeral reaches, so the NHD cannot be used to initiate candidate study reach selection for an SDAM that distinguishes ephemeral reaches. Additionally, the NHD flowlines and blueline streams on standard topographic maps overlook the smallest streams, potentially underrepresenting the full extent of stream networks in at least some parts of the US Caribbean (Leon et al. 2021). This underscores the importance of supplementing NHD data with more finely detailed channel networks derived from a high-resolution elevation layer ($1\,m^2$), such as the Light Detection and Ranging (LIDAR)–based 3D Elevation Program. Efforts to refine hydrological network maps to include undocumented non-perennial streams, as demonstrated by Leon et al. (2021) in the Luquillo Experimental Forest using high-resolution LIDAR, would benefit future SDAM efforts if extended to other regions of PR and the USVI.

4.3 | Candidate SDAM Hydrogeographic Frameworks

Despite being a small region compared to other regions with developed SDAMs, the US Caribbean has strong gradients controlling stream hydrology. For instance, mean total annual rainfall greatly varies (~700 to > 4000 mm/year) across PR, largely because of steep topography near the ocean (Gómez-Gómez et al. 2014). The ecological life zones framework (Ewel and Whitmore 1973; Figure 4a) emerged as the most suitable framework for SDAM development. Based on discussions with the RSC, the ecological life zones framework best captures important gradients, such as precipitation, temperature and vegetation, that influence streamflow variability and relationship strength with potential indicators. However, to our knowledge, ecological life zones have not been evaluated as a reflection of the hierarchical differences in stream characteristics in the US Caribbean. One concern with using the ecological life zones framework is the limited size of expected stream density within some ecological life zones. Specifically, the SRF and LMRF zones each represent only 0.1% of the US Caribbean area (Ewel and Whitmore 1973). Modifying the framework by combining these zones with the similarly situated LMWF would enable greater representation of study reaches, but there has been no research to support whether streams in these three zones are more or less similar to those draining other zones.

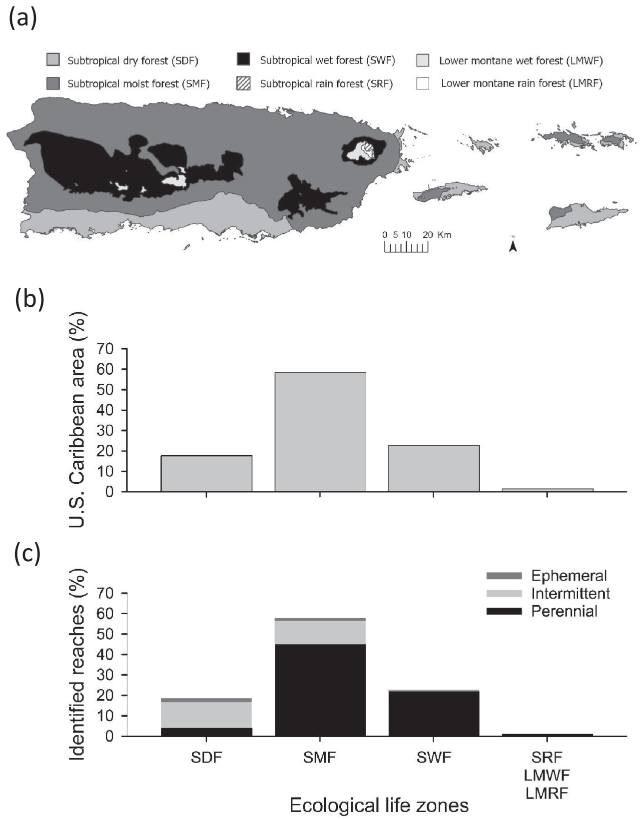

FIGURE 4 | (a) Map of ecological life zones for the US Caribbean (Ewel and Whitmore 1973). The subtropical rain forest and lower montane rain forest ecological life zones are restricted to the Luquillo Mountains in the northeastern part of Puerto Rico. (b) Percent of land area in the US Caribbean distributed among ecological life zones. (c) Percent of the 425 stream reaches extracted from reviewed publications by documented streamflow class distributed among ecological life zones.

The distribution of the candidate study reaches we identified across the ecological life zones was representative of the areal extent of the ecological life zones (Figure 4b,c). However, when considering their documented streamflow duration classification, ephemeral reaches are under-represented across all ecological life zones. In contrast, perennial reaches are underrepresented in the SDF zone but overrepresented in the SMF and SWF zones. The SDF zone represents much of the outlying PR islands and the USVI. The limited number of documented perennial study reaches in the USVI appears to be tied to historical changes in streamflow. St John lacks perennial streams (Browning et al. 2016), and perennial streams in St Croix and St Thomas have experienced notable reductions in streamflow over time, with many streams no longer maintaining consistent perennial flow as they once did (Jordan 1972; Lancellotti and Hensley 2024). Although the drivers of perennial to non-perennial shifts have not been identified, changes in land use and groundwater extraction and recharge are suspected to contribute (Jordan 1972; Gardner et al. 2008). Moreover, increasing precipitation variability and temperatures will likely influence the extent of ecological life zones (Gould et al. 2018). Reductions in the extent of wetter zones and increases in the extent of drier ones could potentially lead perennial reaches to regularly cease flowing in the US Caribbean, as documented elsewhere (Carlson et al. 2024).

Because the ecological life zones framework was designed for land classification, it is unlikely to represent all key controls on streamflow duration. For such reasons, one recommendation from the RSC was to modify the selected framework to consider incorporating dominant lithology, as this can heavily influence streamflow duration (Shanafield et al. 2020). For example, PR's northern karst belt, which covers 27.5% of the main island (Lugo et al. 2001), tends to have fewer surface streams due to its subterranean drainage patterns (Monroe 1976) and lower baseflow compared to volcanic areas (Giusti 1978). In addition, potential vegetation indicators are likely to vary by lithology, as karst forests, with shallower soils and rapid drainage, support smaller, drought-tolerant trees compared to the deeper, more stable soils of volcanic regions; these differences are even more prevalent in the dry southern karst of PR, where rainfall is lower (Lugo et al. 2001). This suggests that karst and non-karst areas within the same ecological life zone may respond differently to similar climatic conditions. Consistent with the recommendation from the RSC, a recent study in St Croix found that a volcanic-dominated subcatchment had higher runoff responsiveness compared to the entire catchment, which includes carbonate hydrogeology. This finding further supports how different geological zones directly influence runoff generation and streamflow dynamics (Hensley et al. 2025). An existing hydrogeographic framework divides PR into eight groundwater provinces partly defined by dominant lithology (Gómez-Gómez et al. 2014). Adapting the ecological life zones framework by incorporating the distribution of dominant lithology (e.g., karst, volcanic and alluvium) may better meet the needs for robust SDAM development and future US Caribbean stream research.

4.4 | Geographic and Temporal Distributions of US Caribbean Stream Research

Geographic concentration and differences in well-established research stations may have contributed to the higher documentation of perennial reaches and limited documentation of intermittent and ephemeral ones. The high concentration of study reaches in northeast PR, especially within the Luquillo Long-Term Ecological Research (LTER) site and Luquillo Experimental Forest (LEF), reflects the influence of established research infrastructure that supports ongoing studies (Scatena 1989; McDowell et al. 2021). Supported by consistent funding, these stations have likely brought more research efforts to perennial reaches within accessible and well-supported locations. In contrast, the southern and western regions of PR, Culebra, Vieques and the USVI, which lack consistently funded research infrastructure, have fewer documented study reaches. The northeastern region has experienced higher human population growth than other parts of PR (Martinuzzi et al. 2007), and this has likely concentrated recent research on water quality, flooding and other environmental concerns commonly prioritized in urban settings.

Temporal changes in research focus are likely influenced by factors such as funding availability, local challenges and the frequency of extreme events (Ramos-Scharrón et al. 2023; Lancellotti and Hensley 2024). Periods of increased research on hydrology, geomorphology and chemistry may reflect shifts in funding towards these topics in response to extreme weather events and disasters like hurricanes and droughts, and growth in general, for certain topics (e.g., environmental flows and urban streams). For example, hydrology data collection increased during decades impacted by Hurricanes Hugo (1989), Georges (1998), Irma (2017) and María (2017). The frequency of extreme events and their impact on biodiversity and freshwater systems have likely driven more interdisciplinary approaches, as reflected by the increase in research on aquatic community patterns and stream ecosystem processes and the greater percentage of documents addressing multiple freshwater science topics, compared to those that focus on a single topic.

5 | Conclusions

Candidate indicators, study reaches and a hydrogeographic framework were identified in this review of published documents to inform the development of a US Caribbean-specific SDAM. This literature review was intended to support a robust assessment tool, but it also revealed gaps, clusters, and trends in stream research in the US Caribbean. Although there has been some research related to drought, desiccation control of disease vectors, and impacts of water diversion in the US Caribbean, relatively little is known about ephemeral and intermittent stream reaches and how they may differ from perennial reaches. Stream drying can lead to indirect changes, such as water quality deterioration, biological interaction intensification and lost connectivity. These topics have been studied to a greater degree in perennial reaches in PR, due to other drivers like wastewater management, instream-flow analysis, invasive species and dams. Perhaps this existing knowledge of Caribbean streams can inform a better understanding of the indirect changes associated with stream drying. There is also a need for more stream research that explores how strong gradients captured by the numerous existing hydrogeographic frameworks are realized in the biotic structure and function of Caribbean streams.

Author Contributions

Katiana Garcia-Rosado: conceptualization, data curation, visualization, writing – original draft, investigation, methodology, writing – review and editing. **Ken M. Fritz:** conceptualization, data curation, formal analysis, funding acquisition, project administration, supervision, resources, visualization, writing – original draft, investigation, methodology, writing – review and editing. **Augustin C. Engman:** investigation, methodology, validation, writing – review and editing. **Tamara Heartsill-Scalley:** investigation, methodology, validation, writing – review and editing. **Sean P. Kelly:** investigation, methodology, validation, writing – review and editing. **Carlos E. Ramos-Scharrón:** investigation, methodology, validation, writing – review and editing. **Sofía Olivero-Lora:** funding acquisition, project administration, supervision, resources, investigation, methodology, validation, writing – review and editing.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are provided in the Supporting Information, and data in manuscript figures are available on request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information. **Data S2:** Supporting Information. **Data S3:** Supporting Information.