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Environmental Management

ISSN 0364-152X
Volume 60
Number 4

Environmental Management (2017)
60:598-614
DOI 10.1007/s00267-017-0907-3

Springer

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Invertebrate-Based Water Quality Impairments and Associated Stressors Identified through the US Clean Water Act

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Received: 10 November 2016 / Accepted: 15 June 2017 / Published online: 1 July 2017

Abstract Macroinvertebrate community assessment is used in most US states to evaluate stream health under the Clean Water Act. While water quality assessment and impairment determinations are reported to the US Environmental Protection Agency, there is no national summary of biological assessment findings. The objective of this work was to determine the national extent of invertebrate-based impairments and to identify pollutants primarily responsible for those impairments. Evaluation of state data in the US Environmental Protection Agency's Assessment and Total Maximum Daily Load Tracking and Implementation System database revealed considerable differences in reporting approaches and terminologies including differences in if and how states report specific biological assessment findings. Only 15% of waters impaired for aquatic life could be identified as having impairments determined by biological assessments (e.g., invertebrates, fish, periphyton); approximately one-third of these were associated with macroinvertebrate bioassessment. Nearly 650 invertebrate-impaired waters were identified nationwide, and sediment was the most common pollutant in bedded (63%) and suspended (9%) forms. This finding is not unexpected, given previous work on the negative impacts of sediment on aquatic life, and highlights the need to more specifically identify the mechanisms driving sediment impairments in order to design effective remediation plans. It also reinforces the importance of efforts to derive sediment-specific biological indices and numerical sediment quality guidelines. Standardization of state reporting approaches and terminology would significantly increase the potential application of water quality assessment data, reveal national trends, and encourage sharing of best practices to facilitate the attainment of water quality goals.

Keywords Clean water act · Invertebrate assessment · Sediment · Water quality management · ATTAINS

Introduction

The United Nations identified the availability and effective management of clean water as one of 17 key sustainable development goals critical to the survival of people and the planet (United Nations 2016). This reflects the importance of the many services provided by aquatic ecosystems, including drinking water, power generation, food sources, waste filtration, buffering of flood flows, nutrient cycling, and recreational use (Millennium Ecosystem Assessment 2005). In the United States (US), water quality monitoring and management is regulated under the Clean Water Act (CWA). States, territories, and authorized tribes (collectively referred to hereafter as "states") are individually responsible for monitoring the chemical, physical, and biological integrity of their waters and reporting their findings to the US Environmental Protection Agency (US EPA). States, therefore, lead individual efforts to evaluate and remediate water quality issues, including those in

Electronic supplementary material The online version of this article (doi:10.1007/s00267-017-0907-3) contains supplementary material, which is available to authorized users.

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watersheds that cross state lines, while the US EPA provides national oversight and guidance.

While water quality assessment includes evaluation of chemical, physical, and biological components of the aquatic environment, often chemical and physical assessments are limited to sampling that reflects one point in time. In contrast, biological monitoring has the advantage of reflecting cumulative effects of chemical, physical, and biological stressors in the environment accumulated over the life time of the organisms being evaluated, which can range from months to years (Rosenberg and Resh 1993; Resh 2008; Herbst et al. 2011). As a result, biological monitoring can provide a more holistic picture of stream condition than physical or chemical monitoring alone (Barbour et al. 1999).

Biological monitoring includes the assessment of one or more communities (e.g., fish, macroinvertebrates, periphyton) to determine if they are similar to those of natural reference streams representative of least disturbed conditions for a given region (US EPA 2011). While guidance has been issued to assist states in designing biological monitoring programs (US EPA 1990; Gibson 1992; Fore 2003), each state environmental agency may use the assemblages, metrics and data deemed most appropriate to determine if state waters are impaired. State monitoring approaches are indicated either in the form of a consolidated assessment and listing methodology (CALM) report (US EPA 2002) or within a section of the prior reporting cycle's water quality assessment report.

There are advantages and disadvantages specific to each biological community used in bioassessment, as each community can provide information of distinct aspects of stream health (Resh 2008). The community or communities selected for monitoring by states is dependent on state-specific goals. Currently, the benthic macroinvertebrate community is most commonly used in CWA bioassessment; 47 of 57 US states and territories include benthic macroinvertebrate monitoring in their assessment programs (Online Resource 1; Figs. 1a, b). Benthic invertebrates include insects, mollusks, crustaceans, worms, and other visible organisms that live in close association with the bed of a water body. These communities are ideal for monitoring because of their high diversity, widespread distribution, limited mobility, and relatively long generation times (Resh 2008). They display a wide range of responses to a variety of stressors and play a critical role in stream ecosystems by acting as detritivores, herbivores, predators, and as a dominant prey base for upper trophic level organisms.

Macroinvertebrate community data are typically evaluated via calculation of state-specific multimetric indices (Online Resource 1). These indices combine invertebrate metrics for a given region that are most useful in differentiating between disturbed and reference conditions to yield a single numerical value (Karr and Chu 1997). They may include measures of richness (e.g., total species, total families); density; percent abundance of specific taxa; functional feeding groups (e.g., scrapers, filter feeders, predators); behavioral characteristics (e.g., swimmers, clingers, burrowers); and other life history traits (e.g., univoltine, bivoltine). The metrics most commonly included are total taxon richness; richness of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddis flies) (EPT); the Hilsenhoff Biotic Index (Hilsenhoff 1987); percent by individuals of EPT; and richness of ephemeropterans (Carter and Resh 2013).

Waters without observed communities comparable to natural reference conditions (i.e., in which index values are less than a predetermined threshold) are classified as *impaired* and are placed on state 303(d) impaired waters lists (referring to Section 303(d) of the CWA). Results of assessment and impairment determinations are reported biennially to the US EPA. While overall impairment determinations (i.e. *impaired, not impaired, threatened*) are summarized in national status reports (US EPA 2016a), there are no summaries of information provided by biotic assessments (e.g., number and type of assessments, number of impairments identified). Such summaries are necessary to identify impacts to aquatic life across the US that are not revealed by chemical and physical assessment alone, to provide insights into cumulative impacts of stressors, and to identify those stressors responsible for the largest impacts on particular communities of the aquatic ecosystem.

Waters placed on state 303(d) impaired waters lists require the development of Total Maximum Daily Loads (TMDLs)(US EPA 2000a), which are loading limits of particular pollutants that should not be exceeded for the health of the water body. Since biological monitoring inherently reflects integrated effects of multiple pollutants over time, the cause(s) of observed effects (i.e., the pollutants for which TMDLs must be developed) are often not immediately apparent. To determine the most probable cause(s) of impairment, a stressor identification process can be conducted. The US EPA's Stressor Identification Guidance Document (US EPA 2000b) outlines a recommended approach for stressor identification that includes the development of a list of candidate stressors, analysis of available evidence related to each potential stressor, and characterization of potential causal relationships between candidate stressors and observed conditions. Additional data may be gathered throughout the process until "sufficient confidence in the causal characterization is reached" (US EPA 2000b). The US EPA Causal Analysis/Diagnosis Decision Information System is an online tool that helps scientists identify stressors and conduct causal assessments (US EPA 2010a).

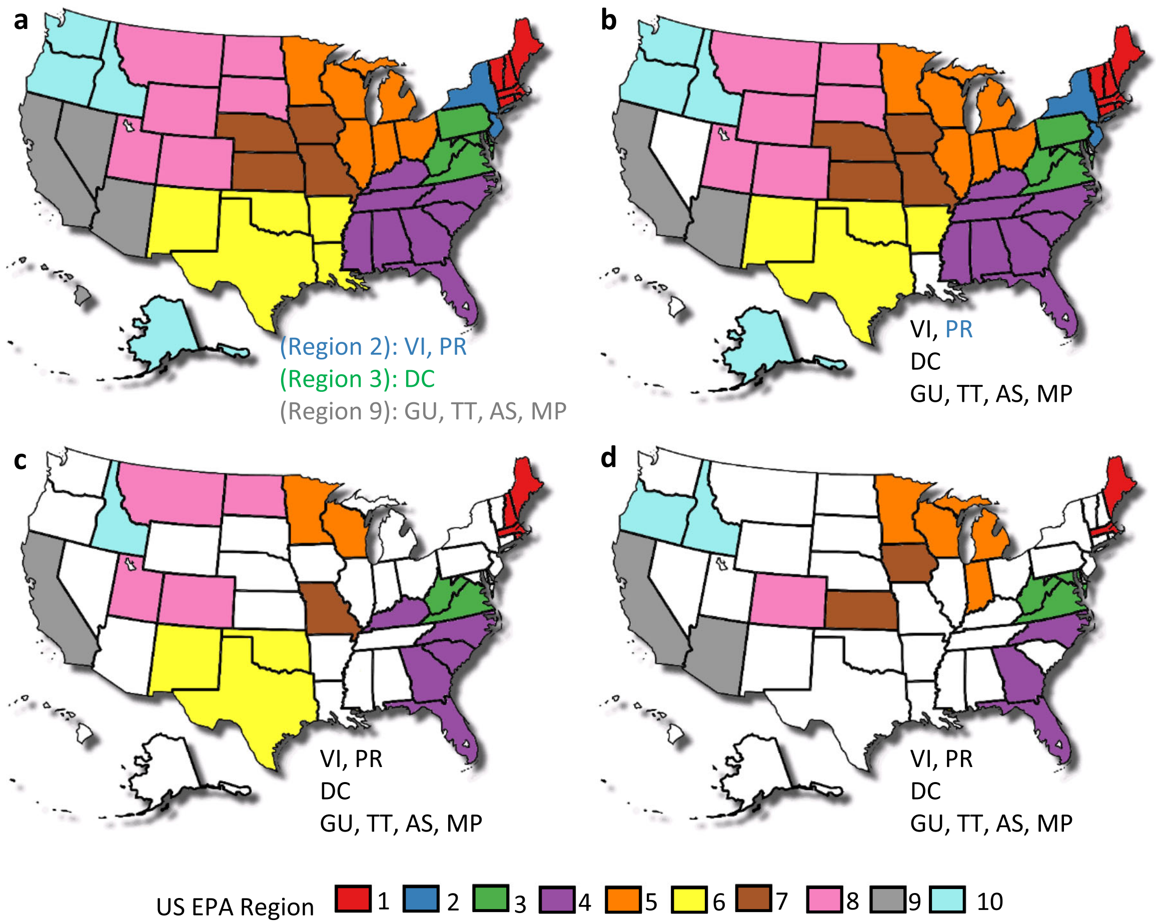

Fig. 1 **a** States colored by US EPA Region VI = Virgin Islands, PR = Puerto Rico, DC = District of Columbia, GU = Guam, TT = Trust Territories, AS = American Samoa, MP = Northern Marianas **b** States that conduct macroinvertebrate biomonitoring (*colored*; VI, DC, GU, TT, AS, and MP do not) **c** States with invertebrate-based impairments per most recent US EPA 303(b) summary (*colored*) **d** States with approved Total Maximum Daily Load reports addressing invertebrate-based impairments (*colored*)

Stressor identification guidance identifies chemical toxicants, effluent, loss of habitat, flow alterations, elevated temperature, siltation, limited dissolved oxygen, excess mineral nutrients, pathogens, and invasive species as potential aquatic life stressors (US EPA 2000b). The relative importance of each of these stressors in contributing to invertebrate-based impairments is unknown. Results of the National Rivers and Streams Assessment (NRSA) suggest that streams with excess phosphorus, nitrogen, and fine sediment relative to reference streams are twice as likely to have impaired invertebrate communities (US EPA 2016b). However, the NRSA assessment is based on odds-ratios (stressor co-occurrence with impaired communities) and does not reflect findings of site-specific stressor evaluations.

Extensive human and financial resources are spent on surface water monitoring programs and TMDL development (US EPA 2001; Bosch et al. 2006). The average cost to develop a TMDL is estimated at $52,000 (ranging from $26,000 to $500,000), and annual cost estimates for pollutant sources (i.e., generators of point and nonpoint source pollution) to implement TMDL programs range from $900 million to $4.3 billion in 2000 year US dollars (US EPA 2001). No national summary of biological assessments and associated pollutants exists, rendering the prioritization of research and management efforts for aquatic life protection difficult to justify. In addition, the identification of trends among states can encourage sharing of successful best practices and may be useful in preventing further stream degradation. Therefore, to address this need, using the most recent US EPA CWA data summary for each state, this effort aims to:

(1) Quantify freshwater rivers and streams throughout the United States that are on the 303(d) list based on the assessment of the macroinvertebrate community (i.e., "invertebrate-based impairments"); and
(2) Categorize pollutants associated with these invertebrate-based impairments for formerly 303(d) listed streams that have approved TMDLs.

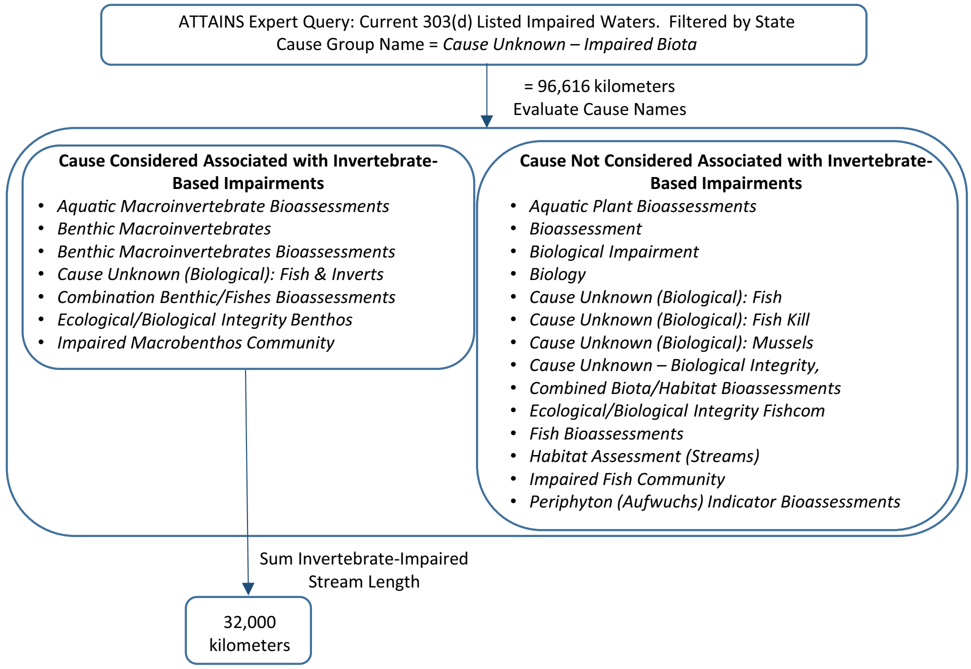

Fig. 2 Approach used to estimate current stream length on 303(d) impaired waters list with invertebrate-based impairments

Methods

Streams on the 303(d) List due to Invertebrate-based Impairments

State water quality monitoring data are submitted to the US EPA and summarized on the agency's Assessment and Total Maximum Daily Load Tracking and Implementation System (ATTAINS), an online database of the Nation's surface waters (US EPA 2016a). When impairment data are submitted to the US EPA, an accompanying cause of impairment is required. There are currently 33 approved Cause of Impairment Groups (US EPA 2016a), although additional causes can be entered. Each group contains Cause Names that states select when listing their waters. The only cause of impairment group that includes cause names referring specifically to biological monitoring is the Cause Unknown—Impaired Biot a group; this designation also indicates an impairment for which the primary stressors are unknown at the time of listing (e.g., the specific pollutant requiring load reduction via the TMDL process).

State-specific impairment data summarized in the ATTAINS public interface as of September 2016 were reviewed (website assessed 4 September 2016). Stream and river impairments classified under Cause Unknown—Impaired Biota were evaluated for each state. Waters with cause names that explicitly mentioned macroinvertebrates or insects and cause names including benthos were considered to have invertebrate-based impairments. Causes with more general designations (e.g., bioassessment, biological impairment, biology) may also include waters with invertebrate-based impairments; however, these were not included in the analysis because details on specific bioassessment methods used were not reported and may involve widely differing targets (e.g. algae, fish). Stream miles for invertebrate-impaired waters were summed and converted to kilometers to determine the total stream length with invertebrate-based impairments (Fig. 2).

It is worth noting that ATTAINS summarizes 303(d) listed waters from the most recent reporting period. The website is updated as data are received from various states; however, more recent state-specific data may be available from individual state websites. In the interest of providing a summary based on US EPA-approved and disseminated information, state-specific websites were not assessed for this objective.

Pollutants Associated with Invertebrate-based Impairments

To determine the most common pollutants associated with invertebrate-based impairments, it was necessary to examine streams formerly on the 303(d) list that now have approved TMDLs. It is important to note that these waters are distinct from and do not include the impaired waters discussed in the prior section because once a TMDL is developed and approved, impaired waters are removed from the 303(d) list (N.B. removal does not necessarily mean that water quality objectives have been met). To determine the pollutants associated with finalized, US EPA-approved TMDLs, those associated with invertebrate-based impairments were identified and the pollutants targeted in those TMDLs were summarized (Fig. 3). US EPA-approved

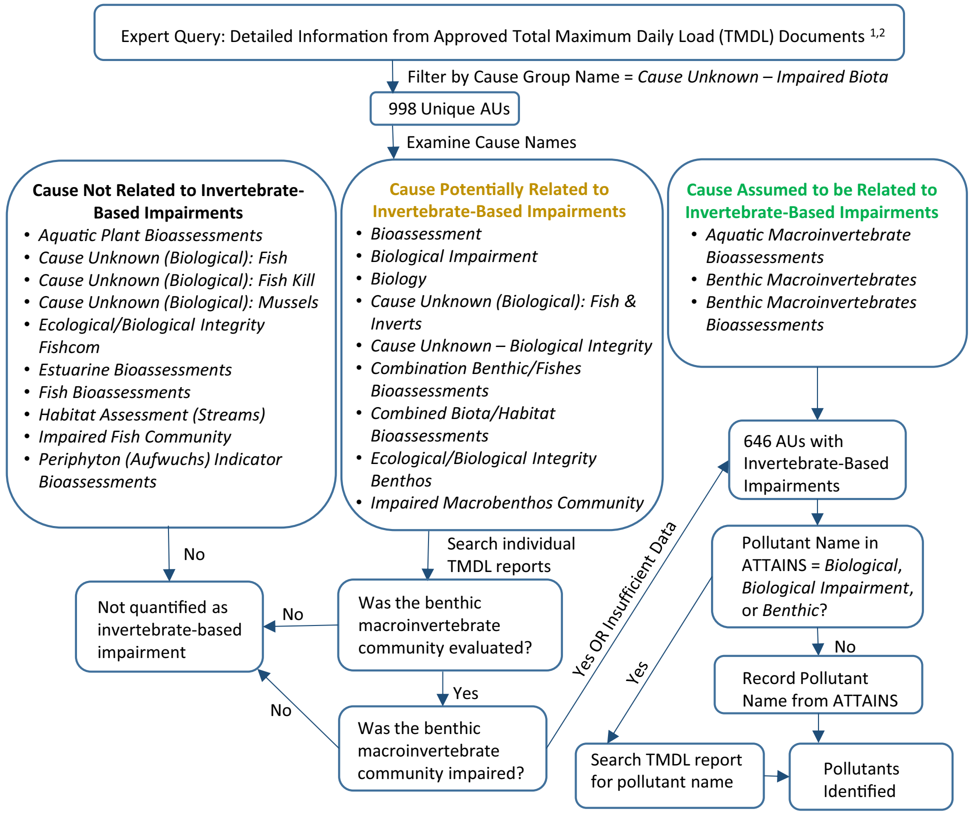

Fig. 3 Approach used to identify assessment units with invertebrate-based impairments and associated pollutants. AU = Assessment Unit [1]Assessment and Total Maximum Daily Load Tracking and Implementation System (ATTAINS) [2]Searched and summarized by state

TMDL reports within the Cause Unknown—Impaired Biota group classification were identified from ATTAINS (US EPA 2016a). Reports included in this summary date from October 1995 (the earliest report date within the database) through those that were posted in the database on or before 1 September 2016.

Unlike waters on the 303(d) list, which are summarized by stream length, TMDL reports are developed for Assessment Units (AUs), which are river or stream segments considered to have homogeneous water quality. AUs are identified based on the National Hydrography Dataset (US EPA 2005) and are delimited at points where a change in water quality may be expected, such as confluences with other water bodies, point source discharges, and impoundments. Each TMDL report categorized in ATTAINS under Cause Unknown—Impaired Biota was examined to determine if the AU was identified as impaired based on the findings of macroinvertebrate assessments. Similar to the analysis of currently impaired waters in the prior section, AUs with cause names clearly linked to macroinvertebrate assessments (i.e., including the term macroinvertebrate) were considered to have invertebrate-based impairments. In contrast to the approach used to identify currently impaired waters, those AUs with more ambiguous cause names (e.g., biological, biological integrity) or names referencing more than one biological community (e.g., fish and inverts), were evaluated further by reviewing individual TMDL reports to determine if the basis for impairment included evaluation of the benthic macroinvertebrate community. In general, if the macroinvertebrate community was assessed and the AU was impaired, it was assumed that the impairment listing was based on an impairment of the invertebrate community. In some cases, sufficient data were reported to determine that the invertebrate community was assessed and not impaired, and that the impairment listing was based on other lines of evidence; in these cases the AUs were not counted as having an invertebrate-based impairment. In cases for which insufficient data were presented to determine whether or not macroinvertebrates were included in the assessment process, it was assumed that impairments were not invertebrate-based. Cause names clearly not linked to macroinvertebrates (e.g., fish kills) were identified as not being linked to invertebrate impairments without further investigation (Fig. 3). Due to inconsistencies identified between TMDL reports and ATTAINS data for West Virginia, each approved TMDL classified as Cause Unknown—Impaired Biota from this state was evaluated (including those with cause names of benthic invertebrates) to determine if invertebrate impairments were present and to identify associated biotic stressors.

Once AUs associated with invertebrate-based impairments were identified, associated pollutants were identified within ATTAINS or by examining associated TMDL reports. More than one pollutant could be associated with a given AU. In some cases, specific pollutants were noted within ATTAINS, whereas in other cases the database listed “biological” as the pollutant, requiring further examination of the TMDL report to determine the identified pollutant. When inconsistencies between ATTAINS and final TMDL reports were identified, the information in the final approved TMDL report was assumed to be correct. The majority of WV TMDLs to address biological impairments identified pollutants that serve as surrogates for the actual biological stressors identified. For example, TMDLs for iron were established rather than TMDLs for the stressor sediment in waters where iron was a co-located impairment and loading limits for iron were determined to be greater than those needed to address the sediment impairment. Similarly, TMDLs were established for fecal coliform for waters in which organic enrichment was identified as the stressor of the macroinvertebrate community but pathogen impairment was also present. Stressors specified in approved WV TMDL reports were summarized rather than pollutants so that that this summary reflects the causal stressors rather than co-located impairments. Use of surrogate TMDLs was not evident in other states.

Results and Discussion

Streams on the 303(d) List due to Invertebrate-based Impairments

The US EPA reports that 644,086 km of streams and rivers have aquatic life use impairments (US EPA 2016a); 15% (96,616 km in 29 states; Table 1) were classified in the Cause Unknown—Impaired Biota group. One-third of the streams in this group were listed with causes that can be linked to invertebrate-based impairments (32,000 km in 23 states; Table 1). With the exception of US EPA Region 2, each region included listed waters in the Cause Unknown—Impaired Biota category (Fig. 1c). ATTAINS public portal does not provide the level of detail required to determine which of the other streams impaired for aquatic life use (the 85% not categorized as Cause Unknown—Impaired Biota) were evaluated using biological community assessment. This finding demonstrates the challenges of identifying macroinvertebrate-impaired streams despite the fact that this assessment approach is used by the majority of states (state-specific invertebrate assessment methods are detailed in Online Resource 1). In efforts to explain these results, the assessment and listing methodologies of the 24 state agencies that assess macroinvertebrate communities but were not identified as having invertebrate-based impairments using the described methods (Figs. 1b, c) were evaluated to determine if state-specific approaches used to report invertebrate-based impairments (i.e., Cause Groups used) were specified.

New Jersey’s 2016 listing methodology indicates that if biological data indicate impairment, the cause is identified on the 303(d) list as Cause Unknown—Impaired Biota; and if these waters also have chemical or physical data exceeding applicable criteria, the chemical parameters and biological impairment are identified as pollutants on the 303(d) list (New Jersey DEP 2015). If this most current assessment and listing approach is consistent with that used in prior listing cycles, New Jersey’s invertebrate-impaired waters should have been identified by the methods used herein; therefore, no rivers or streams in New Jersey are currently listed as impaired based on biological data.

Five states (Mississippi, Kansas, Nebraska, Oregon, and Washington) had listings under Cause Unknown—Impaired Biota which could not be clearly linked to invertebrate assessments (causes were Biological Impairment, Biology, Cause Unknown—Biological Integrity, Biological, and Bioassessment, respectively). Although there is uncertainty in the status of invertebrate impairments in these states, it is clear that biological assessment results in at least some cases were reported under the Cause Unknown—Impaired Biota listing category. An additional three states (Indiana, Michigan, and Iowa) had no current Cause Unknown—Impaired Biota listings, but have completed invertebrate-based TMDLs (discussed in the next section) classified under this cause group listing; therefore, these state agencies also use the Cause Unknown—Impaired Biota category.

For Vermont, Tennessee, Illinois, Ohio, and Wyoming, while state agencies use biological data to identify aquatic life use impairments, “causes” of impairment are not considered to be biological. Rather, attempts are made to identify the pollutants associated with the biological impairment and then a Cause Group is selected that reflects pollutants when listing the water on the 303(d) list (Illinois EPA 2014; Vermont DEC 2014; Wyoming DEQ 2014; Ohio EPA 2016; Tennessee DEC 2016). Vermont Department of Environmental Conservation notes that the pollutant will be listed as “undefined” if a pollutant cannot be clearly identified prior to listing (Vermont DEC 2014). Illinois EPA notes that their assessment database, which follows the standardized database created by US EPA, does not store physicochemical, biological, or habitat results, but does store assessment determinations based on those data (Illinois EPA 2014). In a similar vein, Maryland Department of the Environment may initially classify streams under a biological cause classification (terminology unspecified by the Maryland CALM), but once stressors are identified using a state-specific biological stressor identification analysis, the biological listing is removed and the stream is reclassified as impaired under the identified pollutant(s) (Maryland DE 2015).

Pennsylvania’s CALM specifically defines Cause Groups used by the state; Cause Unknown (distinct from

Table 1 Stream and river water quality impairments associated with invertebrate-based assessments

US EPA Region	State/ Territory	Assessed Waters Report Year[a]	Impaired Waters Report Year[a]	Kilometers assessed for all designated uses	303(d) Impaired Waters Listed Under Cause Unknown—Impaired Biota			
					Cause Name not assumed to be invertebrate-based	Kilometers[b]	Cause Name considered to be invertebrate-based	Kilometers[c]
1	Connecticut	2014	2014	4566	–	–	–	–
	Maine	2012	2012	51,079	Periphyton (Aufwuchs) indicator bioassessments (Streams); habitat assessment (Streams)	294	Benthic macroinvertebrates bioassessments	335
	Massachusetts	2014	2014	4534	Fish bioassessments; habitat assessment (Streams); combined biota/habitat bioassessments (Streams)	333	Aquatic macroinvertebrate bioassessments	334
	New Hampshire	2010	2010	27,297	Fish bioassessments; habitat assessment (Streams)	509	Benthic macroinvertebrates bioassessments	680
	Rhode Island	2014	2014	1477	--	--	Benthic macroinvertebrate bioassessments; aquatic macroinvertebrate bioassessments	207
	Vermont	2014	2014	10,588	–	–	–	–
2	New Jersey	2012	2012	30,565	–	–	–	–
	New York	2014	2014	83,542	–	–	–	–
	Puerto Rico	2014	2014	9743	–	–	–	–
	Virgin Islands, U.S.	2012	2012	650	–	–	–	–
3	Delaware	2006	2006	4033	Habitat assessment (Streams)	433	–	–
	District of Columbia	2014	2014	62	–	–	–	–
	Maryland	2012	2012	36,608	–	–	–	–
	Pennsylvania	2006	2004	138,457	–	–	–	–
	Virginia	2014	2012	35,947	–	–	Benthic macroinvertebrates bioassessments	2709
	West Virginia	2010	2010	33,016	–	–	Benthic macroinvertebrates bioassessments	9785
4	Alabama	2014	2014	20,346	–	–	--	--
	Florida	2010	2010	16,859	–	–	Benthic macroinvertebrates bioassessments	620
	Georgia	2012	2012	22,729	Fish bioassessments	3796	Benthic macroinvertebrates bioassessments	1007
	Kentucky	2012	2012	19,000	Habitat assessment (Streams); combined biota/habitat bioassessments (Streams); fish bioassessments	830	Combination benthic/fishes bioassessments; benthic macroinvertebrates bioassessments	44
	Mississippi	2014	2014	8897	Biological impairment	29,641	–	–

Table 1 continued

US EPA Region	State/ Territory	Assessed Waters Report Year[a]	Impaired Waters Report Year[a]	Kilometers assessed for all designated uses	303(d) Impaired Waters Listed Under Cause Unknown—Impaired Biota			
					Cause Name not assumed to be invertebrate-based	Kilometers[b]	Cause Name considered to be invertebrate-based	Kilometers[c]
	North Carolina	2014	2014	61,528	Ecological/biological integrity fishcom	882	Ecological/biological integrity benthos	2451
	Tennessee	2012	2012	45,708	–	–	–	–
5	Illinois	2010	2006	27,375	–	–	–	–
	Indiana	2010	2008	38,576	–	–	–	–
	Michigan	2010	2010	123,017	–	–	–	–
	Minnesota	2012	2012	25,638	Fish bioassessments	4748	Aquatic macroinvertebrate bioassessments	2967
	Ohio	2010	2008	84,463	–	–	–	–
	Wisconsin	2006	2008	24,353	–	–	Benthic macroinvertebrates bioassessments; combination benthic/ fishes bioassessments	28
6	Arkansas	2008	2008	16,060	–	–	–	–
	Louisiana	2012	2012	15,306	–	–	–	–
	New Mexico	2014	2014	10,201	–	–	Benthic macroinvertebrates bioassessments; benthic macroinvertebrates	205
	Oklahoma	2014	2014	22,368	Fish bioassessments	2573	Benthic macroinvertebrate bioassessments	1198
	Texas	2010	2010	37,894	Impaired fish community	341	Impaired macrobenthos community	332
7	Iowa	2014	2014	13,782	–	–	–	–
	Kansas	2014	2014	47,211	Biology	8802	–	–
	Missouri	2014	2014	16,948	Fish bioassessments	766	Aquatic macroinvertebrate bioassessments; benthic macroinvertebrate bioassessments	967
	Nebraska	2014	2014	16,821	Cause unknown—biological integrity	1987	–	–
8	**Colorado**	2012	2012	114,320	–	–	Benthic macroinvertebrates bioassessments	868
	Montana	2014	2014	32,635	Combined biota/habitat bioassessments (Streams); periphyton (Aufwuchs) indicator bioassessments (Streams)	39	Benthic macroinvertebrates bioassessments	100
	North Dakota	2014	2014	90,159	Fish bioassessments	856	Benthic macroinvertebrate bioassessments; combination benthic/ fishes bioassessments	2652

Table 1 continued

US EPA Region	State/ Territory	Assessed Waters Report Year[a]	Impaired Waters Report Year[a]	Kilometers assessed for all designated uses	303(d) Impaired Waters Listed Under Cause Unknown—Impaired Biota: Cause Name not assumed to be invertebrate-based	Kilometers[b]	Cause Name considered to be invertebrate-based	Kilometers[c]
	South Carolina	2012	2012	9366	–	–	Benthic macroinvertebrate bioassessments	1516
	South Dakota	2014	2014	9912	–	–	–	–
	Utah	2014	2014	11,277	–	–	Benthic macroinvertebrates bioassessments	2650
	Wyoming	2012	2012	28,184	–	–	–	–
9	American Samoa	2014	2014	371	–	–	–	–
	Arizona	2010	2010	3984	–	–	–	–
	California	2012	2012	107,747	–	–	Benthic macroinvertebrates bioassessments	122
	Guam	2010	2010	136	–	–	–	–
	Hawaii	2014	2014	4131	–	–	–	–
	Nevada	2012	2012	8718	–	–	–	–
	North Mariana Islands, Commonwealth of	2014	2014	133	–	–	–	–
	Trust Territories	–	–	–	–	–	–	–
10	Alaska	2010	2010	969	–	–	–	–
	Idaho	2012	2012	101,525	Combined biota/habitat bioassessments (Streams); habitat assessment (Streams); fish bioassessments; aquatic plant bioassessments	7722	Benthic macroinvertebrates bioassessments	224
	Oregon	2006	2006	74,087	Biological	54	–	–
	Washington	2008	2008	3214	Bioassessment	13	–	–
	TOTALS			1,788,115		64,616		32,000
	Percentage of aquatic life impaired rivers and streams[d]:					10.0%		5.0%

Bold indicates states with invertebrate-based impairments on most recent 303(d) list

[a] Most recent impairment year data summarized in US EPA ATTAINS, accessed 4 September 2016

[b] Cause Name listed in ATTAINS includes the term “invertebrate” or “insect” or “benthos”

[c] Cause Name listed in ATTAINS does not include the term “invertebrate” or “insect” or “benthos”

[d] Total length nationally assessed for aquatic life use 881,537 miles (1,418,693 km) (US EPA 2016a). Total length nationally impaired for aquatic life use 400,218.8 miles (644,087 km) (US EPA 2016a).

– None listed

Cause Unknown—Impaired Biota) is used when the cause of the impairment cannot be determined (Pennsylvania DEP 2015). The state has 88 AUs currently classified in the Cause Unknown category (US EPA 2016a). These AUs may include those with invertebrate-based impairments, but were not examined further in this assessment.

Listing methodologies for Alabama, Alaska, Arkansas, Arizona, Connecticut, New York, Puerto Rico, and South Dakota did not provide information on the Cause Group within ATTAINS selected for invertebrate-impaired waters (New York State DEC 2009; Connecticut DEEP 2014; Michigan DEQ 2014; Puerto Rico EQB 2014; South Dakota DENR 2014; Alabama DEM 2015; Alaska DEC 2015; Arizona DEQ 2015; Arkansas DEQ 2016). Arizona Department of Environmental Quality implementation procedures for the narrative biocriteria standard states that guidance for 303(d) listing will not be provided until the state's Impaired Waters Identification Rule language is updated (Arizona DEQ 2015).

The first objective of this research was to quantify freshwater rivers and streams that are listed as impaired based on assessment of the macroinvertebrate-community. The subsequent difficulties encountered in fulfilling this objective, which resulted from non-standardized state reporting approaches and terminologies, provided an unanticipated opportunity to explicitly demonstrate the challenges that may be encountered when attempting to uncover widespread water quality trends using the ATTAINS framework. As detailed above, states use a variety of approaches to list biologically impaired waters, and the majority of these approaches do not clearly indicate that the impairment was identified based on a biological assessment of specific communities. Even when state assessment and impairment listing methods are clearly defined, methods may differ by stream segment depending on designated uses. ATTAINS does not specify the assessment methods used for individual stream segments, and this information is also not commonly included in state assessment reports. In addition, there is not a transparent way to identify additional impairments that are likely to be the results of an original invertebrate assessment that are not classified as such in the database (e.g., when the cause is identified as a pollutant at the time of listing as is done in Vermont, Tennessee, Illinois, Ohio, and Wyoming), due to the variety of other potential reasons that particular pollutants may have been identified in such listings. The methodology used herein to identify invertebrate-impaired streams was intentionally conservative so as to reduce the potential for misidentifying streams as invertebrate-impaired when they are not.

Collectively, the nuances detailed above presented a substantial obstacle to achieving a clear view of the impairment status of the benthic macroinvertebrate community both at the state and national levels, and would likewise obscure impairment trends for other biological communities which may be of value to researchers and water quality professionals.

It is important to keep in mind that state water quality assessments conducted under the CWA are not designed to indicate nation-wide water quality trends (US EPA 2016a), and that these data are providing the desired information regarding the impairment status of state waters. Scaling listing information up to reveal national insights will remain challenging due to the differences in state-specific assessment and reporting methods. However, the significant work conducted by states to gather water quality data could find far broader application with relatively small adjustments in the scope of data reported and standardization of assessment and impairment terminology. Specific recommendations are discussed in the following paragraphs.

The ATTAINS database is in the midst of a redesign as part of the establishment of a national Water Quality Framework, which seeks to integrate national data and information systems with the goal of streamlining water quality assessment and reporting, more fully supporting water quality managers, and "providing a more complete picture of the nation's water quality" (US EPA 2014). Currently ATTAINS includes a data element for "assessment methods" that is an optional element not reported as a component of the public database. A workgroup on data elements and schema for the ATTAINS redesign concluded that this element was not useful because it is not widely used by the states or US EPA (RTI International 2014a). While this may be true for the overall purposes of the CWA assessments, increased reporting of this data element could greatly increase the applicability of the database to evaluate broader water quality questions. An "assessment type" data element (e.g., "physical/chemical," "habitat," "pathogen," "biological") is also present in the integrated reporting data template as an optional data entry; however, these data are not provided in the public database. Making these data required and including them in the public database would increase the ability of researchers and water quality professionals to evaluate freshwater status as indicated by specific assessment methods. Further, providing a data element that would indicate the specific assessment methods used, (i.e., What biological community was assessed? What physical/chemical parameters were evaluated?), would improve the usefulness of the database and make it more searchable for those interested in stressor-specific questions. Likewise, it is unclear why some database elements are excluded from public access. A complete listing of database elements, indications of which are required vs. optional, and points of contact for the data would enable researchers to determine what data are collected and how those data may be accessed if not available via the current internet portal. This simple act of summarizing available data and points of access may

Table 2 Summary of pollutants identified in approved TMDLs for assessment units with invertebrate-based water quality impairments

	US EPA Region	1		3			4				5				7		8	9		10		Total	Percent of invertebrate-impaired AUs associated with pollutant
	State/ Territory[a]	ME	MA	MD	VA	WV[e]	FL	GA	NC	MS	IN	MI	MN	WI	IA	KS	CO	AZ	CA	ID	OR		
	Individual AUs listed under Cause Unknown—Impaired Biota [b]	46	3	1	150	178	1	283	6	145	79	18	11	4	2	27	1	1	9	29	4	998	
	Individual AUs with invertebrate-based impairments[c]	40	0	0	142	170	1	56	5	124	32	12	8	0	1	22	1	0	3	25	4	646	
	Total Approved TMDLs for AUs with invertebrate-based impairments[d]	60	0	0	180	308	1	56	5	191	37	12	9	0	2	27	1	0	9	29	4	931	
Pollutant class	Pollutant																						
Sediment	Sediment	5	NA	NA	107	102	0	54	0	64	0	8	3	NA	1	0	0	NA	0	14	0	358	55%
	Sediment/Siltation	0	NA	NA	0	0	0	0	0	48	0	0	0	NA	0	0	0	NA	3	0	0	51	8%
Turbidity	Total Suspended Solids	1	NA	NA	1	0	0	0	0	0	30	4	2	NA	0	18	0	NA	0	3	0	59	9%
Salinity/total dissolved solids/ chlorides/sulfates	Total Dissolved Solids	0	NA	NA	17	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	17	3%
	Chlorides	0	NA	NA	3	0	0	1	0	0	0	0	0	NA	0	0	0	NA	0	0	0	4	<1%
Nutrients	Nitrogen	5	NA	NA	9	0	0	0	0	22	0	0	0	NA	0	4	0	NA	3	0	0	43	7%
	Nitrite/Nitrate	0	NA	NA	0	0	1	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	1	<1%
	Nutrients	0	NA	NA	0	0	0	0	0	2	0	0	0	NA	0	0	0	NA	0	0	0	2	<1%
	Phosphorus	5	NA	NA	19	0	0	0	0	26	7	0	0	NA	0	4	0	NA	3	2	0	66	10%
Organic enrichment/ Oxygen depletion	Organic enrichment	0	NA	NA	4	118	0	1	0	0	0	0	0	NA	0	0	0	NA	0	0	0	123	19%
	Dissolved Oxygen	0	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	1	<1%
	Biochemical BOD	0	NA	NA	0	0	0	0	0	20	0	0	0	NA	0	1	0	NA	0	0	0	21	3%
	Oxygen Demand	0	NA	NA	0	0	0	0	0	0	0	0	2	NA	0	0	0	NA	0	0	0	2	<1%
	Nitrogenous BOD	0	NA	NA	0	0	0	0	0	0	0	0	1	NA	0	0	0	NA	0	0	0	1	<1%
	Carbanaceous BOD	0	NA	NA	1	0	0	0	0	7	0	0	1	NA	0	0	0	NA	0	0	0	9	1%
Other cause	Pollutants in Urban Stormwater	36	NA	NA	4	0	0	0	5	0	0	0	0	NA	0	0	0	NA	0	0	0	45	7%
Temperature	Temperature	0	NA	NA	0	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	10	4	14	2%
pH/acidity/caustic conditions	Alkalinity	0	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	1	<1%
	pH	0	NA	NA	0	26	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*26*	4%
Chlorine	Chlorine	0	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*1*	<1%
Ammonia	Ammonia	0	NA	NA	2	0	0	0	0	0	0	0	0	NA	1	0	0	NA	0	0	0	*3*	<1%

Table 2 continued

	US EPA Region	1		3			4				5				7		8	9		10		Total	Percent of invertebrate-impaired AUs associated with pollutant
	State/ Territory[a]	ME	MA	MD	VA	WV[e]	FL	GA	NC	MS	IN	MI	MN	WI	IA	KS	CO	AZ	CA	ID	OR		
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	Individual AUs with invertebrate-based impairments[c]	40	0	0	142	170	1	56	5	124	32	12	8	0	1	22	1	0	3	25	4	646	
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	Ammonia Nitrogen	0	NA	NA	0	0	0	0	0	2	0	0	0	NA	0	0	0	NA	0	0	0	*2*	<1%
Metals (other than mercury)	Aluminum	0	NA	NA	0	33	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*33*	5%
	Cadmium	1	NA	NA	0	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*1*	<1%
	Copper	1	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*2*	<1%
	Iron	1	NA	NA	0	29	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*30*	5%
	Lead	4	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*5*	<1%
	Manganese	0	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*1*	<1%
	Zinc	4	NA	NA	1	0	0	0	0	0	0	0	0	NA	0	0	1	NA	0	0	0	*6*	<1%
Toxic Organics	PAHs	0	NA	NA	6	0	0	0	0	0	0	0	0	NA	0	0	0	NA	0	0	0	*6*	<1%
Percent of TMDLs Linked to Sediment or Turbidity	by State	15%	NA	NA	76%	60%	0%	96%	0%	90%	94%	100%	63%	NA	100%	82%	0%	NA	100%	68%	0%	72%	144%[d]
	by Region	15%		67%			89%				90%				83%		0%	100%		59%			

[a] Only states with Approved TMDLs for AUs classified under Cause Group Cause Unknown—Impaired Biota are included in this table. Includes approved TMDLs entered in to ATTAINS on or before September 1, 2016.

[b] Distinct AUs contained in USEPA ATTAINS data base for *Cause Unknown—Impaired Biota*

[c] Distinct AUs contained in USEPA ATTAINS data base for Cause Unknown—Impaired Biota with Cause linked to invertebrate-impairment; subset of prior row.

[d] Individual TMDL loading limits are established for single pollutants; more than one pollutant (TMDL) may be identified for a single AU.

[e] WV pollutants listed are based on the biological stressors identified in TMDL reports rather than the pollutants for which TMDLs are developed. In all cases, the sediment stressor is addressed with a surrogate TMDL for iron and organic enrichment stressor is addressed with a surrogate TMDL for fecal coliform. This is done because reductions called for to address impairments of these surrogate pollutants are estimate to be greater than or equal to those needed to address the sediment or organic enrichment impairments.

AU assessment unit, *BOD* biological oxygen demand, *NA* not applicable, *PAHs* polycyclic aromatic hydrocarbons, *TMDL* total maximum daily load enable a substantial increase in the ability of the broader scientific community to make use of the national data to address research questions or determine national trends. Currently, a substantial familiarity with the CWA reporting process as a whole is required to determine what data may be available.

The ATTAINS redesign workgroup did suggest the addition of a new optional data element reflecting monitoring activities, which would allow database users to link monitoring data stored in the National Water Quality Portal to the specific water quality assessment being performed, but acknowledged complications involved with linking these data (RTI International 2014a). Regardless of the form, a publically reported data element indicating the type and conclusions drawn from specific monitoring data on individual water quality assessments would greatly increase the ability of regulators, water quality managers, and scientists to consolidate information such as that sought here regarding the results of biological monitoring efforts nationwide. Current efforts to standardize components of the reporting process and improve data exchange between states and the U.S. EPA (RTI International 2014b) should allow states to provide this increased level of detail without substantially increasing their reporting burden. Assessment determinations are made using a weight of evidence approach, so allowing the data structure to reflect the multiple lines of evidence used in the assessment determination and conclusions drawn from each element evaluated is important. In addition, such reporting results and conclusions drawn from specific physical and chemical monitoring would enable a nationwide evaluation of parameters that may be of particular interest for water quality managers (e.g., data on conductivity, metals, nutrients) or of relevance to tracking national trends. This would allow for a significant increase in application and usefulness of the large volume of national water quality monitoring data.

Pollutants Associated with Invertebrate-based Impairments

Waters currently on the 303(d) list have not had TMDLs completed and formally approved and may be at many different stages in terms of stressor identification. US EPA encourages states to develop schedules for TMDL completion within 8–13 years of 303(d) listing (US EPA 2000a). For consistency's sake, TMDLs in progress (i.e., not yet approved) were not included in this analysis; only final US EPA-approved TMDLs were evaluated here. For the Cause Unknown—Impaired Biota group, this excluded "draft" TMDLs for three AUs and "proposed" TMDLs for one AU (US EPA 2016a).

Twenty of the 57 states had approved TMDL reports classified within the Cause Unknown—Impaired Biota group (998 total AUs; Table 2). As illustrated in the preceding section, only 15% of current aquatic life impairments were classified under this cause group. As such, it is possible that the 37 states without approved TMDLs in the Cause Unknown—Impaired Biota group do have biological impairments, but that these impairments were classified under specific pollutant cause categories or changed classification from Cause Unknown—Impaired Biota to that of a particular pollutant following the stressor identification process.

Of the twenty states that had approved TMDL reports classified within Cause Unknown—Impaired Biota, 16 states had AUs with invertebrate-based impairments (678 AUs; Table 2; Fig. 1d). Over half (52%) of TMDLs clearly developed for invertebrate-based impairments were from US EPA Region 3, and another 27% were from US EPA Region 4 (Fig. 4). This heterogeneity in the number of invertebrate-related TMDLs per region reflects key differences in how states report these impairments and may also reflect different areal extents of the regions and waters they contain. In addition, this heterogeneity reflects differences in the total number of completed TMDLs for all water body types by region (Fig. 4), which is likely due to different state- and region-specific pressures. The legal history of TMDLs provides a potential explanation of the heterogeneity in the number of TMDLs approved per US EPA region, which is likely to relate to differences in state- and regional-specific pressures to publish TMDLs resulting from citizen lawsuits. While TMDL provisions were established as part of the Clean Water Act in 1972, the initial focus of regulatory implementation was on minimizing pollutant inputs from point sources via the establishment of optimal performance standards. Development of TMDLs was accordingly quite limited early on, but

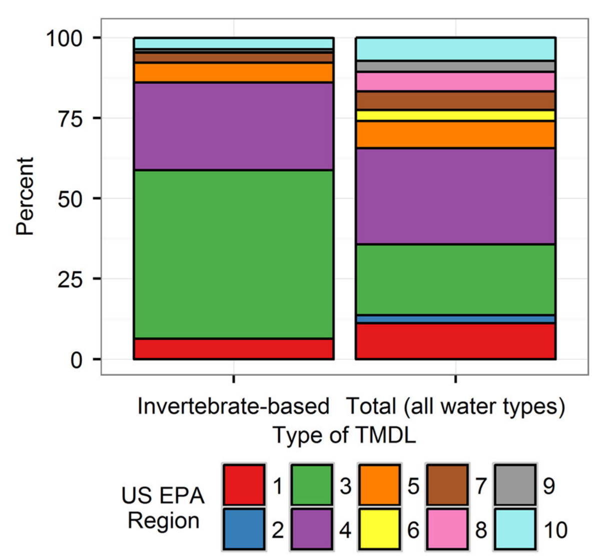

Fig. 4 Invertebrate-based TMDLs (rivers and streams) and total approved TMDLs (for all water bodies) by U.S. EPA Region

increased in the late 1980s and 1990s in response to citizen lawsuits in various states. The first such suit was filed in Illinois (US EPA Region 5) in 1984 (Scott v. City of Hammond, 741 F.2d 992 (7th Cir. 1984)), and involved the state being sued under the constructive submission theory, which argued that because the state had not submitted an impaired waters list to the US EPA, it had in effect submitted a list of no impaired waters requiring TMDLs. The US EPA by law was required to approve or disapprove this list, and thus it would be forced to disapprove the list and take action itself to develop an impaired waters list and TMDLs (Tuholske 2001). This litigation set the precedent that the US EPA was responsible for implementing the TMDL program when states did not act, and a suite of associated litigation followed. By the early 2000s, approximately 40 legal actions were filed by environmental groups in 38 states which resulted in court orders or consent decrees in 22 states requiring US EPA to establish TMDLs when states failed to do so. This included no states in Region 1 and Region 2, five states in Region 3, five states in Region 4, no states in Region 5, three states in Region 6, three states in Region 7, one state in Region 8, two states in Region 9, and three states in Region 10 (US EPA 2001; Houck 2002). In response to litigation regarding pollution of the Chesapeake Bay, the US EPA established the Chesapeake Bay TMDL, which addresses nitrogen, phosphorus, and sediment pollution in Bay states within Region 2 (New York) and Region 3 (Delaware, Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia; US EPA 2010b). While the US EPA previously maintained a website summarizing TMDL litigation by state, they no longer maintain the website nor provide access to an archived version of this site (Chris Lewicki, personal communication).

The 16 states that had AUs associated with invertebrate-based impairments are listed in Table 2 along with the pollutants targeted in associated approved TMDLs. Multiple TMDLs can be derived for an individual AU. A total of 931 TMDLs were established for the 646 invertebrate-impaired AUs.

On a national level, sediment (identified either as sediment or sediment/siltation depending on state-preferred terminology) was the most commonly identified pollutant for invertebrate-based impairments, being identified as a primary stressor for 63% of these AUs (Table 2; Fig. 4). Total suspended solids, another sediment-related metric, was identified as a pollutant for an additional 9% of AUs. In total, these sediment-associated metrics were identified as

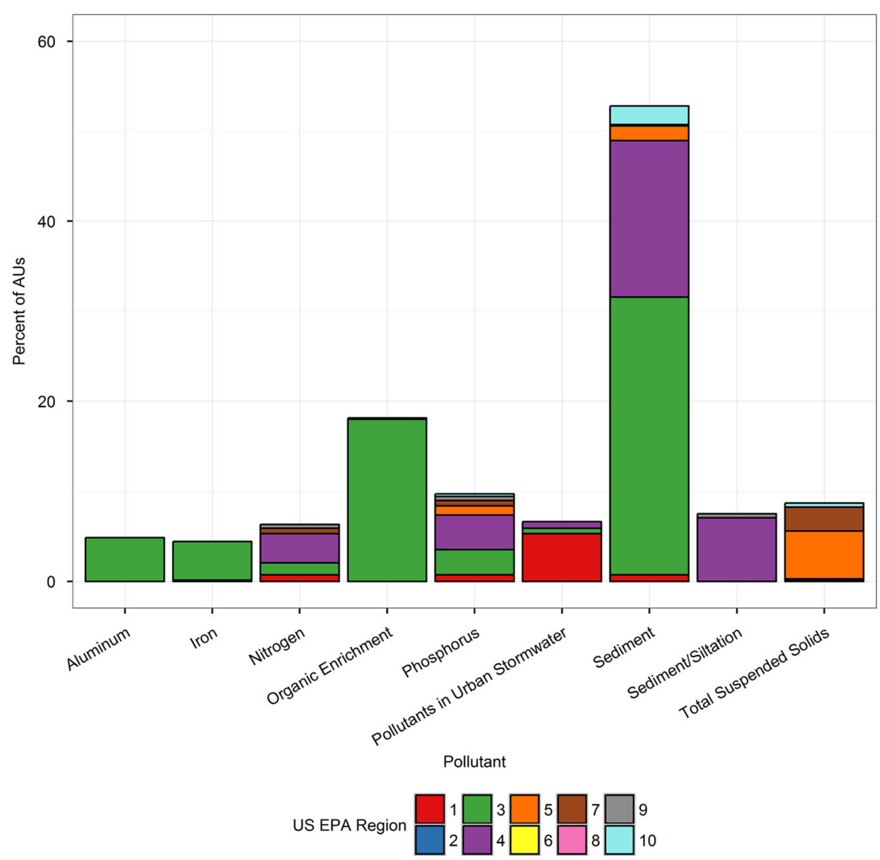

Fig. 5 Pollutants identified for invertebrate-impaired Assessment Units (AUs) in approved TMDL reports coded by US EPA Region. Only pollutants identified in at least 5% of AUs are included

primary pollutants for 72% of invertebrate-impaired AUs nationwide. Pollutants most commonly co-listed for a given AU include nutrients (nitrogen and phosphorus) and some combination of metals. Fig. 5.

This national trend held within six of the ten US EPA Regions; sediment (in some form) was identified as the primary pollutant for the majority of invertebrate-impaired AUs in Regions 3, 4, 5, 7, 9, and 10 (Table 2). No TMDLs for invertebrate-based impairments were established from Regions 2 or 6. The primary pollutant for Region 1 was urban stormwater (identified for 36 of 40 AUs). For Region 8, only one invertebrate-based TMDL was approved; it identified zinc as the primary pollutant. On a state-level, 10 of the 16 states that had TMDLs written for invertebrate-based impairments identified either sediment or turbidity as the primary pollutant in the majority of cases. Other pollutants that were identified in at least 5% of invertebrate-based TMDLs included organic enrichment (19% of AUs, the vast majority from West Virginia), phosphorus (10%), pollutants in urban stormwater (7%), nitrogen (7%), aluminum (5%), and iron (5%).

The identification of sediment as the primary pollutant associated with invertebrate-based impairments is in line with NRSA findings that streams with a "poor" sediment condition were twice as likely to have invertebrate-based impairments than streams not in poor sediment condition. Poor sediment condition in the NRSA report was defined as relative bed stability in the 5th percentile of reference streams. In contrast to NRSA suggestions that nitrogen and phosphorus would play a larger role than sediment in invertebrate impairments (US EPA 2016b), these nutrients were identified as stressors in only 10% (phosphorus) and 7% (nitrogen) of the AUs identified herein. The additional stressors indicated by CWA reporting as important to at least 5% of impaired waters (organic enrichment, pollutants in urban stormwater, aluminum, and iron) were not assessed in the NRSA report. These pollutants may warrant additional focus by water quality managers based on the frequency with which they have been identified as stressors on invertebrate health. This finding demonstrates a key value in further analysis of the data from CWA assessments, which provide site-specific examinations of potential causal relationships between stressors and effects, in contrast to the odds-ratio approach used in the NRSA. In addition, CWA assessments have the potential to uncover stressors of unanticipated importance that are not currently included in NRSA assessments.

Conclusions

While the majority of states include macroinvertebrate biomonitoring as a component of their CWA surface water monitoring programs, specific bioassessment findings are not readily identifiable in the US EPA ATTAINS database due to differences in reporting approaches and state terminology. Data reported depend on data elements available in the ATTAINS structure and water quality report requirements. Standardizing terminology and requiring state agencies to report details of their biological, physical, and chemical assessment data and conclusions drawn from those data units (i.e., basis of impairment decision) within the national database framework would greatly expand the utility of this tool for identify common pollutants of concern and challenges particular to specific biological communities. This would also facilitate sharing best practices and national tracking of progress in achieving CWA goals.

To the best of the authors' knowledge, this is the first work to summarize primary pollutants of concern to macroinvertebrate communities based on national CWA findings. At present, TMDLs have been approved to address 646 individual invertebrate-impaired AUs. Sediment was overwhelmingly the most common pollutant of invertebrate-impaired waters, responsible for 72% of invertebrate-impaired AUs. Sediment impacts on aquatic life have long been recognized (Gammon 1970; Sorensen et al. 1977; Newcombe and MacDonald 1991; Waters 1995; Wood and Armitage 1997; Jones et al. 2012); however, much remains unknown regarding the mechanisms and thresholds of effects (Collins et al. 2011). A thorough understanding of sediment impacts on aquatic ecosystems is complicated by the difficulty inherent in measuring and predicting the fate and transport of sediment as well as the transient nature of sediments once they reach water bodies (Gao 2008; Droppo et al. 2014; Wohl et al. 2015). These results highlight the importance of ongoing research related to sediment impacts on the aquatic environment and efforts to derive sediment-specific biological indices and numerical sediment quality guidelines. Successful protection and restoration of sensitive aquatic communities within the United States will benefit from a consolidation of state knowledge and increased understanding of those pollutants most impacting aquatic life.

Acknowledgements HG has a Cunningham Doctoral Assistantship funded by the Virginia Tech Graduate School, an Interfaces of Global Change Interdisciplinary Graduate Education Program Graduate Research Fellowship from the Virginia Tech Global Change Center, and a William R. Walker Graduate Research Fellow Award from the Virginia Water Resources Research Center. The manuscript was substantially improved by comments from Paul Angermeier, Lawrence Willis, and two anonymous reviewers.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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