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A Systematic Review of Water Vulnerability Assessment Tools

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Abstract The important relationship between health and water necessitates consideration of water vulnerability. Water vulnerability is contingent upon biophysical and social drivers operating at multiple scales, and is difficult to assess. This paper offers a systematic review of 50 water vulnerability assessment tools. We identify and synthesise the contents of these assessment tools (710 indicators) into five dimensions and 22 sub-dimensions and consider the extent to which they reflect environmental and social aspects. The findings are discussed in light of a holistic approach to water resources management, and specifically Integrated Water Resources Management (IWRM). Significant opportunities exist to enhance the efficacy of water vulnerability assessment tools by incorporating indicators and operational measures for social considerations (e.g., adaptation, institutions, governance) that are developed outside the context of water.

Keywords Water vulnerability · Assessment tools · Integration · Integrated Water Resource Management · Systematic review

1 Introduction

Freshwater of acceptable quality and adequate quantity to serve human needs and to fulfill ecosystem functions is of utmost importance. For example, Rockström et al. (2009) examined global freshwater resources as one of the nine boundaries that constitute the 'planetary

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playing field for humanity'. Their analysis indicates that, while humanity may still have some latitude to maneuver, "… the remaining safe operating space for water may be largely committed already to cover necessary human water demands in the future" (online). There are several reasons for this. Milly et al. (2008) observed how climatic change undermines the foundational assumption that the best predictor of future hydrologic conditions is the observed record, and that the hydrologic cycle therefore fluctuates within a predictable envelope of variability (stationarity). The death of stationarity (Milly et al. 2008) has profound implications not only for future water system designs, but also for the billions of dollars of existing infrastructure already installed. While the impacts of climate change on water are a fundamental concern, Vörösmarty et al. (2000) also point to ongoing human influences on the water cycle in the context of global population changes and economic development to 2025, principally in terms of water supply and demand. Climate change, in this light, will exacerbate already serious problems.

These reviews illustrate the magnitude of the threats to global freshwater resources. Access to clean, safe water is not the only determinant of health, defined broadly by the World Health Organization as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" (WHO 1946, p. 2). Nonetheless, it is widely recognised within the health community that unsafe water and poor health outcomes are closely related (e.g., Schuster-Wallace et al. 2008; WHO and UNICEF 2010; WB 2009). The magnitude of this relationship leads Schuster-Wallace et al. to claim "safe water as the key to global health" (2008, p. 1). The relationship between water and health also underscore the importance of assessing *water vulnerability*. We follow the United Nations Environment Programme's understanding that "vulnerability represents the interface between exposure to the physical threats to human well-being and the capacity of people and communities to cope with those threats" (UNEP 2002, p. 302). Drawing upon the broader vulnerability literature (Kelly and Adger 2000; Luers 2005), vulnerability in the context of water resources refers to the susceptibility of a system (individual, community, place) to damage as a function of exposure to external forces (shocks, stress, disturbances), sensitivity of the system, and the ability of the system to respond (cope, recover, adapt).

Interest in assessing the vulnerability of water is widespread. Policy making has involved the employment of indicators since the 1920s (Sullivan and Meigh 2005). However, it was not until the early 1960s that the quest to classify lakes and rivers led to the development of indices to assess the vulnerability of water resources (Jiménez-Cisneros 1996). The numerous indices in existence since the 1950s vary in terms of their comprehensiveness and focus (Jiménez-Cisneros 1996). Despite the lack of consistency among the indices, they have been helpful for identifying and understanding the complexities inherent in environmental monitoring and management (e.g., WB 1998; Dale and Beyeler 2001; Sullivan and Meigh 2005). For example, Lane et al. (1999) directed attention to both environmental and social-economic indicators to measure the impacts of global warming on water resources in the United States. Melloul and Collin (1998) used vulnerability indices effectively to assess aquifer water quality in Israel's Sharon region. Assessing the vulnerability of groundwater resources is a common rationale for the development of indices because of the multiple threats to groundwater that result from activities on or beneath the land's surface, and because of the difficulty of observing those threats directly (Liggett and Talwar 2009).

The vulnerability of freshwater resources is multifaceted. Biophysical conditions are a key determinant of vulnerability, but so too are socio-economic factors (Vörösmarty et al. 2000; Rockström et al. 2009). To be useful to water managers and policy makers, water vulnerability assessments need to be holistic. This reflects the increasing need to consider social and environmental determinants of health in tandem, as illustrated in the Millennium

Ecosystem Assessment (2005) and embodied in the ecohealth approach in which water has become a pervasive theme (Parkes et al. 2008; Colwell and Wilcox 2010). Parkes et al. (2008) further stress the need to link the perspective of ecohealth with the broader focus on integration in water resource management (McDonnell 2008; Timmerman et al. 2008). Thus, recent efforts to assess water vulnerability are moving in this direction. For example, in the context of the Water Poverty Index, Sullivan and Meigh (2007) emphasised the need for integration of biophysical and social science knowledge via iterative processes that are adaptable to different scales. Alessa et al. (2008) proposed a tool for Arctic communities to assess their vulnerability and resilience in the context of water resources; the tool they discussed combines both physical and social indicators at the community/watershed scale. Most recently, Sullivan (2011, p. 627) asserts that "it is now recognised that effective water management is much more dependent on effective governance than on hydrologic regimes". From this departure point, she proposes the Water Vulnerability Index—a multi-dimensional approach (supply-driven and demand-driven) to assess water vulnerability.

This paper is guided by three objectives. First, we seek to provide an overview of current water vulnerability assessment tools. In this regard, we offer a systematic review and critical appraisal of water vulnerability assessment scholarship. Second, we examine the nature and extent to which these water vulnerability assessment tools reflect both environmental/biophysical and social considerations. Third, we discuss the extent to which existing tools for water vulnerability assessments reflect a holistic approach that is consistent with the principles of integrated water resource management (IWRM). Undertaking a project[1] that involves assessing water vulnerability with three Indigenous communities is the catalyst for this systematic review. Initiating a systematic review of assessment tools was a logical starting point for the project as we were immediately confronted with the myriad of ways water vulnerability is assessed. Our intention is not to offer a definitive approach (i.e., one assessment tool to replace all the others), as context needs to be considered in regards to water resources (Ingram 2008). Instead, our motivation for this research is to better understand the examples where people have applied tools to assess water vulnerability and to examine the degree to which they resonate with the need for a holistic perspective. This work thus contributes a synthesis of existing water vulnerability assessment tools for scholars and water resource managers that can be adapted to their particular contexts.

The remainder of the paper is organized according to the following sections. Methods employed to conduct the systematic review are set forth in Section 2. Results of the research are presented in Section 3. Section 4 discusses the vulnerability assessment tools in relation to the need for holistic approaches to water resource management and IWRM. In the closing section, suggestions are made for future inquires and strengthening water vulnerability assessments.

2 Methods

Systematic reviews of existing literature are geared to the comprehensive identification and appraisal of all studies relevant to a specific subject (Petticrew and Roberts 2006; Dixon-Woods et al. 2006; Sutton et al. 2009). The approach is gaining popularity in the environmental field (e.g., Pullin and Stewart 2006; Stewart et al. 2007; Ford and Pearce 2010). Systematic reviews are well suited to situations where a subject has been the focus of

[1] Social Sciences and Humanities Research Council (SSHRC) of Canada project #865-2008-0065

considerable research, and where an 'overall picture' is deemed to be useful for orienting future research, policy and methods (Petticrew and Roberts 2006). The review presented in this paper adheres to the general methodological guidelines set forth for systematic reviews (e.g., Petticrew and Roberts 2006; Pullin and Stewart 2006; Pullin and Knight 2009):

- Question definition. This study seeks to capture a snapshot of the state of water vulnerability assessment tools. The systematic review was guided by the following research questions: What is the 'overall picture' of water vulnerability assessment tools? What environmental and social considerations are reflected therein? How reflective are existing water vulnerability assessment tools of a holistic approach and IWRM?
- Search protocol. An effort was made to maximise the scope of the search protocol to understand the state of water vulnerability assessment tools. Attention specifically focuses on the tools by which water vulnerability is determined. Determining water vulnerability is a multi-faceted process and often associated terminology is variously employed. To capture the assorted ways in which water vulnerability is determined the following key search terms were used: water vulnerability assessments, water vulnerability assessment tools and/or water vulnerability measurements; water vulnerability instrument, water vulnerability index, water vulnerability indicators. Utilising these search terms is an acknowledged limitation of the study and reflects our specific focus on how the vulnerability of water resources to a variety of threats is determined. Claims about the outcomes that emerge from the use of water vulnerability assessment tools are beyond the scope of this paper.

Searches to gather peer-reviewed and non-peer reviewed literature included the personal libraries of the researchers and their research groups, academic databases (Taylor & Francis Journals Online, Elsevier, SpringerLink, Google Scholar, ProQuest, Science Direct, JSTOR, Scholar's Portal, and Scopus), and the internet (via Google). These searches were not limited by geography or scale. In following the protocol forwarded by CEE (2010) for internet searches, the initial 50 'hits' were viewed fully and the subsequent 50 checked for relevance. An acknowledged limitation is that searches only included items written in English. A temporal period was not specified and searches continued until saturation was reached.

- Screen results. The initial searches revealed 245 possible citations. Of these, 133 were excluded because they were beyond the scope of the inquiry. The remaining items were screened with consideration given to 1) the focus of the document (i.e., water vulnerability assessment) and 2) the presence of a way to determine water vulnerability. This includes assessment instruments (a means by which water vulnerability is assessed), indices (a device that reveals water vulnerability, usually a value arrived at through the aggregation of data measuring quantities), and/or indicators (a property or characteristic, usually measurable, to gauge the condition of water vulnerability or an aspect therein). The remaining 112 items were then further analysed to reveal those referencing both human and biophysical elements. For example, items that only focused on groundwater or aquifer vulnerability or those surveys that pertained only to water vulnerability with respect to humans were eliminated. Final scrutiny of the remaining 55 items revealed 50 different tools to assess water vulnerability. It is important to note that these water vulnerability assessment tools are not uniform and we use the term to encompass instruments, indices, and compendiums of indicators.
- Analysis. Each item was analysed to answer the questions posed in the systematic review. A process of coding was used (see Strauss and Corbin 1990) in which multiple passes are iteratively made through each item. In the first pass, axial coding was used to

identify the orientation, scale and context. In the second pass, open coding was used to examine the indicators constituting each water vulnerability assessment tools. These indicators were then categorised and eventually grouped together into sub-dimensions and dimensions.

3 Results

3.1 An Overall Picture of Water Vulnerability Assessment Tools

After following the search and screening protocols specified in Section 2, 55 items were obtained for analysis. To gain initial insights into the diversity of the water vulnerability assessment tools, each item was carefully considered by both name and substantive content. An effort was made to identify named and un-named ways to assess water vulnerability, to report the frequency of their use in the literature and to discern the originating/key source. The 55 items addressed 50 different ways to determine water vulnerability. Table 1 identifies the name of the assessment tool, the frequency of items addressing it and the original or most comprehensive source for each of the 50 different water vulnerability assessment tools included in the systematic review. This summary is intended to help other researchers and managers identify relevant sources of information and links to water vulnerability assessment tools.

The presence of a discernable name was evident for 30 of the 50 assessment tools. The 20 un-named assessment tools were analysed for their resemblance (similarities and differences) to each of the named assessment tools to ensure uniqueness. To convey an 'overall picture' of the state of water vulnerability assessment tools, each document was scrutinised as to its orientation (theory vs. empirical), scale (temporal/biophysical) and location/social-political context. Study orientation sought to determine whether the item was primarily theoretical or empirical in nature. Those identified as being primarily theoretical/conceptual were those explicitly identified as such and/or those which had a strong conceptual component or did not use original data. Conversely, an item was identified as being primarily empirical in orientation when it explicitly stated the intention of conveying the results of a case study and/or presenting original data and/or if it had both a conceptual basis and presented original evidence. A total of 20 items were found to be primarily theoretical, and 30 items primarily empirical.

The items included in this systematic review were examined according to temporal and spatial/jurisdictional dimensions. Figure 1 presents the publication dates (if given) of the items in the systematic review. While the systematic review was not temporally limited, it is clear that most (37) documents have been published within the past decade. When disaggregating the two items lacking a publication date, all were found to be published after 1989. It should also be noted that the number of items identified in the final category only include those published prior to end of the data collection in July, 2010.

Consideration was given to the location or socio-political context to which the water vulnerability assessment tool pertained (see Table 2). More than 30 % of these pertained to North America, 18 % did not identify a specific location and 18 % pertained to a set number of other sites or locations. The remaining applications were located elsewhere throughout the world, with the exception of Australia and Antarctica where no applications were identified.

The biophysical and jurisdiction scale to which the water vulnerability assessment tool was applied was also examined in order to achieve a general sense of the spatial and

Table 1 Items (assessment tools) included in the systematic review

Name of index/instrument	Main Source	Number of items employing the instrument	Number of dimensions reflected	Number of sub-dimensions reflected	Number of indicators
Alberta River Water Quality Index	Government of Alberta 2009	1	1	1	4
The Arctic Water Resource Vulnerability Index (AWRVI)	Alessa et al. 2008	1	5	10	24
Vulnerability Index of the MRB (Freshwater Resources Vulnerability)	Babel and Wahid 2009	1	3	7	24
No title	Barcellos et al. n.d.	1	1	2	7
No title	Beekman et al. 2003	1	3	7	14
Scottish Water Quality Index (SWQI)	Bordalo et al. 2001	1	1	1	11
CCME Water Quality Index	Canadian Council of Ministers of the Environment 2001	2	1	1	3
The Watershed Sustainability Index	Chaves and Alipaz 2007	1	4	5	9
No title	Chu et al. 2003	1	3	4	5
The Water, Economy, Investment and Learning Assessment Indicator (WEILAI)	Cohen and Sullivan 2010	1	4	13	29
No title	Collins and Bolin 2007	1	2	5	27
Oregon Water Quality Index	Cude 2001	1	1	1	8
No title	Doll 2009	1	2	2	3
Water Quality Index (WQI)	dos Santos Simoes et al. dos Santos et al. 2008	2	1	1	9
An inventory of freshwater related indicators in Canada	Dunn 2009	1	5	15	116
No title	Eberts et al. 2005	1	1	1	10
Vulnerability-resilience indicators	Eriksen and Kelly 2007	1	3	10	18
Exposure Indicators for the Developing World	Ezzati et al. 2005	1	3	8	41
Water Scarcity Index	Falkenmark 1989	1	2	3	4
No title	Feitelson and Chenoweth 2002	1	2	3	10
Thornthwaite Water-Balance Model	Frei et al. 2002	1	2	4	21
Canadian Water Sustainability Index (CWSI)	Government of Canada 2007	2	3	8	15
No title	Hambright et al. 2000	1	1	1	10
No title	Hamouda et al. 2009	1	5	13	30
	House 1989	1	1	1	13

Table 1 (continued)

Name of index/instrument	Main Source	Number of items employing the instrument	Number of dimensions reflected	Number of sub-dimensions reflected	Number of indicators
Potable Water Supply Index (PWSI)					
Aquatic Toxicity Index (ATI)	House 1989	1	1	1	12
Potable Sapidity Index (PSI)	House 1989	1	1	1	12
No title	Howard and Bartram 2005	1	2	6	11
No title	Hurd et al. 1999	1	4	8	12
Availability Index (AV Index)	Jiménez-Cisneros 1996	1	1	1	16
No title	Kulshreshtha 1998	1	2	5	12
No title	Lane et al. 1999	1	4	9	17
No title	Lasage et al. 2008	1	3	8	15
International Water Poverty Index	Lawrence et al. 2002	1	5	12	25
No title	Lioubimtseva and Henebry 2009	1	5	12	41
No title	Lundin et al. 1997	1	2	6	21
No title	Malone and la Rovere 2004	1	4	8	13
A Proposed Water Vulnerability Index	Mejia (2010)	1	3	7	15
Sustainable Development Indicators	Mukheibir and Sparks 2003	1	2	5	13
No title	Nganga 2006	1	4	11	21
No title	Perles Roselló et al. 2009	1	5	8	21
A New Water Quality Index	Said et al. 2004	1	1	1	5
Water Vulnerability Index	Segnestam et al. 2000	1	2	4	8
Water Quality Index for Dalmatia County, Croatia	Stambuk-Giljanovic 1999	1	1	1	8
Water Wealth Index	Sullivan et al. 2006	1	5	15	26
No title	Sullivan 2002	1	4	10	21
The Rural Water Livelihoods Index	Sullivan et al. 2009	1	3	4	8
Water Poverty Index	Sullivan et al. 2003	3	5	12	23
Millennium Development Goals	UN and WWAP 2006	1	5	18	54
Water Indicators for a Project-Based Approach	Winograd et al. 2000	1	3	10	28

jurisdictional dimensions. Each item was thus categorised as small scale (local/community), regional jurisdiction (political boundary), watershed/basin (biophysical boundary), national, international and/or no scale given. These categories are intended as generally identifiable

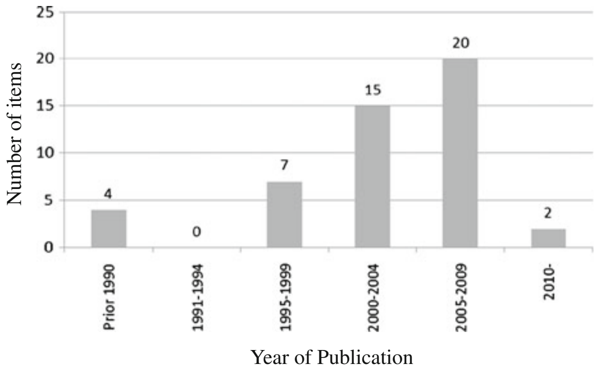

Fig. 1 Water vulnerability assessment tools included in the systematic review by publication date

rough divisions as scale is rarely precisely defined or explicitly stated. Table 3 conveys the range of scales to which these assessment tools were applied. National or countrywide was the most frequently occurring scale (38 %) with watershed\basin, small-scale and regional scales respectively accounting for 22 %, 14 % and 14 % of the applications.

3.2 What Environmental and Social Considerations were Reflected?

The second question guiding the systematic review addressed the environmental and social considerations reflected in the water vulnerability assessment tools. To understand the scope of social and ecological considerations encompassed in these assessment tools, each one identified in Table 1 was analysed. As detailed in Section 2, this occurred through the iterative process of coding each indicator or specific measure of water vulnerability given. Of the 50 items, 32 (64 %) contained indicators with explicit information on how each is measured, six (12 %) provided measurements for some of their indicators and 12 (24 %) did not give information about how the indicators are measured. In subsequent iterations of coding, the indicators were categorised into sub-dimensions and then dimensions. Through this constant comparison technique, each assessment tool was compared to the existing dimension. If an item fit within an existing dimension it was added, otherwise a new category was created.

Table 2 Location/socio-political contexts in which water vulnerability assessment tools have been applied

Location / socio-political context	Number of items	% of items
Antarctica	0	0
Africa	6	12
Asia	7	14
Australia	0	0
Europe	2	4
Multiple locations given	7	14
No locations identified	9	18
North America	15	30
South America	4	8

Table 3 Scales at which water vulnerability assessment tools have been applied

Scale	Number of items	% of items
No scale identified	2	4
Multiple scales identified	2	4
Small [local] scale	7	14
Watershed/basin	11	22
Regional	7	14
National	19	38
International	2	4

Table 4 summarises the results of the synthesis of water vulnerability assessment tools. The process of synthesising the indicators into categories revealed a total of five dimensions and 22 sub-dimensions. The primary dimensions identified were: water resources, other physical environment, economics, institutions and social. Figure 2 illustrates the number of sub-dimensions and indicators within each of dimension. A total of 710 indicators were identified within the 50 water vulnerability assessment tools. The water resources dimension encompassed the greatest number and highest percentage (50 or 100 %) of assessment tools and contained the most indicators (323 or 45 % of all indicators). Economics had the greatest number of sub-dimensions (7 or 32 %) as well as encompassed the next highest number of assessment tools (33 or 66 %). The dimensions of institutions and social encompassed the smallest number of assessment tools (17 or 34 % and 13 or 26 %, respectively) as well as the fewest indictors (49 or 7 % of all indicators and 34 or 5 % of all indicators, respectively).

The number of assessment tools containing indicators within each sub-dimension, as well as the total number of indicators for each sub-dimension, was considered. As shown in Table 4, the total number of indicators for each sub-dimension was relatively high compared to the range of indicators used to capture the sub-dimension by any one assessment tool as well as the average number of indicators used to measure the sub-dimension. The number and percentage of assessment tools containing indicators within each of the sub-dimensions ranged from a high for the sub-dimension of resource supply (33 assessment tools or 66 %) to the low for the sub-dimensions of conflict and cultural capacity (both 4 assessment tools or 8 %). The sub-dimension of water quality had both the greatest total number of indicators (94 or 13 %) as well as the highest average number of indicators used to capture it (6). The next three sub-dimensions with the greatest number of indicators were livelihood (93 or 13 %), water resource/supply (72 or 10 %) and water resources infrastructure (70 or 10 %). Conflict had the fewest indicators (2 or <1 %). The most frequent indicators for each of the 22 sub-dimensions are detailed in Table 4.

The number of dimensions, sub-dimensions and indicators present in each of the water vulnerability assessment tools are shown in Table 1. Several of the named as well as the un-named assessment tools (see the list in Table 1) span all five of the dimensions. The 22 sub-dimensions were most strongly reflected by the Millennium Development Goals (18 or 81.8 %) (UN-WWAP 2006), an Inventory of Freshwater Related Indicators in Canada (15 or 68.2 %) (Dunn 2009) and the Water Wealth Index (15 or 68.2 %) (Sullivan et al. 2006). The greatest number of indicators was found in the Inventory of Freshwater Related Indicators in Canada (Dunn 2009) and in the Millennium Development Goals (UN-WWAP 2006), with 116 and 54, respectively. The number of indicators reflected in an assessment tool ranged considerably from 3 to 116.

Assessment tools were then analysed for how they incorporated environmental and social considerations. A score to gauge the comprehensiveness and integrativeness of each

Table 4 Synthesis of water vulnerability assessment tools

Dimension	# and % of assessment tools captured by the dimension	Sub-dimensions	# and % of assessment tools containing indicators within the sub-dimension	Total # of unique indicators from all assessment tools	The # of indicators (min-max) associated with the sub-dimension in assessment tool	Average # of indicators used to capture sub-dimension by an assessment tool	Most frequent indicator(s)
Water resources	50 (100 %)	Resource / supply	33 (66 %)	72	1–13	3	Groundwater availability; Availability (non-specified) (5)
		Access	24 (48 %)	55	1–9	3	Population with access to sanitation (6)
		Use	18 (36 %)	32	1–7	3	Industrial water use (4)
		Quality	32 (63 %)	94	1–29	6	Presence of coliforms (total, fecal) (11)
		Infrastructure	17 (34 %)	70	1–16	4	Storage; Treatment technology scale (primary, secondary, tertiary) (3)
Other physical environment	24 (48 %)	Climate change	8 (16 %)	25	1–11	3	Evapotranspiration; Precipitation levels (2)
		Environmental pressures	13 (26 %	27	1–6	2	Industrial organic pollutants; Water stress (2)
		Environment	21 (42 %)	37	1–8	2	Land use; Land cover; Aquatic life; Vegetation; Biodiversity (2)
Economics	33 (66 %)	Economic capacity	26 (52 %)	39	1–6	2	Human Development Index (HDI) Rank (5)
		Labour	4 (8 %)	4	1–1	1	Frequency of 1 for all indicators
		Equity	7 (14 %)	8	1–2	1	Inequality [GINI coefficient] (3)

Table 4 (continued)

Dimension	# and % of assessment tools captured by the dimension	Sub-dimensions	# and % of assessment tools containing indicators within the sub-dimension	Total # of unique indicators from all assessment tools	The # of indicators (min-max) associated with the sub-dimension in assessment tool	Average # of indicators used to capture sub-dimension by an assessment tool	Most frequent indicator(s)
		Demographics	16 (32 %)	24	1–5	3	Population; Children under five mortality rate (6)
		Livelihood	23 (46 %)	93	1–15	4	Hydropower potential (3)
		Human health	15 (30 %	31	1–10	2	People affected by diarrheic diseases; Access to healthcare (2)
		Education	11 (22 %)	16	1–7	3	Literacy; Education levels (2)
Institutions	17 (34 %)	Governance	14 (28 %)	39	1–6	3	Land area set aside in protected area status (3)
		Conflict	2 (4 %)	2	1–1	1	Frequency of 1 for all indicators
		Political	7 (14 %)	8	1–2	1	Political stability (2)
Social	13 (26 %)	Engagement	7 (14 %)	9	1–2	1	Frequency of 1 for all indicators
		Cultural capacity	4 (8 %)	6	1–2	2	Frequency of 1 for all indicators
		Knowledge capacity	6 (12 %)	10	1–3	2	Frequency of 1 for all indicators
		Technical capacity	5 (10 %)	9	1–4	2	Frequency of 1 for all indicators

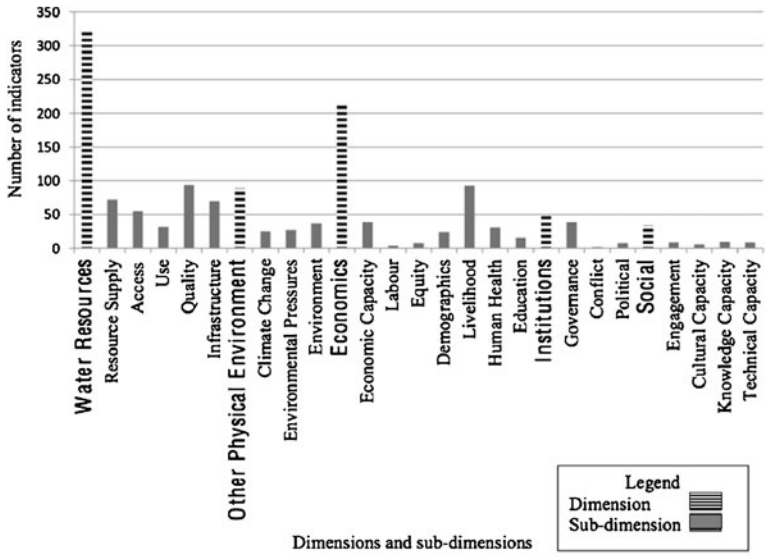

Fig. 2 Number of indicators by dimension and sub-dimension

assessment tool was derived by calculating the percentage of dimensions as well as a percentage of sub-dimensions covered by the instrument using the equation:

$$CI_k = \left(\left(\frac{N_{kd}}{5} \right) + \left(\frac{N_{ksd}}{22} \right) \right) \times 10$$

where $CI_{k,}$ is the comprehensiveness and integrativeness of the water vulnerability assessment k, N_{kd} is the number of dimensions reflected by water vulnerability assessment k and N_{ksd} is the number of sub-dimensions reflected by water vulnerability assessment k. Figure 3 plots the assessment tools analysed according to their score and their number of indicators. The analysis of the assessment tools reveals a considerable range of scores (from a low of 2.45 to a high of 18.18) as well as general clusters (around scores of 2.5, 6, 10 and 15). The least comprehensive and integrative assessment tools also tended to have fewer indicators, with only one that had achieved a score lower than 10 having more than 30 indicators. Conversely, the assessment tools with a score greater than 10 had no fewer than 10 indicators and a maximum of 116 indicators. Perhaps most striking were the three water vulnerability assessment tools that had both a high (top 5) score and a high number of indicators (top 5). Considered to have both breadth and depth, these were the Inventory of Freshwater Related Indicators in Canada (Dunn 2009), Millennium Development Goals (UN-WWAP 2006) and the non-titled assessment tool by Hamouda et al. (2009).

4 Discussion

The vulnerability of water resources is not contingent upon a sole domain or sphere (Vörösmarty et al. 2000; Rockström et al. 2009). 'Attention to both human and biophysical elements' was therefore purposefully set forth as an inclusion criterion for the systematic review (see Section 2). A holistic approach is frequently advanced for water management

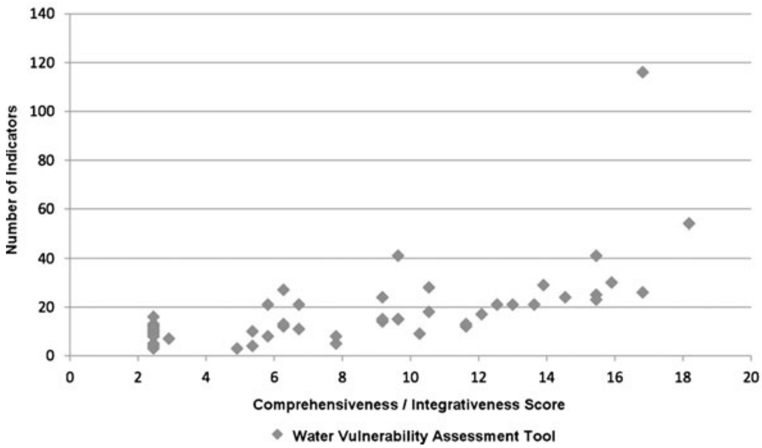

Fig. 3 Water vulnerability assessment tools analysed by comprehensiveness / integrativeness score and number of indicators

(Mitchell 2005), and underlies the perspective of ecohealth (Parkes et al. 2008). Mitchell (2005) explains how two interpretations have developed in association with the holistic approach to water resources management. The earlier interpretation is referred to as *comprehensive* and stresses the need to define the system in the broadest way so as to understand all variables and relationships. The second interpretation is referred to as *integrative* and emphasizes key or selected variables and relationships, while still maintaining a systems orientation. Mitchell (2005) observes that these interpretations are not mutually exclusive and argues for a blended or hybridized approach to realize the benefit of both interpretations. IWRM emerged from this holistic approach (Mitchell 2005) and is being promoted for adoption worldwide in regards to water resources management (Global Water Partnership 2003). The third objective posed at the outset of this systematic literature review therefore queried the extent to which water vulnerability assessment tools reflect a holistic approach and IWRM. This section draws upon the literature and results from the preceding sections to discuss this objective.

The Global Water Partnership (2003, p. 21) defines IWRM as, "a process which promotes the coordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

IWRM accounts for the hydrological cycle, quality and quantity concerns, diversity of users and administrative responsibilities at various scales, distribution of resources and temporal variability, connections to land use and transboundary claims (Gumbo and van der Zaag 2001; Svendsen 2001). IWRM further intends to bring together and broaden the range of environmental and social values (e.g. biodiversity, social and cultural) and highlights the importance of institutions relating to water (Bellamy and Johnson 2000; Chenoweth et al. 2001; Cortner and Moote 1994). Adaptive management is closely aligned with IWRM as a means of addressing resource complexity and uncertainty in management by highlighting the roles of experimentation, action and learning (e.g., Jeffrey 2006; Jeffrey and Gearey 2006; Galaz 2007; Ingram 2008; Timmerman et al. 2008).

The outcomes of the initial screening process for the present systematic review and the overall picture of water vulnerability assessments instruments *vis-à-vis* IWRM reveal the extent to which these assessments generally have not considered biophysical and human elements adequately. Thus, evolution of water vulnerability assessment tools is required if they are to facilitate a holistic perspective (i.e., integrative and/or comprehensive) and be sensitive to conditions of uncertainty. Only 55 of the 112 items identified in the initial screening criteria encompassed both elements to some degree. Even though the nature of IWRM is strongly conceptual—with a gap towards practical application and results (Biswas 2004; Jeffrey and Gearey 2006; Ingram 2008)—a majority (60 %) of the water vulnerability assessment tools analysed were primarily empirical in nature. Half of the water vulnerability assessment tools examined in the review were applied at watershed/basin, small and regional scales. IWRM is commonly applied at these scales.

Assessment tools analysed in the review generally mirror shifts within the water resource management and IWRM paradigms described above. Two key findings lead to this assertion. First, the reflection of environmental and social considerations in the water vulnerability assessment tools derived from the analysis demonstrate a marked emphasis on conventional considerations of water supply and water demand. There is limited emphasis on the institutional and social dimensions. Second, the results show considerable variability in terms of comprehensiveness and integrativeness (number of dimensions, sub-dimensions), but interestingly they also show that the three assessment tools with a high score and number of indicators were authored after 2006 (two of which are in 2009). This is consistent with the analysis by Timmerman et al. (2008) and their observation of limited attention to social dimensions of vulnerability in the daily practice of water management.

As noted above, key features of IWRM (adaptation, institutions, and governance) are not strongly reflected in water vulnerability assessment tools. Interestingly, the vulnerability literature beyond the context of water stresses these key features, often in association with adaptive capacity and resilience (e.g., Adger 2006; Gallopin 2006; Füssel 2007). For example, several assessments in reference to climate change have been developed and applied in a variety of situations to capture biophysical and social aspects of vulnerability and adaptive capacity (e.g., Yohe and Tol 2002; Adger et al. 2004; Vincent 2004; Sullivan and Meigh 2005; Wall and Marzall 2006; Hahn et al. 2009). Two important prospects are thus raised. First, an opportunity exists to conduct a systematic review of the water resources literature using the search terms adaptive capacity and resilience to see if the above key features of IWRM appear. Second, a possibility exists to enhance consideration of these key features in water vulnerability assessment tools by looking broadly at literature on adaptive capacity (e.g., Smit and Wandel 2006; Carpenter and Brock 2008; Armitage and Plummer 2010) and social-ecological resilience (e.g., Folke 2006; Nelson et al. 2007; Chapin et al. 2010).

5 Conclusions

Converging interests from the fields of environmental health and social determinants of health have forged well-established linkages among ecosystems, health and society (Parkes et al. 2008). Water is essential in this relationship. The connection between water and health is irrevocable as "water is a cross-cutting theme linking nearly all major global health challenges, including biodiversity conservation, climate change, poverty alleviation, and infectious diseases" (Colwell and Wilcox 2010, p. 151). The importance of biophysical and human aspects of water vulnerability is well understood (Vörösmarty et al. 2000; Rockström et al. 2009) and efforts to understand water vulnerability will only intensify as current and emerging drivers of change (climatic, social, economic) interact to impact human health and wellbeing.

This research sought to better understand the breadth of water vulnerability assessment tools and the degree to which they resonate with a holistic approach. From this systematic review, an overall picture was revealed, and the environmental and social considerations reflected by the 50 applicable water vulnerability assessment tools were analysed. Coding of the assessment tools revealed 710 indicators, 22 sub-dimensions and five dimensions. Variability in comprehensiveness and depth within the five dimensions was considerable. The holistic approach is both comprehensive and integrative (Mitchell 2005). IWRM emerges from this approach and draws attention to a diverse range of values associated with water, aspects of uncertainty and complexity, and connections between biophysical aspects of water and its governance. The discussion illuminates the limited extent to which the water vulnerability assessment tools analysed reflect a holistic approach.

There are no panaceas for water management. Indeed, attempts based on such thinking have resulted in a record of failed water policy solutions over the past several decades (Meinzen-Dick 2007; Ingram 2008). This systematic literature review uncovered the individualised nature of water vulnerability assessments, showcasing their considerable variation in terms of comprehensiveness and little overlap in terms of indicators. This may reflect the need for a contextual approach to water resources as suggested by Ingram (2008). Although a concerted effort was made in the systematic review through the search protocol and screening to arrive at a comparable group of water vulnerability assessment tools, their individualized nature may be a manifestation of the various motives for their creation and means by which they were developed. Additional avenues for exploration will be to ask the following questions of each water vulnerability assessment tool. What was the original purpose? How was it developed? What was the intended outcome(s)? Answers to these questions may assist in better understanding the individualized nature of the results achieved in this systematic review.

While it is certainly not meaningful to use the same water vulnerability assessment tool in all places and at all scales, the assessment tools analysed in this research commonly make reference to both human and biophysical elements. In this way, the systematic review offers an informed basis or starting point upon which researchers and water managers may construct water vulnerability assessment tools tailored to their situation. Increasing the consistency among water vulnerability assessment tools, while still permitting contextual sensitivity, may help to facilitate comparisons, better realize transferability and highlight best practices. If water vulnerability assessment tools are generally to realise their potential in reference to both environmental and social determinants of health, the holistic approach, and IWRM in the near term, concerted efforts are required to enhance social and institutional considerations in this area of scholarship, specifically adaptation, institutions and governance. These considerations focus attention on capturing the susceptibility and response capacity of a system to water related risks. Opportunities to improve existing assessments by incorporating social and institutional variables will also bring challenges. Capturing and measuring these aspects in meaningful ways will be difficult as they do not readily lend themselves to numerical expression. How best to combine quantitative and qualitative data together in an instrument remains an important research question.

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