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Problematizing Water Vulnerability Indices at a Local Level: a Critical Review and Proposed Solution

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Abstract Effectively assessing water vulnerability is essential as threats to water resources mount. Appraisals that take an integrative perspective incorporating physical and social considerations at a community scale are particularly important as they address the breadth of vulnerability sources and concentrate on a level where action frequently occurs. This paper critically reviews seven water vulnerability indices according to good practices for composite indices. The analysis reveals several shortcomings and discusses how they limit the validity of water vulnerability indices. A seven step framework is proposed to overcome these limitations. It builds upon previous approaches to assessing water vulnerability and incorporates good practice of developing composite indices. The framework offers guidance to enhance effectiveness and promotes tailoring of water vulnerability assessments to particular situations. Improving the accuracy of information from such assessments ultimately enhances the capability to respond to water related challenges.

Keywords Water vulnerability · Water vulnerability indices · Index design

1 Introduction

The capability of humans to accurately and expediently identify threats to fresh water is imperative. Approximately 80 % of the world's population is confronting water security threats (Vörösmarty et al. 2010). Assessing one or more aspects relating to water is a diverse and a major research theme in Water Resources Management (e.g., Aydin et al. 2014; Jubeh and Mimi 2012; Norman et al. 2013). Interest in assessing water vulnerability (ie. physical threats as well as the capability of humans to cope) dates back to the 1920s (Sullivan and Meigh 2007) and more than 50 such instruments or tools now exist for this purpose (see Plummer et al. 2012).

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Existing water indices are praised for being simple to use and easy to understand, promoting transparency and accountability, having broad applicability and adaptability, and enabling prioritization of action in areas of need (Alessa et al. 2008; Chavez and Alipaz 2007; Sullivan et al. 2003). These assessment tools reflect the variety of possible choices in terms of focus, design, implementation, and analysis. Many authors explicitly identify the preliminary or exploratory nature of their work and call for improved and more rigorous process of water vulnerability index development (Sullivan 2010; Babel and Wahid 2009). While some limitations of indices have been discussed in association with assessing water vulnerability (e.g., Feitelson and Chenoweth 2002; Molle and Mollinga 2003), substantive reflections upon methodological choices and reporting is nascent.

This paper reviews water vulnerability indices and proposes ways to improve their accuracy and reporting. Seven water vulnerability indices were chosen from the recent systematic review by Plummer et al. (2012). They share similar objectives, are applicable at the local level, take an integrative approach, and provide a transparent methodology. They are critically assessed according to good practices for composite index construction, implementation, and reporting and then applied to a case study to illuminate their transferability. In response to the shortcomings revealed, we propose a multi-step framework to guide development of community water vulnerability indices, which has been missing in the literature up to date. By proposing the framework, this paper provides a much needed and long overdue guidance on the essential steps needed to construct and refine a composite water vulnerability index at a local level.

2 A Critical Review of Water Vulnerability Indices and Their Transferability

This critical review concentrates on those water vulnerability assessment tools which share similar objectives, are applicable at the local level, take an integrative approach, and provide a transparent methodology. It is scoped in this way because the local scale is viewed as the most important and relevant in solving water problems as this is where actions occur ‘on the ground’ (Sullivan et al. 2003), an integrated perspective acknowledges the range of vulnerability sources (biophysical as well as social) related to water (Chavez and Alipaz 2007; Plummer et al. 2012), and transparent methods are required for the appraisal. All of the water vulnerability assessment tools identified in the systematic survey of this body of scholarship by Plummer et al. (2012) were considered along each of the aforementioned parameters. The following seven tools met all the parameters: Water Poverty Index (WPI) (Sullivan 2002; Sullivan et al. 2003; Sullivan and Meigh 2007), Water Vulnerability Index (WVI) (Sullivan 2010), Rural Water Livelihood Index RWLI) (Sullivan et al. 2009), Water, Economy, Investment and Learning Assessment Indicator (WEILAI) (Cohen and Sullivan 2010), Watershed Sustainability Index (WSI) (Chavez and Alipaz 2007), Arctic Water Resource Vulnerability Index (AWRVI) (Alessa et al. 2008), and Vulnerability Index of Water Resources of a River Basin (VIWRRB) (Babel and Wahid 2009).

While concentration on methodological and reporting considerations is limited regarding water vulnerability indices, composite indices are used widely in numerous fields (e.g., economics, management, environment and social studies). A composite index aggregates multiple individual indicators to provide a measure of a complex and multidimensional issue. Significant progress has been made in establishing good practices of index development that address issues such as conceptual framework, measurement model, missing data, data quality, measurement scales, normalization of the data, weights and aggregation methods (OECD 2008; Saisana and Tarantola 2002; Saisana et al. 2005; Saltelli et al. 2008). These good practices are expanded upon and then applied in the following sections to evaluate the seven water vulnerability indices and summarized in Table 1.

2.1 Conceptual Model and Measurement Model

Developing a conceptual framework and selecting indicators to capture the concept being measured is the initial step in creating an index (Pintér et al. 2008). According to good practice, indicators should be valid, accurate, measurable, and correspond to data that is likely available (Chavez and Alipaz 2007; Pintér et al. 2008). They need to be constructed in a transparent manner (Sullivan 2001), be understandable by the intended audience (Chavez and Alipaz 2007; Pintér et al. 2008; Sullivan 2001), relevant for the community (Chavez and Alipaz 2007; Winograd et al. 1999), and have potential to summarize, quantify and communicate relevant information (Malone and LaRovere 2005). Specific to assessments at a community level, indicators should be generated locally (Sullivan 2001) through participatory processes (Sullivan and Meigh 2007; Sullivan et al. 2003).

Almost all of the seven indices reviewed described the process of developing a conceptual framework of water vulnerability. It usually involved a literature review and/or some form of participatory process with stakeholders, for example consultation meetings and workshops (Sullivan et al. 2003) or Delphi Technique (Alessa et al. 2008). Despite general agreement on the need for indicators to capture the whole concept of water vulnerability, other factors gained prominence when indicators were being chosen, such as data availability (e.g., Chavez and Alipaz 2007; Sullivan 2010; Sullivan et al. 2009), cost of data collection (Winograd et al. 1999; Sullivan 2001), desire to minimize the number of indicators so the index is more widely applicable in data-scarce regions (Winograd et al. 1999; Chavez and Alipaz 2007) and to avoid perceived washing out of components (Sullivan et al. 2009). However, indicator removal due to the above mentioned reasons could damage the conceptual foundation of the assessment. The existing water vulnerability indices are also hampered by the practice of using a single indicator to capture an entire dimension of water vulnerability. For example, Chavez and Alipaz (2007) argued that two indicators (Human Development Index value and biochemical oxygen demand) were sufficient to capture quality of life and water quality respectively. However, in such an approach the completeness of the assessment is questionable.

2.2 Data Sources, Data Collection and Missing Data

Decisions about data sources and collection methods also affect the soundness of composite indices (OECD 2008). In the seven water vulnerability indices analyzed, only limited attention was given to how data sources may influence the reliability of the assessment. While secondary data are often simple and relatively accessible at low cost, relying exclusively on secondary sources poses limitations as data availability is often constrained, dependent on the different collection agencies and subject to their methodologies. Sullivan et al. (2003) argue that such sources may be inconsistent, unreliable or invalid. Despite the limitations of secondary data sources, very few of the indices (Sullivan 2002; Cohen and Sullivan 2010) used primary data collection.

A related challenge is dealing with missing data. Some of the popular approaches to deal with missing data include indicator removal, case deletion, and data imputation (OECD 2008),

Table 1 Comparison of methodology used by eight water vulnerability indices

	Water Poverty Index (WPI)	Water Vulnerability Index (WVI)	Rural Water Livelihoods Index (RWLI)	Water, Economy, Investment and Learning Assessment Indicator (WEILAI)
References	Sullivan 2002; Sullivan et al. 2003; Sullivan and Meigh 2007	(Sullivan 2010)	(Sullivan et al. 2009)	(Cohen and Sullivan 2010)
Scale of application	(Sullivan and Meigh 2007) – WPI at community scale	Local municipal scale	Countries	Local level, villages
Empirical examples	Pilots sites in South Africa, Tanzania and Sri Lanka	87 local municipalities which fall within the Orange Basin in South Africa	Applied to 158 countries in the world	Eight Administrative Villages in four counties: TianDeng, LeYe, NaPo, and TianLin in China.
Applicability to other locations	Country level and community level	Yes, as long as there is consistency and availability of data	Yes, can be also applied to livelihood zones	Developed specifically for water-focused rural poverty assessment in China
Components (dimensions) identified)	Water resources; water access; water uses; capacity for water management; and environmental aspects	Supply –driven vulnerability (water resource, extreme event, land cover, storage) and demand-driven vulnerability (demographic, household, economic, bulk demand)	Access to water and sanitation services, crop and livestock water security, clean and healthy water environment, secure and equitable water entitlement	Water resources, water access, water resource management capacity, sanitation, education, health and hygiene, food security, and environment
Process of identifying components and indicators	Participatory process through consultation meetings with stakeholders, including water users, policy makers, water sector professionals, aid agency personnel, and scientists. These meetings were held in each of the 3 participating countries: South Africa, Tanzania and Sri Lanka.	Based on investigation of local perceptions of water vulnerability and other qualitative information obtained from interviews and workshops. The final selection of variables was based on data availability and expert opinion. Water quality indicators were left out when no data was available.	Based on previous theoretical frameworks and multiple consultations with experts. However, due to the focus on countries, only indicators for which enough global data was available were used.	Based on previous theoretical frameworks: the WPI (Sullivan 2002), the sustainable livelihoods analytical framework (Scoones, 1998) and the basic needs framework and entitlements work (Sen 1984; Sen 2000) and on the analysis of the context (China). Supported with Confirmatory Factor Analysis.
Recommendations regarding number of components and indicators	No specific recommendations; 17 indicators	No specific recommendations	Minimize as far as possible in order to avoid the 'washing out' of the individual importance, however the concept being measured needs to be fully captured.	No specific recommendations
Determining values for indicators/parameters	Aggregated values from household surveys conducted in four locations in each of the 3 countries, 1521 household surveys in total; Information obtained from local authorities; Field investigations	Secondary data only: the Statistics South Africa databases and national hydrologic and meteorological data from other relevant sources identified in the paper.	Secondary sources, different units of measurement that need normalization	Questionnaire, interviews and measurements in the field. Some indicators were measured based on more than one source of data.

Table 1 (continued)

	All the above information was combined.			
Normalization/ standardization	Components are standardized to fall in the range 0 to 100; giving a final WPI value between 0 and 100. Scores for each index and sub-index are calculated by the formula: $x_i - x_{min} / x_{max} - x_{min}$ where x_i, x_{max} and x_{min} are the original values for location i, for the highest value country, and for the lowest value country respectively	Yes, data was normalized, but no details were provided.	Data were normalized using a 0–100 scale where high numbers indicated favourable conditions. $x_i - x_{min} / x_{max} - x_{min}$	Data were normalized using a 0–100 scale where high numbers indicated favourable conditions. Method depends on the indicator. Some: percentages, ordinal data: scaled; different formulas; other: $x_i - x_{min} / x_{max} - x_{min}$ In many cases where a given dataset's high value was not necessarily the best or optimum value achievable the data was amplified by 20 % (as was done in the WPI)
Missing values	One of the over- arching objectives is to try to use existing data where possible, rather than requiring the need for further data collection. Proxy data were used when possible, other missing data were ignored.	No discussion; indicators (variables) with too many missing values were removed from the index.	Drop indicators and components from the index, drop countries that were missing two or more components, for the remaining missing values if possible impute the values based on expert judgment, past data or similar cases.	Missing data from survey were mostly ignored.
Weights for dimensions and sub-dimensions	Equal	Equal, but recommends determining weights based on investigation of local perceptions	Equal weights for components and subcomponents.	Expert weights are used to aggregate the subcomponents used to calculate each dimension, but no overall composite WEILAI score is calculated.
Aggregation (determining the index value)	WPI is derived as the weighted average of five components. The highest value is taken to be the best situation (the lowest possible level of water poverty), 0 is the worst.	WVI=SDWV+DDWV Both dimensions are weighted averages of their components	RWLI=average of its components	Thematic index, a collection of composite indicators, presented together but not aggregated into a composite index
Recommended interpretation of the results	Index value and pentagram to enable a more comprehensive understanding of the meaning of the results	Index value, multi-axis graph to show components values, future water vulnerability analysis (substituting projected values)	Index value, multi-axis graphs, maps	Values of components need to be interpreted. Evaluate at about 3–4 years to measure temporal processes.
Limitations	No explanation of normalization method, no analysis of the impact of missing data approach, equal weights	Choice of indicators based on data availability, not only the conceptual model, no explanation of normalization method, reliance solely on secondary data, equal weights	Using only indicators for which enough global data was available, secondary data sources, normalization method based on minimum and maximum scores in the study population, equal weights	Normalization method based on minimum and maximum scores in the study population

Table 1 (continued)

	Watershed Sustainability Index (WSI)	Arctic Water Resource Vulnerability Index (AWRVI)	Vulnerability Index of Water Resources of a River Basin
References	(Chavez and Alipaz 2007) (Catano et al. 2009)	(Alessa et al. 2008)	(Babel and Wahid 2009)
Application scale	River basin (intermediate level)	Local/community scale	River basin level or local level
Empirical examples	Verdadeiro watershed in Brazil (Chavez and Alipaz 2007) watershed of the Reventazón River in Costa Rica (Catano et al. 2009)	Three case study communities/ watersheds in Alaska	Mekong River basin
Applicability to other locations	The WSI could be applied to all basins up to 2500km^2. Larger basins should be divided into smaller areas and WSI should be calculated for each and aggregated.	Specific to Arctic communities at local scale	No discussion
Components (dimensions) identified	Hydrology, environment, life, and policy (pressure-state-response sub-dimensions in each)	Physical component (natural supply, municipal supply, water quality, permafrost, subsistence habitat subcomponents) and social component (knowledge capacity, economic capacity, institutional capacity and cultural capacity)	Resources stresses, development pressures, ecological insecurities, and management challenges
Process of identifying components and indicators	No discussion of the process of identifying components. Indicators were selected based on their relevance and availability (the index applies the most basic indicators that are generally available for all basins).	Components were identified based on existing water indices. Construction of constituent indices and choice of indicators were arrived at using the Delphi technique (series of questionnaires with controlled feedback sent to water experts with experience in Arctic regions).	Choice of components based on literature review and analysis of the study river basins and their management systems (using DPSIR framework from UNEP). Involved experts and workshops. Some values for indicators were estimated based on experts' opinion. Strict numerical validity was not considered the core issue.
Recommendations regarding number of components and indicators	The index uses a small number of components and indicators in order to allow for higher simplicity and wider applicability.	All relevant indicators are included, but effort was undertaken to reduce redundancy and correlation between indicators.	No discussion, all relevant issues were included
Determining values for indicators/ parameters	Majority of indicators are evaluated using secondary data sources (HDI, etc.). A few are subjectively evaluated by authors based on information about the basin (Chavez and Alipaz 2007). Catano et al. (2009) proposed to use a survey.	The AWRVI is implemented by using existing public domain databases as much as possible. Some indicators require municipality or direct community input.	Qualitative and quantitative methods, expert judgment and secondary data, for example scores for 'conflict management capacity' parameter was determined by expert consultations

Table 1 (continued)

Normalization/ standardization	Both the quantitative and qualitative indicators were divided in five scale scores (0, 0.25, 0.50, 0.75, and 1). A value of 0 is assigned to the poorest level, and 1 to optimum conditions. The levels and scores are arbitrary and were proposed based on possible ranges and thresholds of the selected indicators and recommendations from literature. Full description is provided in the paper.	Each indicator is represented on a standardized 5-point rating scale (0, 0.25, 0.5, 0.75, 1) that normalizes each indicator, where the low end of the scale represents vulnerability and the high end represents resilience. The breakpoints for an indicator were based on the expected minimum and maximum values for the typical distribution of the phenomenon measured in the region. Breakpoints were taken at percentiles for linear distribution or at each order of magnitude for logarithmic distributions.	All indicators were measured in a way that produces values from 0 to 1. (ratios etc.) For example: water scarcity parameter: if per capita water resources availability per year is greater than 1700m^3 per person per year, then the parameter value is 0. Water variation parameter: if the coefficient of variation of precipitation over the last 50years is greater than 0.3 then the parameter value is 1 (highest vulnerability)
Missing values	No discussion nor recommendations in Chavez and Alipaz (2007).In a later application of WSI (Catano et al. 2009) placeholder values of 0.75 were used for missing values in policy dimensions.	When data is missing for an indicator that indicator is eliminated from the index computation to prevent biasing; a measure of confidence is introduced by computing a lack of data score.	Evaluation of the different components is based on the related indicators, considering a number of constraints related to data and information, including lack of access to some official data – but no explanation
Weights for dimensions and sub-dimensions	Equal weights for components and sub-components.	Equal weights for components and sub-components.	Equal weights for components and indicators. (otherwise it is biased)
Aggregation (determining the index value)	WSI=(H+E+L+P)/4	$AWRVI=[AWRVI_{physical}+AWRVI_{social}]/2$	VI=(RS+DP+ES+MC)/4
Recommended interpretation of the results	Values range from 0 to 1. Use a similar classification as the UNDP's HDI (low sustainability for WSI<5, intermediate for WSI between 0.5 and 0.8, and high for WSI>0.8). Investigate the indicators that have the lowest scores.	Resilience and vulnerability are used as opposite ends of the scale. The value of the index but also the set of physical and social scores.	Value ranges from 0 to 1, with 1 indicating the most vulnerable situation. Low (0.0–0.2); moderate (0.2–0.4); high (0.4–0.7) and severe (0.7–1.0). Analysis of the index value and values for components and indicators.
Limitations	No explanation of the process of choosing components, using only the most basic indicators that are generally available, mostly secondary data, no clear approach to missing data, equal weights	Reliance on publicly available databases when deciding on indicators, no sensitivity analysis to missing values, no weights	Limited indicators, mostly secondary data, no clear approach to missing values, equal weights

all with their own limitations. Removal of indicators has been criticized for damaging the conceptual model (Moldan and Dahl 2007) while case deletion and data imputation for leading to biased results (OECD 2008). Given these risks, it is widely recommended that an evaluation of how the selected missing data approach affects the final result should be conducted (Saisana and Tarantola 2002).

However, missing values receive very limited attention in the water vulnerability indices analyzed. Some authors do not discuss them (Babel and Wahid 2009), others recommend removing indicators for which data are not available (Chavez and Alipaz 2007; Sullivan 2010) while others recommend removing subjects with missing data (Sullivan et al. 2009). Sullivan et al. (2009) also suggested generating missing values based on historical values, values for similar subjects or using expert judgment. Only Alessa et al. (2008) discussed the negative impacts of missing values on the level of confidence in the composite index. They recommended calculation of a 'lack of data score', based on the work by Van Beynen and Townsend (2005).

2.3 Measurement Scales and Normalization

Indicators commonly use different measurement scales, and before aggregating the data, the scores need to be first 'normalized'. Some of the normalization methods that have been proposed in literature include ranking of indicators, standardization (z-scores), re-scaling, and categorical scales (OECD 2008). Again, sensitivity analysis with respect to normalization method is recommended in order to assess the impact of this choice on the final results of assessment (OECD 2008).

The seven indices use different methods of data normalization. The most popular method was to normalize scores based on the maximum and minimum scores for the study population (e.g., Cohen and Sullivan 2010; Sullivan 2002; Sullivan et al. 2009). This approach has several limitations that negatively affect reliability of the results. First, it evaluates the performance relative to the set being considered, which is highly questionable in situations when all communities analyzed are vulnerable. Second, the results of the assessment may change as some communities are added or removed. Third, even a small change in value of an indicator will impact the value of the index, although the meaningfulness of the change may be questionable. Finally, inter-temporal comparisons are not possible. To overcome some of these limitations, a different scale was used to calculate both the WSI and the AWRVI. Both indices normalize each indicator using a standardized 5-point rating scale, where the low end of the scale represents vulnerability and the high end represents resilience. The levels and scores for these scales were proposed based on possible ranges of the selected indicators and meaningful breakpoints. As a result, if applied to different time intervals, the WSI and the AWRVI can illustrate the changes in vulnerability over time.

2.4 Weights and Data Aggregation

An issue central to the construction of a composite index is the aggregation method and derivation of weights to combine different dimensions and indicators in a meaningful way. Proponents of using weights praise them for the ability to address the relative importance of different issues, reflecting local input, and recognizing site specific conditions; while opponents criticize them for subjectivity, sensitivity to manipulation, limits on comparability, and (in case of participatory approaches) vulnerability to value judgments and cultural biases of those who created them (Feitelson and Chenoweth 2002). Weighted average as a method of aggregation is also criticized for its compensatory nature, when it yields high scores even when one of the index's components or indicators is very low or equal to zero.

Six of the seven indices analyzed in this paper use weighted average as the method of aggregation, assuming equal weights for all indicators and components. Sullivan et al. (2009) compared different approaches to determining weights, but did not implement weights when aggregating data. Only Cohen and Sullivan (2010) conducted sensitivity analysis of their index scores to different weighting schemes and concluded that the data should not be aggregated into a composite index at all. None of the indices proposed a way to address indicators with non-compensatory nature.

2.5 Sensitivity Analysis and Presentation of Results

Testing for robustness and sensitivity is considered indispensable to index development and application (Singh et al. 2007; Saisana et al. 2005; Tarantola et al. 2000). Sensitivity analysis considers how the results of assessment change when the assumptions with which it was undertaken are altered. An appropriate sensitivity analysis can help evaluate the robustness of the composite index, increase its transparency and frame policy discussions (Singh et al. 2007). Saisana and Tarantola (2002) recommend that the values of composite indices be reported in the form of confidence bounds.

Despite the above arguments, none of the analyzed indices provides a well-articulated procedure for interpreting results in relation to the underlying assumptions, evaluating impact of missing data, or conducting sensitivity analysis. Recommendations for interpretation of the composite index scores and scores for individual dimensions are generally not elaborated upon and represent a substantial void. One notable exception is Alessa et al. (2008) who recommended calculation of the lack of data score to assess the impact of missing values. With respect to presentation of results, a narrow range of graphical tools is used, limited to radar graphs and maps. No graphical tools were proposed to illustrate results of sensitivity analysis, except by Cohen and Sullivan (2010) where sensitivity of composite score to weighting is illustrated and used to defend the decision not to aggregate the data.

2.6 Applicability and Transferability

Water vulnerability indices need to translate across community contexts and perform robustly if they are to offer utility to a wider audience of researchers, managers, citizens, and policy makers. In this section we apply each of the seven water vulnerability indices to a single case study to gauge what the index reveals and the extent it is transferable. The case study comes from a major research project titled First Nations and Source Waters: Understanding Vulnerabilities and Building Capacity for Governance, which sought to assess water vulnerability and capacity building in three First Nation communities in Canada. Several stand-alone publications (Dupont et al. 2014; Baird et al. 2013, 2015; Plummer et al. 2013; Cave et al. 2013) report findings from the project.

The data gathered through the project for one of the communities (the Mississaugas of the New Credit First Nations) is drawn upon to consider the applicability/transferability of the respective water vulnerability indices. The traditional territory of the Mississaugas of the New Credit First Nation spanned present day Southern Ontario, Canada, but through a series of land treaties and agreements they were pressured to purchase reserve land near Hagersville, Ontario, Canada. Approximately 850 people live on the reserve, while about the same number reside elsewhere.

A majority of the seven indices could not be applied to the case study. The WPI and the three indices based on it were not applicable, because they can only be used when several communities are analyzed simultaneously and the highest values in the set indicate no vulnerability. The VIWRRB and the WSI were applicable to the case study since they can be used for a single case. However, given the limited secondary data available for the First Nations communities, the applicability of both the indices is limited due to a high number of missing values. In both cases there are no guidelines regarding imputation of missing values, and the indices can only be calculated when the indicators with missing values are eliminated from the formula, biasing the results. The VIWRRB value was calculated for the case study site, indicating moderate vulnerability. However, given that it is based only on a few available indicators, it fails to take into account numerous other aspects of water vulnerability and cannot be considered reliable. The WSI value was not possible to calculate, because the majority of its indicators capture change over a 5 year time period and there is no prior data for the case study. Finally, the AWRVI is only relevant to the Arctic environments and its set of indicators is not applicable to other communities. Exploring the aforementioned water vulnerability assessment indices in relation to the illustrative case study reveals challenges of their applicability and transferability.

3 A Proposed Approach for Development of Community Water Vulnerability Indices

An approach is put forward in this section of the paper for developing community (local scale) water vulnerability indices that are methodologically robust. The approach was developed and tested through a research project to assess the water vulnerability of three First Nations communities in southern Ontario, Canada (Plummer et al. 2013). It responds to the critical review of existing water vulnerability indices and their specific methodological shortcomings. In offering a series of seven steps to guide those developing community water vulnerability indices, the approach is broadly transferable and may be tailored in application, see Fig. 1. The results of applying the approach in practice are also documented in detail.

3.1 Step 1: Develop the Conceptual Model of Water Vulnerability

Conceptualization provides the foundation upon which a community water vulnerability index is built. It should draw upon two elements: a synthesis/summary of the relevant scholarship/literature and participatory process involving experts and stakeholders. A comprehensive review of these elements themselves is beyond the scope of this paper, but novel approaches are emerging with respect to both. For example, systematic reviews are gaining attention (Petticrew and Roberts 2006) and processes of knowledge co-production, which go beyond consultation or input from stakeholders are being emphasized (Armitage et al. 2011).

In order to develop a water vulnerability index to assess the case study community, a conceptual model of water vulnerability was developed based on analysis of 50

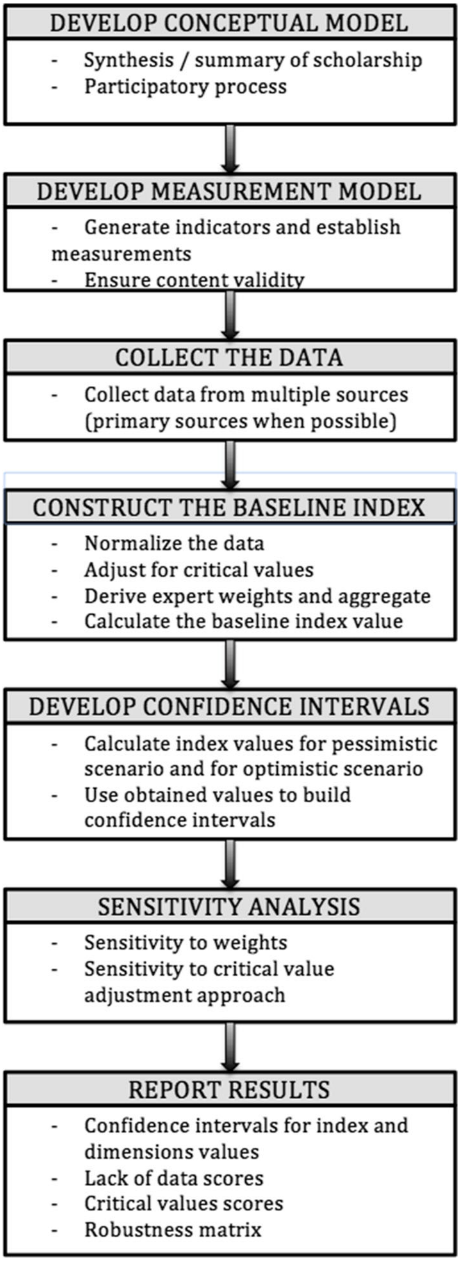

Fig. 1 Proposed framework for development of water vulnerability indices

water vulnerability assessment instruments (Plummer et al. 2012), input from five university researchers, and six community stakeholders. The resulting conceptual model is constituted by five dimensions of water vulnerability: water resources, other physical environment, economics, institutions, and social; each consisting of 3 to 6 sub-dimensions.

3.2 Step 2: Develop the Measurement Model

The measurement model needs to have content validity, i.e., capture the whole conceptualized phenomenon of water vulnerability. Indicators may be generated as part of the conceptualization process, with an emphasis on measurability. Removal of indicators for reasons of model simplification, cost, lack of data and/or lack of a substitute indicators should be avoided. Oversimplification of indicators is also problematic as the measurement model should completely capture the phenomenon and be sufficiently fine grained to detect subtle changes.

The measurement model to capture the conceptual framework of water vulnerability was developed based on the existing literature (Plummer et al. 2013) and with input from stakeholders. During this process, an effort was undertaken to identify all relevant indicators in order to minimize the distortion of the conceptual model. The resulting measurement model comprised 106 indicators grouped into 23 sub-dimensions and 5 dimensions; see Plummer et al. (2013) for more detailed discussion of the conceptual framework and measurement model development process.

3.3 Step 3: Collect the Data

Reliability of the water vulnerability assessment is substantially influenced by the choice of data source(s) for the indicator(s). When possible collect primary data as it is clearly advantageous in community assessments that require detailed information. Use multiple sources of data. Data sources should be clearly identified and the process of combining multiple sources of data should be openly reported. When indicators do not have available data they should still be kept in the measurement model.

Multiple techniques were used to gather reliable water related information about the case study community. They included: a comprehensive search of records, documents, and data relating to water within and beyond the community (i.e., in the watershed with relevance to the community); 10 semi-structured interviews with key informants identified to be knowledgeable and involved in various aspects of water in the community; and, a survey with community residents (N 100) using a venue incept survey technique. Comprehensive details about this case and the research project through which the data was gathered are provided by Plummer et al. (2013).

3.4 Step 4: Construct the Baseline Index

3.4.1 Normalize the Data

Various scales of measurement and different types of data are to be anticipated as indicators gauge different aspects of water vulnerability. The same scale must be used for all measurements before they may be combined into a composite index. While multiple techniques exist for this purpose, a normalization technique using a standardized 5-point rating scale with breakpoints permits temporal tracking of vulnerability and small differences in values for individual indicators influence the index only when thresholds are crossed (see Chavez and Alipaz 2007; Alessa et al. 2008).

In the assessment for the case study community the indicators were measured in different ways, with data coming from secondary data sources, surveys and qualitative interviews. Information collected about each indicator in the community was evaluated by a group of experts with respect to its contribution to water vulnerability. The experts used a scale from 1 to 5, where a score of 1 represented a highly vulnerable community and 5 represented a highly robust community with respect to a given indicator. In order to obtain index values ranging from 0 to 1 (for the ease of interpretation and comparison to other indices used in the literature) the scale from 1 to 5 was linearly transformed into a scale from 0 to 1.

3.4.2 Aggregate the Indicators Using Critical Value Adjustment

In order to find the baseline index value, first identify all indicators with values below a critical threshold. In the proposed approach, indicator values rated as posing moderate or greater vulnerability (0.25 or less) were considered ‘critical’. Second, the indicators measuring each sub-dimension should be aggregated by finding their un-weighted average. Next, the score for each sub-dimension should be adjusted for critical values, following the formula:

$$SUB_{ij} = \frac{\sum_{k=1}^{n_{ij}} x_{kij}}{n_{ij}} \times \left(\frac{n_{ij} - m_{ij}}{n_{ij}} \right) \tag{1}$$

SUB_{ij}	score for sub-dimension i of dimension j
x_{kij}	value of k-th indicator in sub-dimension i of dimension j
n_{ij}	number of indicators that sub-dimension i of dimension j is composed of
m_{ij}	number of indicators in sub-dimension i of dimension j that are equal or lower than the critical value of 0.25

The proposed adjustment for critical values reduces the value of the sub-indices and the vulnerability index in situations where some indicators have values below a critical threshold, therefore avoiding the purely compensatory nature of linear aggregation.

In the calculations at this stage (baseline scenario), following the work by Alessa et al (2008), an indicator is eliminated from the index computation when data is not available, and the denominator in a sub-index is reduced by 1 for every indicator that is eliminated.

3.4.3 Aggregate the Sub-dimensions and Dimensions Using Expert Weights

The values for sub-dimensions obtained in the previous step should be aggregated using expert weights to obtain values for dimensions and the index itself. Introducing weights provides a means to capture the importance given to specific aspects of water vulnerability by experts and/or members of the community. Participatory approaches to developing weights are particularly appropriate for community water vulnerability assessments. It is recommended to use two approaches (rank-sum and budget allocation) to derive weights and use their average in the final baseline index calculation.

For the New Credit case study, the rank-sum weights were derived from input obtained from 11 stakeholders representing the community, indigenous organizations, and universities. Individual ranks assigned by the 11 participants were converted into individual weights for each sub-dimension or dimension and then the average weights were calculated. The steps are given as follows:

For a given dimension, let m represent the number of individuals and n – the number of sub-dimensions. Assume that each individual i assigns a rank of $r_{i,j}$ to sub-dimension j. For each individual i, convert ranks $r_{i,j}$ into individual weights $W_{i,j}$ following the formula:

$$W_{ij} = \frac{N - R_{ij} + 1}{\sum_{k=1}^{n} (N - R_k + 1)} \quad i = 1, \ \ldots, m, \quad j = 1, \ \ldots, n \tag{2}$$

Next, calculate the aggregate weight of each factor by averaging its weights obtained from all m individuals.

$$W_j = \frac{1}{m} \sum\nolimits_{i=1}^{m} W_{i,j}, \quad j = 1, \ \ldots, n \tag{3}$$

Recognizing the limitations of the ranking approach, the 'budget allocation' technique to determine weights was also used, whereby participants were given a number of points that they could assign to dimensions and sub-dimensions depending on their perceived importance. The aggregated budget allocation weights were derived by adding all points assigned to a given dimension or sub-dimension by all the participants and converting them to weights. For the purpose of the final index calculation the average of rank-sum weights and budget-allocation weights was used.

3.4.4 Calculate the Baseline Index Value

Given the five dimensions of water vulnerability identified in the conceptual framework and the weights derived from the stakeholders, the resulting baseline index of water vulnerability is calculated as follows:

$$WVI = \frac{w_{water} WATERV + w_{env} ENV + w_{econ} ECONV + w_{inst} INSTV + w_{soc} SOCV}{w_{water} + w_{env} + w_{econ} + w_{inst} + w_{soc}} \tag{4}$$

where:

WVI	is the water vulnerability index
WATERV	is the vulnerability related to water resources
ENVV	is the vulnerability related to other physical environment
ECONV	is the vulnerability related to economics
INSTV	is the vulnerability related to institutions
SOCV	is the vulnerability related to social aspects
w_i	is the weight assigned to dimension i; i {water, env, econ, inst, soc}

3.5 Step 5: Develop Index Confidence Interval Bands

3.5.1 Calculate Index Values for Different Scenarios

The previous step described calculation of the baseline value for the water vulnerability index, when indicators with missing data are eliminated from the analysis. However, in order to address the impact of missing data on index calculation, confidence intervals should also be calculated and reported. At this stage, two scenarios (pessimistic and optimistic) are to be considered in addition to the baseline scenario. The optimistic scenario assumes that all missing indicators are performing in the best way possible and a score of 1 (highly robust) is substituted prior to computation. The optimistic scenario illustrates the best possible assessment result for the community. The pessimistic scenario assumes that all the missing indicators are performing very poorly and is calculated after a score of 0 is substituted for all missing indicators. In concert, the reporting of values for sub-dimensions, dimensions and the index obtained under the three scenarios allows for a more meaningful interpretation of the results and can help identify areas where additional efforts should be directed first in order to collect extra information.

3.5.2 Build the Confidence Interval for the Overall Index Value

The values obtained under the different scenarios should be used to determine the range of possible index values (i.e. the pessimistic value being the lower limit and the optimistic value the upper limit). This helps stakeholders better understand uncertainty and interpret indices properly. However it is not intended to be a statistical confidence interval. For the case study community, the values of the water vulnerability index under optimistic, baseline, and pessimistic scenarios were calculated and the corresponding confidence interval was (0.447; 0.625) with the value of 0.554 for the baseline scenario. The baseline result indicates a moderate level of vulnerability, which is typically interpreted as a situation when the community is generally in good condition but is facing some challenges. However, since the low end of the confidence interval falls below 0.5, it is possible that the community is actually faced with a higher level of vulnerability.

3.5.3 Build Confidence Intervals for Water Vulnerability Sub-dimensions and Dimensions

Confidence intervals for individual sub-dimensions and dimensions should also be built, in order to provide more insight into the uncertainty in measurement of water vulnerability in the community. The scores obtained for the case community are reported in Table 2 and illustrated in Figs. 2 and 3.

Figure 2 presents the results in form of the commonly used spider-diagrams, but incorporating data for all three scenarios, in order to show the range of different possible vulnerability scores. Figure 3 presents the data in form of confidence intervals, allowing for easy identifications of dimensions (capitalized sub-indices) and sub-dimensions (lower case) for which the scores fall or may fall below a chosen threshold.

Analysis of the results under the baseline scenario suggests that the dimensions most contributing to vulnerability in New Credit are ‘other physical environment’ and ‘economics’ while ‘water resources’ dimension appears to be the most robust, with a score of 0.712. The analysis of confidence intervals indicates additional potential sources of vulnerability. It shows that in comparison with the baseline scenario, under which 8 sub-dimensions have scores below 0.5; in the pessimistic scenario an additional 5 sub-dimensions could also be below this threshold. As a result, the unavailable information with respect to these sub-dimensions could significantly change the assessment of water vulnerability of the community.

An analysis of the index confidence interval bands indicates further that scores for some dimensions or sub-dimensions are below the threshold of 0.5 under all three scenarios: ‘labour and equity’ with confidence interval (0, 0.28) and ‘governance’ with index confidence interval (0.27, 42). An analysis of the range of the index confidence interval bands can further our

Table 2 Water vulnerability scores for New Credit: the recommended approach

	Expert weights	Pessimistic scenario	Baseline scenario	Optimistic scenario	Lack of data score	Critical data score
Water vulnerability		0.447	0.554	0.625	18.9 %	24.5 %
Water resources	0.26	0.489	0.712	0.785	21.9 %	3.1 %
Resource/supply	0.27	0.443	0.732	0.792	22.2 %	0.0 %
Access	0.16	0.792	0.792	0.792	0.0 %	0.0 %
Use	0.1	0.031	0.500	0.875	75.0 %	0.0 %
Quality	0.31	0.521	0.750	0.792	16.7 %	0.0 %
Infrastructure	0.17	0.485	0.660	0.704	14.3 %	14.3 %
Other physical environment	0.12	0.146	0.309	0.506	35.3 %	23.5 %
Climate change	0.32	0.111	0.111	0.111	0.0 %	66.7 %
Environmental pressures	0.38	0.028	0.250	0.694	66.7 %	16.7 %
Environment	0.3	0.332	0.590	0.684	25.0 %	12.5 %
Economics	0.18	0.381	0.481	0.592	39.3 %	21.4 %
Economic capacity	0.2	0.120	0.333	0.560	40.0 %	20.0 %
Labour and equity	0.14	0	0.000	0.281	50.0 %	50.0 %
Demographics	0.06	0.074	0.360	0.669	54.5 %	18.2 %
Livelihood	0.1	0.333	0.750	0.833	33.3 %	0.0 %
Human health	0.25	0.875	0.875	0.875	0.0 %	0.0 %
Education	0.25	0.389	0.389	0.389	0.0 %	33.3 %
Institutions	0.27	0.497	0.537	0.568	7.7 %	15.4 %
Governance	0.48	0.273	0.357	0.422	12.5 %	25.0 %
Conflict	0.2	0.625	0.625	0.625	0.0 %	0.0 %
Government and activities	0.32	0.750	0.750	0.750	0.0 %	0.0 %
Social	0.17	0.587	0.587	0.587	0.0 %	12.5 %
Engagement	0.18	0.225	0.225	0.225	0.0 %	40.0 %
Culture	0.16	0.594	0.594	0.594	0.0 %	0.0 %
Knowledge	0.19	0.625	0.625	0.625	0.0 %	0.0 %
Technical capacity	0.18	0.750	0.750	0.750	0.0 %	0.0 %
Perceptions	0.28	0.688	0.688	0.688	0.0 %	0.0 %

All scores were obtained using expert weights and with an adjustment for critical values

understanding of the uncertainty of the obtained results. It can be noted that although both ‘use’ and ‘livelihood’ sub-dimensions have high baseline scenario scores, they at the same time have very wide index confidence interval bands. Analysis of these results suggests that additional effort is required for data collection with respect to these sub-dimensions in order to improve quality of the assessment. Inclusion of the three scenarios in the water vulnerability assessment approach proposed in this paper improves on the existing methods which usually either eliminate indicators with missing values right at the measurement model design stage or ignore them during the analysis.

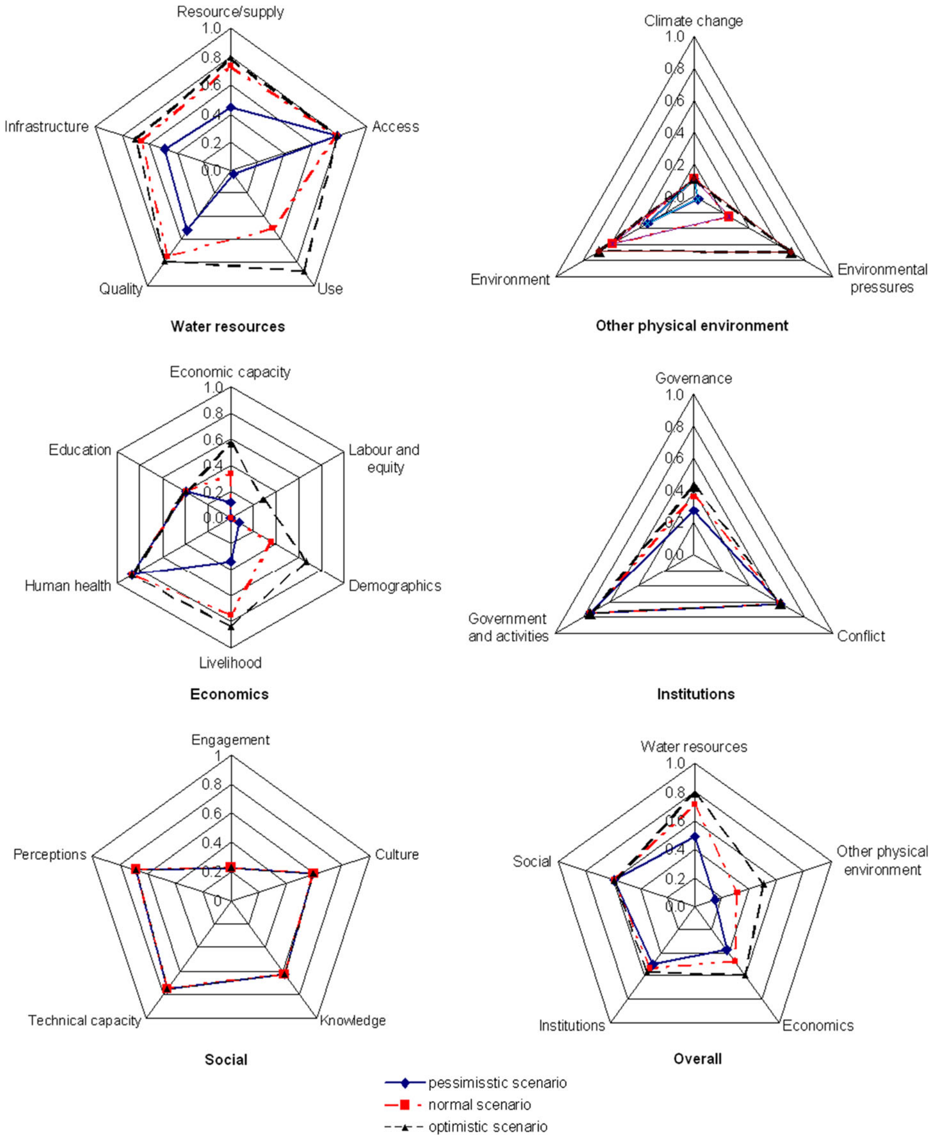

Fig. 2 Water vulnerability scores for New Credit under different scenarios

3.6 Step 6: Conduct Sensitivity Analysis

Community water vulnerability assessment indices must appropriately address elements of uncertainty and subjectivity. Sensitivity analysis is thus a critical step in the proposed framework as it recognizes and evaluates the impact of choices to deal with these uncertainties on the index value. Sensitivity to missing values is taken into consideration in the previous step, when index confidence interval bands, instead of point scores, are evaluated and interpreted. Additionally, sensitivity analysis with respect to weighting scheme and critical value adjustment should be conducted.

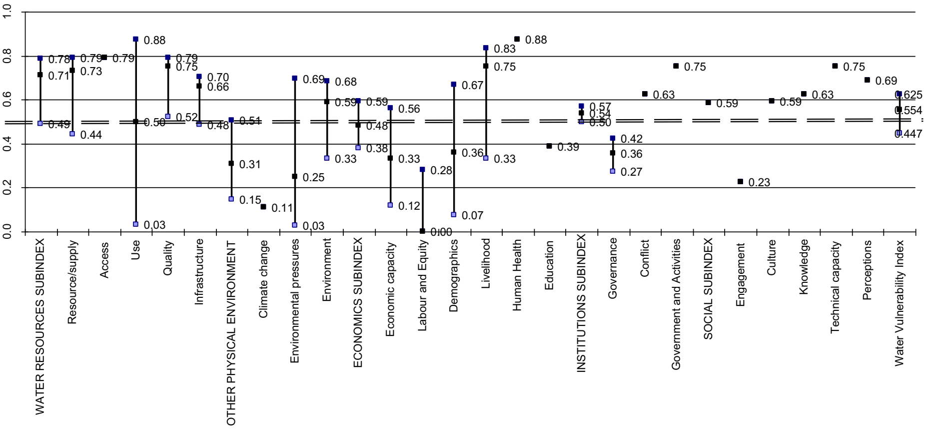

Fig. 3 Confidence intervals for water vulnerability scores for New Credit case study

Sensitivity analysis conducted for the case study indicated high sensitivity of results to the methodological choices. If the conventional approach with no weights, no critical values, and with removal of indicators with missing values was used, the water vulnerability score for New Credit would be 0.606. It would not allow discovery of the many vulnerabilities faced by the community and would lead to overly positive assessment. An additional analysis of sensitivity to different critical values and weights should also be conducted.

3.7 Step 7: Report the Results

Reporting and properly interpreting the assessment results is paramount. This should include reporting of baseline scores and index confidence interval bands for individual dimensions and sub-dimensions.

The interpretation and analysis of results should also be accompanied by a proper analysis of the lack of data score and the critical data score, see Table 2. The lack of data score offers a coarse measure of confidence in the index values and is computed as the percentage of indicators that have no data in a sub-dimension or a dimension (Alessa et al. 2008; Van Beynen and Townsend 2005). The critical data score is computed as the percentage of indicators that fall below the critical value in a sub-dimension or a dimension. It should be noted that even one indicator at a critical level that is not compensatory in nature may mean that the community is extremely vulnerable (e.g., if there is absolutely no access to clean water).

Simultaneous analysis of lack of data scores and critical value scores for each dimension and sub-dimension will help stakeholders to identify areas in the most need for mitigating action that otherwise would not be identified. Figure 4 presents lack of data scores and critical data scores for all the dimensions and sub-dimensions of water vulnerability in the case study. The area (size) of each circle indicates the weight (importance) of the given dimension or sub-dimension in its index.

'Climate change' and 'engagement' have high proportion of indicators at or below critical levels but no missing indicators. On the other hand, 'water use' has high percentage of missing indicators, but no indicators at critical level among the ones for which data are available. Only 8

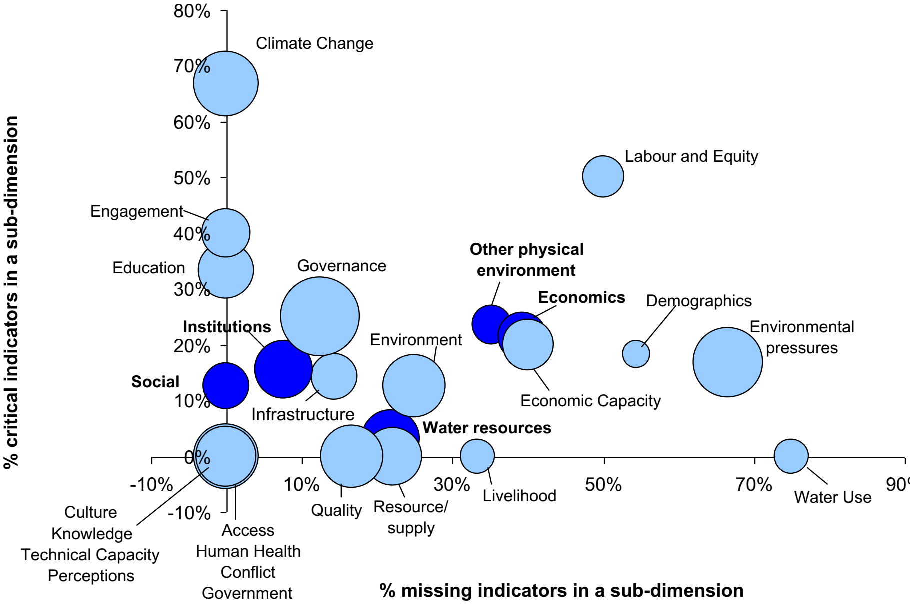

Fig. 4 Relative position of dimensions and sub-dimensions based on missing and critical values

out of 22 sub-dimensions have no missing indicators and no critical level indicators. The analysis of critical and missing values shows that although water vulnerability scores (as presented in Table 2 baseline scenario) are useful as the first step in assessment of a water vulnerability of a community, the areas of vulnerability can reliably be identified only after an appropriate sensitivity analysis.

4 Conclusions

Assessing water vulnerability is a longstanding concern to numerous stakeholders and continues to grow in importance amidst intensifying threats to water security. While a myriad of water vulnerability assessment tools exist, composite indices are frequently turned to because of their simplicity and understandability, broad applicability, and utility in identifying concerns and providing a basis for prioritizing action. Composite indices are highly sensitive to choices made during their conceptualization, analysis, and reporting. This critical review illustrates several noteworthy limitations of seven widely used water vulnerability indices in light of good practices for composite indices. It also demonstrated their limited applicability and transferability to other communities.

Searching for a universal water vulnerability assessment index is problematic. As Meinzen-Dick (2007) argues, there is a need to move beyond panaceas in water institutions as solutions to water management problems are to some degree place and situation specific. At the same time, she observes that critical factors may be identified that are adaptable to particular circumstances. In this spirit, a seven step framework was proposed to guide the construction, implementation, and reporting of community water vulnerability assessment indices. The steps in the proposed framework respond to shortcomings identified in the critical review, reflect good practices related to composite indices, and are transferable. The steps in the framework set out critical factors to which all community water vulnerability assessments should adhere, while also providing the ability to tailor aspects as required. Improving water vulnerability assessment at a community scale enhances the quality and quantity of information available for the stakeholders involved with making critical water resource decisions to address water related physical threats as well as the capability of humans to cope water related challenges.

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