

Assessing Vulnerability to Natural Hazards: Impact-Based Method and Application to Drought in Washington State

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Abstract: This article presents a technique for performing vulnerability assessments, using measures of exposure, sensitivity, and adaptive capacity. Historically, vulnerability assessments have focused on analyzing the hazard itself, absent information on its causes and mitigations. The vulnerability assessment method (VAM), presented herein, acquires data and information from affected stakeholders to assess not only the hazard, but also the causes of vulnerability, potential for adaptation, previous impacts, and ways to mitigate future impacts. We apply the VAM to a case study of Washington State, assessing drought vulnerability across 34 subsectors. Results indicate highest vulnerability for dryland farmers, farmers with junior water rights, fisheries, ski area operators, berry farmers, and the green industry. Through validation exercises, we demonstrate the VAM's internal consistency and external applicability. Contributions of the VAM include its incorporation of stakeholder data, integrated and quantitative assessments of vulnerability components, and applicability to other regions, scales, and types of hazards.

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Introduction

Drought is one of the nation's most costly natural disasters (FEMA 1995; Lott and Ross 2006; NOAA and WGA 2004). Further, droughts are expected to become more frequent and severe, with increasing demands, limited and uncertain supplies, and effects of climate change and climate variability. Faced with these challenges, decision makers need information to help prepare for droughts, allocate resources effectively, and reduce impacts.

Disaster management has typically focused on analyzing the hazard, such as the severity of a drought due to a shortfall of precipitation. Increasingly, however, we recognize the need to analyze not only the hazard, but also the vulnerability to the hazard, such as the impacts of that shortfall on users, the causes of those impacts, and the actions that can reduce the impacts. In addition, disaster management has been moving away from solely emergency response, initiated during or after an event, toward mitigation and preparedness, initiated before an event, in order to reduce impacts more effectively (Wilhite 1987; Wilhite et al. 2000; Hooke 2000). Both of these trends generate increased attention to vulnerability.

Many have emphasized the importance of vulnerability assess-

ments, and presented useful frameworks (Cannon 1994; Eakin and Conley 2002; Hayes et al. 2004; Knutson et al. 1998; Metzger et al. 2005; Polsky et al. 2003; Turner et al. 2003; Schröter et al. 2004; Wilhelmi and Wilhite 2002; Yohe and Tol 2002), yet relatively few have presented methods to assess vulnerability empirically. As the literature illustrates (Abraham 2006; Hayes et al. 2004; Odeh 2002; Schröter et al. 2004; Turner et al. 2003; Wilhelmi and Wilhite 2002; Wu et al. 2004; Yohe and Tol 2002), ambiguity surrounds not only the components of vulnerability, but also the operationalization and measurement of those components. Some empirical studies use indicators to characterize vulnerability (Brooks et al. 2005; Cutter et al. 2003; Hurd et al. 1999; Metzger et al. 2005; Schröter et al. 2004; Sullivan et al. 2003), although indicator values may not adequately reflect impacts, especially at the local level, and may not be relevant across multiple regions and sectors. Further, even in empirical studies, data often focus on the hazard itself (e.g., magnitude of a water shortage) rather than overall vulnerability, which would also consider impacts (e.g., losses due to water shortages) and the ability to reduce and mitigate those impacts, both short term and long term (e.g., water reallocation, water conservation). What is needed are empirical assessments to understand how vulnerability is experienced "on the ground," by those who are vulnerable, to elucidate the causes and effects of that vulnerability, and to provide data-based guidance to decision makers. This work is motivated by and seeks to address those needs.

In this paper, we present a vulnerability assessment method (VAM) that uses measures of exposure, sensitivity, and adaptive capacity. A foundation of the method is the acquisition of data and information from those who are vulnerable, which permits not only quantitative assessments, but also a deeper understanding of the factors that influence vulnerability. We then apply this method to the assessment of drought vulnerability in the state of Washington, examining 34 subsectors (sectors within regions) across the state. To evaluate the method, the model, and the results, we conduct both internal and external validation exercises. We conclude with findings from the assessment and broader lessons.

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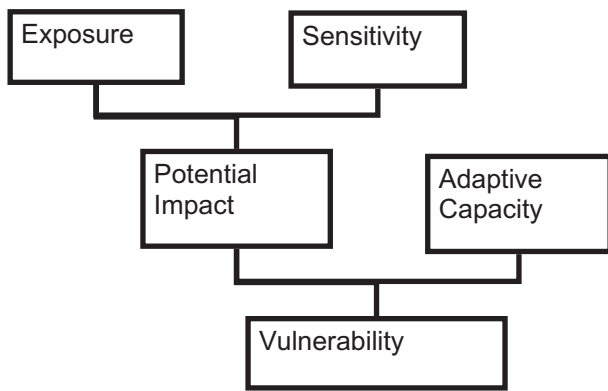


Fig. 1. Conceptual model of vulnerability [adapted from Schröter and Metzger (2004), with permission]

Vulnerability Assessment Method

To assess vulnerability, we develop a conceptual model (Fig. 1) that builds upon work of the Intergovernmental Panel on Climate Change (IPCC 2001) and illustrated by Schröter and Metzger (2004). In our model, vulnerability is based on three primary variables: (1) exposure; (2) sensitivity; and (3) adaptive capacity. Exposure incorporates frequency and severity of drought; severity includes magnitude, duration, and spatial extent. Sensitivity is the susceptibility of a water user (or users) to the effects of the drought. Adaptive capacity is the ability of a water user to manage or reduce adverse effects of a drought, through actions taken before, during, or after the drought. Exposure and sensitivity determine the potential impact. Adaptive capacity determines the portion of the potential impact that becomes an actual impact. The combination of the three components results in a net impact or vulnerability to the drought.

With this conceptual model, we then operationalize and measure the variables. To generate operational and relevant measures of vulnerability, we developed an assessment approach to evaluate exposure, sensitivity, and adaptive capacity, using data and evaluations from water users themselves. This approach provides an important perspective on vulnerability by obtaining information from those who experience the vulnerability, and by examining links between the hazard, the impacts, and ways to mitigate the impacts.

To conduct the assessments, described in the next section, we performed an in-depth study of water users, using interview questions that investigated factors of vulnerability. We used a five-point Likert scale (1=very low, 2=low, 3=medium, 4=high, and 5=extreme) to assess each of the three components from Fig. 1 (exposure, sensitivity, and adaptive capacity) for each water user. Each Likert scale ranking corresponds to a score (Table 1). The component scores were combined to generate a vulnerability score (V)

$$V = (E + S)/A \quad (1)$$

where E =exposure; S =sensitivity; and A =adaptive capacity. For instance, higher hazard exposure and higher sensitivity lead to higher potential impacts and higher vulnerability; higher adaptive capacity leads to lower vulnerability. In this algorithm, exposure and sensitivity are weighted equally, although weights can be easily varied. Next, we used data on exposure, sensitivity, and adaptive capacity to calculate vulnerability scores for each individual, and then averaged within sectors and subsectors for each region.

Table 1. Vulnerability Component Scoring System

Ranking scale	Score
Exposure	
Extreme	5
High	4
Moderate	3
Low	2
Very low	1
Sensitivity	
Extreme	5
High	4
Moderate	3
Low	2
Very low	1
Adaptive capacity	
Extreme	5
High	4
Moderate	3
Low	2
Very low	1

While each individual's score was given equal weight relative to other individuals, the weighting protocol can also be easily modified. The next sections detail the application and evaluation of this method, and the interpretation and relevance of results.

Case Study: Drought in Washington State

In the last decade, Washington State has experienced two major droughts. A statewide drought emergency was declared on Mar. 14, 2001 and on Mar. 10, 2005; in both cases due to drought criteria of less than 75% of normal supply and expected undue hardships (Office of Governor Gary Locke 2001; Office of Governor Chris Gregoire 2005). Throughout the state, both droughts inflicted significant impacts: increased production costs and reduced revenue in the agricultural sector, reduced deliveries to junior water rights holders, reduced power generation, increased power costs, reduced survival of adult and juvenile salmonids, and reduced visitation to ski areas (Fontaine and Steinemann 2007). Estimates of drought damages to agriculture ranged from \$270–400 million in 2001 (Stephens et al. 2001) and \$195–299 million in 2005 (Stephens et al. 2005).

Given the significant impacts of previous droughts and the need to prepare for future droughts, the writers conducted a statewide study, in collaboration with agencies of Washington State, to analyze impacts from recent droughts, identify the most vulnerable regions and sectors, and determine ways to reduce drought vulnerability. Using the VAM developed above, we assessed the vulnerability in five sectors (agriculture, environment, municipal and industrial, recreation, and power) from six regions in the state (Fig. 2).

To perform the assessment, we conducted telephone interviews with 67 individuals who were designated as key representatives of each region and sector affected by previous droughts, and likely to be affected by future droughts. These individuals included farmers, water supply system managers, fisheries agency officials, recreation operations managers, and hydropower sector officials. They were identified in consultation with an advisory panel of officials from Washington State agencies, including the Depart-

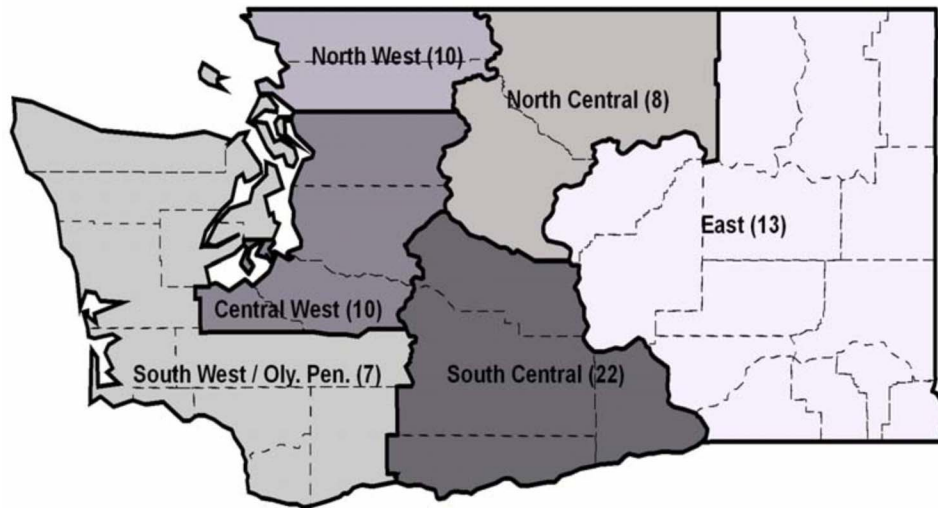


Fig. 2. State regions, with number of interviewees (in parentheses)

ment of Ecology; Department of Agriculture; Department of Community, Trade, and Economic Development; Office of Financial Management; and Washington State University.

This sampling approach was designed to target key sources of expertise, as judged by state officials, rather than to produce a statistically representative sample or a comprehensive assessment of all drought impacts in the state. The intent was to gain data and insights from those designated as especially knowledgeable and experienced in dealing with droughts, and to provide an assessment that could guide initial decision making, discussion, and additional study.

We assessed the variables of exposure, sensitivity, and adaptive capacity using data obtained from interviews. The interviews included both structured and semistructured questions, which investigated the following dimensions of drought vulnerability: water supplies and demands (past, current, and future), frequency and severity of previous droughts, causes and consequences of previous droughts, types of drought impacts, actions taken in the past to reduce drought impacts, risks and types of potential future drought impacts, actions and resources that could reduce those impacts, and the feasibility and effectiveness of adaptations. The interviews sought to elicit a set of quantitative data by which to assess the variables. Recognizing, however, that vulnerability often depends on both quantitative and qualitative factors, the interviews also elicited aspects of vulnerability that provided nuanced considerations and integrated perspectives that were incorporated into the assessment. Interview data were analyzed

through sorting, coding, categorization, and consideration of causal relationships.

Based on an analysis and synthesis of data from each interview session, Likert scale rankings were used to represent an integrated assessment of each vulnerability component (i.e., exposure, sensitivity, and adaptive capacity). A strength of this interviewer assessment approach is the ability to consider and integrate multiple dimensions of vulnerability, based on the interactions with stakeholders. A limitation with this approach is related to its strength, in that it depends on human interpretation and other subjective factors, and, thus, can introduce bias. Note that different interviewing and assessment approaches would be acceptable; the overall goal is to obtain and represent information on vulnerability from stakeholders themselves. Table 2 provides an example of data used to quantify each independent variable, to calculate an overall individual vulnerability score using Eq. (1). Using the procedure detailed earlier, we combined individual vulnerability scores within each subsector. We also conducted internal and external validity tests, described in the following section.

Results

Using the VAM, we evaluated drought vulnerability in 34 subsectors in Washington State. Results are presented by region, sector, and subsector in Table 3, and rank ordered by VAM scores for each subsector in Table 4.

Table 2. Example of Data Collected to Perform Vulnerability Component Ranking

Component	Interview data collected	Ranking	Score ^a
Exposure	Received less than 50% of normal water entitlements during 2 of the past 5 years. Water shutdown comes at inopportune times for crops.	Extreme	5
Sensitivity	Raises primarily perennial tree fruit that commonly produce low quality fruit under subnormal supply. Crops are very costly to replace if damaged.	High	4
Adaptive capacity	No backup/emergency water supplies and less than 10% of acreage in annual crops (limited ability to spread water).	Low	2
Total score			4.5 ^b

^aSee Table 1 for a score determination matrix.

^bCalculated from component scores using Eq. (1).

Table 3. Sectors Analyzed within Each Region, and Average Subsector Vulnerability Scores

Region and sector	Subsector	Average vulnerability score
Northwest region		
Agriculture	Irrigated berries	1.88
Agriculture	Irrigated row crops	2.17
Agriculture	Green industry	3.50
Agriculture	Dairy	2.00
M&I	Purveyor	2.50
Environment	Fisheries	3.25
Central west region		
Agriculture	Green industry	3.67
M&I	Large municipality supplier	1.63
Environment	Fisheries	2.33
Southwest/Olympic Peninsula region		
Agriculture	Green industry	3.50
Agriculture	Irrigated diverse agriculture	2.33
Agriculture	Dairy	2.00
Agriculture	Irrigated berries	3.50
M&I	Municipal	2.50
Environment	Fisheries	1.75
North central region		
Agriculture	Irrigated fruit trees	2.50
Agriculture	Cattle ranchers	2.33
Environment	Fisheries	3.46
M&I	Municipal	3.00
South central region		
Agriculture	Irrigated junior rights	3.28
Agriculture	Irrigated junior rights	
Agriculture	Wine grapes	1.67
Agriculture	Irrigated senior right	2.00
Agriculture	Dryland	4.50
Agriculture	Cattle	2.33
M&I	Municipal	3.00
Environment	Fisheries	4.08
East region		
Agriculture	Irrigated surface water	2.50
Agriculture	Irrigated ground water	2.33
Agriculture	Dryland	4.36
M&I	Municipal	2.78
Environment	Fisheries	3.06
No specific region		
Recreation	Golf courses	1.50
Recreation	Ski areas	4.00
Power	Hydropower	1.67

Vulnerability was ranked the highest for the following subsectors: dryland farmers in the south central and east regions, fisheries in the south central and north central regions, ski area operators, the green industry in the western regions, berry farmers in the southwest/Olympic Peninsula region, and farmers with junior water rights in the south central region. Dryland farmers in the south central region, for example, are highly vulnerable (VAM subsector average of 4.5) because of high exposure ($E=4$), ex-

treme sensitivity ($S=5$), and low adaptive capacity ($A=2$). They need to make critical decisions on crops, prior to the planting and growing season, but often have limited and uncertain information on future water supplies. Farmers with junior water rights in the south central region, for another example, are also highly vulnerable (VAM subsector average of 3.28), with high to extreme exposure ($E=4$ to 5), medium to extreme sensitivity ($S=3$ to 5), and low to medium adaptive capacity ($A=2$ to 3). They receive estimates of their water entitlements for the upcoming season, which can increase their ability to adapt to drought, especially with a formal state drought declaration that streamlines the permitting process for emergency wells and water transfers. In many cases, however, these adaptive measures come at a high cost (e.g., the costs to drill a new groundwater well, the costs to purchase water rights, or the lost revenue from fallowing fields to transfer water to more valuable or sensitive crops), which can reduce the marginal net benefit of the adaptive methods and thereby increase vulnerability.

Exposure was ranked the highest for dryland farmers, junior water right holders, hydropower generators, ski areas, and fisheries in watersheds with large surface water withdrawals. In the past, the power sector has been severely affected by drought, particularly the 2001 drought, which caused record-low streamflows across much of Washington State and coincided with increased power prices resulting from insecure southwestern energy supplies. Since 2001, the power sector has reduced vulnerability by reducing sensitivity (e.g., by increasing thermal power generation sources) and increasing adaptive capacity (e.g., by developing a resource adequacy standard). Overall, exposure was rated high or extreme for more than half of the interviewees, which reflects the designation of interviewees from "hot spots" in the state: sectors and regions that had severe impacts from previous droughts, and were likely to have severe impacts in future droughts.

Sensitivity was reported high for dryland farmers, junior water right holders farming exclusively tree fruit, and fisheries populations already highly stressed by surface water withdrawals and other habitat impacts. Populations of anadromous salmonids in many Washington rivers have already been adversely affected by dams, river channelization, reduced large wood recruitment, water quality deterioration, and hydrograph alterations resulting in reduced natural freshets and reduced flooding; consequently, these populations are highly sensitive to drought. Long rearing salmonids are especially sensitive because they may spend a year or more in the river system as juveniles before migrating out to sea.

Adaptive capacity was reported high for large municipalities and hydropower generators. For municipalities, large surface water reservoirs can enable them to adapt before needing to impose water use restrictions (e.g., by storing water earlier in the spring for use in the late summer, and by performing water intensive maintenance activities in the spring rather than summer). In addition, many reservoir operators include input from fisheries commissions when developing their annual operation plans, and modify operations to minimize impacts on fish populations (e.g., by using stored water to supplement natural flows during the spring to aid downstream migration of juvenile salmonids, and during the fall to aid upstream migration of mature salmonids prior to spawning).

Validation Exercises

To validate the model and results, we performed both internal validation and external validation. Internal validation checks the

Table 4. Vulnerability Assessment Results

Category (region, sector, subsector)	VAM subsector average	VAM ranking	Internal validation ^a	External rankings ^b	Modified VAM scores ^d
South central, agriculture, dryland	4.50	High	High	Medium	4.50
East, agriculture, dryland	4.36	High	High	Medium	4.36
South central, environment, fisheries	4.08	High	High	Medium	4.08
Recreation, ski areas	4.00	High	High	Medium	4.00
Central west, agriculture, green	3.67	High	High	Medium	3.17
North west, agriculture, green industry	3.50	High	High	Medium	2.00
Southwest/Olympic Peninsula, agriculture, green industry	3.50	High	High	Medium	3.00
Southwest/Olympic Peninsula, agriculture, irrigated berries	3.50	High	Medium	Low	2.00
North central, environment, fisheries	3.46	High	High	Medium	3.46
South central, agriculture, junior rights	3.28	High	High	High	3.28
Northwest, environment, fisheries	3.25	High	Medium	High	3.75
East, environment, fisheries	3.06	Medium	Medium	High	3.56
North central, M&I, small municipal suppliers	3.00	Medium	Low	Medium	3.00
South central, M&I, small municipal	3.00	Medium	Low	Medium/low ^c	3.00
East, M&I, small municipal supply	2.78	Medium	Low	Medium	2.78
Northwest, M&I, surveyor	2.50	Medium	Low	Medium	2.50
Southwest/Olympic Peninsula, agriculture, M&I, municipal supply	2.50	Medium	Low	Medium	2.50
North central, agriculture, irrigated tree fruit	2.50	Medium	Medium	Medium	2.50
East, agriculture, irrigated surface water	2.50	Medium	Medium	Low	2.50
Central west, environment, fisheries	2.33	Medium	Medium	Medium	2.33
Southwest/Olympic Peninsula, agriculture, irrigated diverse	2.33	Medium	Medium	Low	2.33
North central, agriculture, cattle	2.33	Medium	Medium	Low	2.33
South central, agriculture, cattle rancher	2.33	Low	Medium	Medium	2.33
East, agriculture, irrigated ground water	2.33	Low	Medium	Low	2.33
Northwest, agriculture, irrigated row crops	2.17	Low	Medium	Low	2.17
Northwest, agriculture, dairy	2.00	Low	Medium	Low	2.00
Southwest/Olympic Peninsula, agriculture, dairy	2.00	Low	Medium	Low	2.00
South central, agriculture, senior rights	2.00	Low	Low	Low	2.00
Northwest, agriculture, irrigated berries	1.88	Low	Medium	Low	1.88
Southwest/Olympic Peninsula, agriculture, environment, fisheries	1.75	Low	Medium	Medium	3.00
South central, agriculture, junior rights, wine grapes	1.67	Low	Medium	High	1.67
Power, hydropower	1.67	Low	Medium	Medium	1.67
Central west, M&I, large municipal supplier	1.63	Low	Medium	Medium	1.63
Recreation, golf courses	1.50	Low	Medium	Low	1.50

^aRankings based on internal assessment of the dependent variable, vulnerability, rather than calculated from the independent variables.

^bRankings based on external assessment of vulnerability.

^cSubsector not used in statistical analysis.

^dVAM component scores for each subsector recalculated based on second round of external validation process.

relationships between independent and dependent variables in the model, thus, it evaluates the internal consistency and performance. External validation checks the model results against an outside standard, thus, it evaluates the external applicability and generalizability.

To perform these validation exercises, we compared the overall subsector VAM scores, calculated from primary data for the three independent variables (exposure, sensitivity, and adaptive capacity), with the vulnerability rankings from both internal and external assessments. In both the internal assessment and the external assessment, overall vulnerability rankings of high, medium, or low were assigned to each subsector. Internal assessment rankings are based on the primary data, obtained from the interviewees, for the dependent variable (vulnerability). External assessment rankings are also based on primary data for vulnerability, obtained from an external, independent evaluator who is regarded as a state expert on drought. This evaluator served as the

Washington State Drought Coordinator during four major droughts (1992, 1994, 2001, and 2005), and brings nearly three decades of experience in state water management.

We conducted three main statistical tests as part of the validation exercises. First, the Fisher's exact test examined the significance of the relationship between the VAM scores and the internal and external assessment rankings. Second, an analysis of variance (ANOVA) tested the equivalence of VAM score means among the three vulnerability ranking categories (high, medium, and low) assigned during internal and external assessment. Third, for significant ANOVA results, the Student-Newman-Keuls (SNK) multiple comparison test determined which categories were significantly different from the others.

Results of these analyses (detailed in the following paragraphs) indicate that the VAM exhibited favorable performance in aspects of the internal assessment and the external assessment (Table 4 and Figs. 3–5). For internal assessment, the VAM rank-

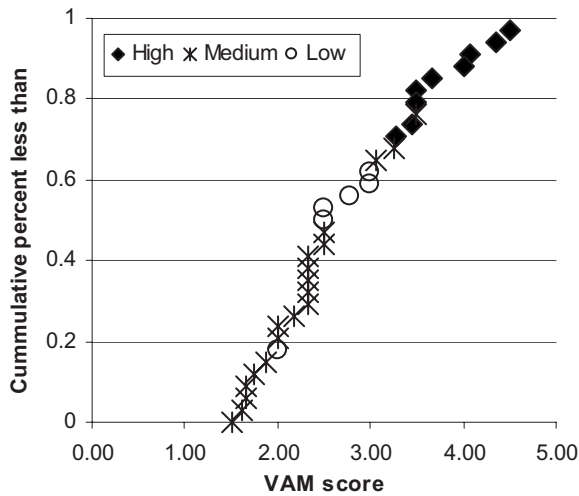


Fig. 3. VAM scores based on internal assessment of vulnerability

ings were consistent with the vulnerability rankings, generated from the independent variables, for all of the seven subsectors with the highest VAM scores (Table 4 and Fig. 3). Statistically, these results are strengthened by the Fisher's exact test, which indicate a significant association between VAM rankings and internal assessment rankings ($p < 0.001$; $\alpha = 0.05$), by ANOVA tests ($p < 0.001$; $\alpha = 0.05$), which indicate at least one significant difference between mean VAM scores for internal assessment categories, and SNK multiple comparison tests, which indicate that the high vulnerability category is significantly different from both the medium and low categories ($\alpha = 0.05$). SNK multiple comparison tests did not identify a significant difference (at $\alpha = 0.05$) between the subsectors receiving medium and low internal vulnerability rankings, indicating that the VAM performed strongest, statistically, for the high vulnerability subsectors.

For external assessment, the VAM rankings were consistent with the external assessment categories for 15 subsectors. In cases where the rankings differed, interview data often differed from data used in the external assessment, which led to further investigation, and a second round of evaluation (as will be described). Fisher's exact test indicated no significant association ($p = 0.31$;

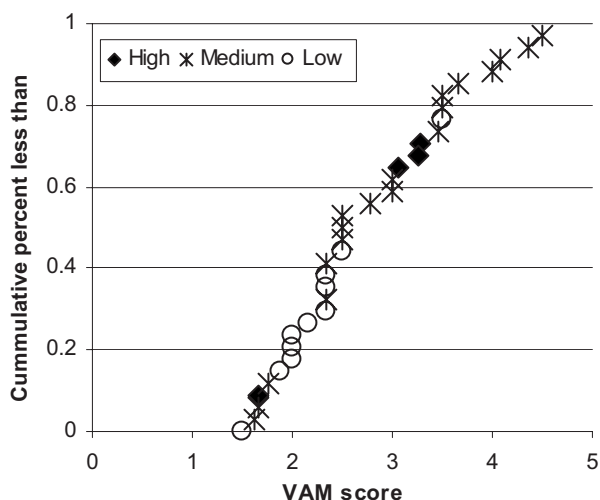


Fig. 4. VAM scores based on external assessment of vulnerability

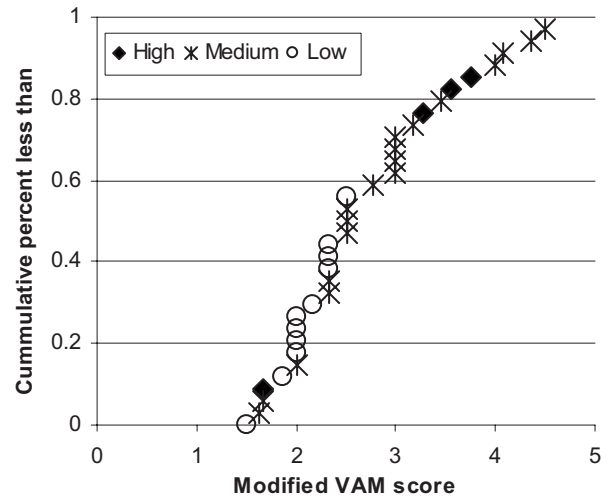


Fig. 5. Modified VAM scores based on external assessment of vulnerability

$\alpha = 0.05$) between VAM rankings and the first round of external assessment rankings. Similarly, ANOVA tests indicated no significant difference ($p = 0.051$; $\alpha = 0.05$) between mean VAM scores for external assessment ranking categories.

To investigate reasons for the differences between the external assessment rankings and the VAM scores, we conducted a second round of assessment with the external evaluator, discussing the results, and through this we acquired additional information on drought vulnerability. For example, in the municipal and industrial sector in the southwest/Olympic Peninsula region, the external evaluator noted a case where a municipality's water right is junior to that of a large paper mill on the same supply line, creating potentially high drought exposure for the municipality. Because initial interviews did not reveal information known to the external evaluator, the VAM results for that sector were lower than the external evaluator's assessment. As another example, for wine grape growers with junior water rights in the south central region (outlier on Figs. 4 and 5), the VAM results indicate low vulnerability to drought, based on information that wine grapes are drought tolerant (low sensitivity) and require less water, overall, than the normal entitlements of junior water users (moderate exposure). The external evaluator assessed a higher vulnerability to drought, given that water rights were based on consumptive use, so the reduction in water allotted to wine grape growers with junior water rights would be proportional to their normal usage, thus, creating the same level of vulnerability as junior water right holders raising more water intensive crops. On the other hand, the internal assessment considered the drought tolerance of the crops, and also that the restricted water supply the growers would receive would be based on the normal supply to all junior water users. After discussion, it was decided to exclude this case from the next phase of assessment. Thus, as this case exemplifies, different perspectives can result in different assessments, yet provide additional information on vulnerability.

The external assessment then incorporated the additional information from the external evaluator into the VAM scores. With the revised VAM scores, Fisher's exact test showed a significant association between VAM rankings and the second round of external assessment rankings ($p < 0.004$; $\alpha = 0.05$), ANOVA tests indicate at least one significant difference between mean VAM scores for external assessment ranking categories ($p = 0.002$;

$\alpha=0.05$), and SNK multiple comparison tests identified a significant difference between means for high and low categories and medium and low categories ($\alpha=0.05$). Thus, through an iterative assessment process, and incorporating a broader base of knowledge about vulnerability, the gap between the VAM and the external assessment narrowed (Fig. 5) and the SNK and ANOVA demonstrate closer alignment between the VAM scores and external assessment rankings. This illustrates the value of a vulnerability assessment as a process of discussion and evaluation.

Overall, the VAM demonstrated internal consistency and external applicability, as indicated by both internal and external validation tests. By assessing both overall vulnerability and its underlying components, the VAM identified subsectors considered highly vulnerable to drought and reasons for that vulnerability.

Discussion and Conclusions

From this study, we offer three main considerations for vulnerability assessments. First, the VAM can provide a useful approach for analyzing individual components of vulnerability, from the underlying causes to the potential for adaptation, in addition to generating an overall numerical assessment for vulnerability. The VAM approach also incorporates information on impacts through the assessment of exposure, sensitivity, and adaptive capacity. This can extend vulnerability assessments that focus on the quantification of the hazard, or some aspect of it, even though the causes and mitigations are central to a goal of assessment: to reduce impacts.

Second, the VAM can represent local and context-specific information on vulnerability, which often cannot be gleaned by examining indicators over a large spatial or temporal scale, or by using indicators that may be inadequate representations of vulnerability. Because information from stakeholders is the foundation of the VAM, the model and assessment approach can be applied to other regions, other types of hazards, or other scales, depending on the stakeholders and the scope of decisions.

Third, because the VAM is based on stakeholder input, the approach provides an integrated assessment of vulnerability that considers factors important to stakeholders, and can promote discussions about vulnerability. As evidenced through the interviews, and the validation exercises, an iterative dialogue can reveal key insights on the causes and consequences of vulnerability, and such dialogues could be extended to broader stakeholder involvement. Thus, a vulnerability assessment may be most useful as a process rather than just a product.

The VAM approach also has its caveats. By applying numerical methods to complex sets of data, both qualitative and quantitative, the VAM may not adequately convey all factors that are important for understanding and mitigating drought vulnerability. Providing narratives along with numbers could help in this regard. While individual stakeholder data provide an essential perspective on vulnerability, they are but one perspective, and not necessarily representative of an entire study area. Further, such data are subject to human bias, experience, and interpretation.

Results from this case study are currently being used to help identify sectors, subsectors, and regions that are most vulnerable to drought, to guide additional drought studies, and to recommend improvements to the state of Washington drought plan. The results are also being used in a statewide study on vulnerability to climate change, investigating the projected impacts on water resources, and the range of adaptations.

Drought vulnerability assessments can use information from previous droughts to prepare more effectively for future droughts. The VAM addresses a need to analyze vulnerability across diverse sectors and regions. In this case, the VAM is used to assess drought vulnerability, but the method can be adapted to assess vulnerability to other hazards. Using data obtained directly from stakeholders affected by the hazard, the VAM enables decision makers to understand not only relative vulnerability to a hazard, but also the underlying sources of that vulnerability and the resources and actions that could reduce future vulnerability.

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Notation

The following symbols are used in this paper:

- A = adaptive capacity;
- E = exposure;
- p = probability in statistical hypothesis testing;
- S = sensitivity;
- V = vulnerability; and
- α = probability of a type-one error.

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