Assessing Water Supply Vulnerability in a Water Scarce State: The Arizona Water Sustainability Evaluation

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Abstract:
In July 2010 the Arizona Department of Water Resources began an analysis of water resource vulnerability and sustainability in Arizona's 51 groundwater basins using information compiled during the seven-year Arizona Water Atlas project. The goal of this study is to answer the question: "Which Arizona communities have enough water?" To complete this task the Department has created a vulnerability assessment with five categories that can affect the sustainability of a basin's water supply: 1) physical supply conditions; 2) current or projected demand conditions; 3) sensitivity to extended drought or shortage; 4) legal and management considerations; and 5) environmental values. Each category contains criteria that will be qualitatively and quantitatively assessed and basin vulnerability classified as either minimum, moderate or high. Between August 2010 and April 2011 the research team met with over 100 stakeholders across Arizona to discuss and refine the vulnerability criteria. This paper discusses the creation of Arizona's water resource vulnerability assessment, the final criteria that will be used to assess a groundwater basins' current and future vulnerability to water supply shortage and lessons learned from the project.

Keywords: Water Supply, Vulnerability Assessment, Public Participation

1. Introduction

Finding the balance between growth and sustainable water use is a widespread problem in the 21st century. This problem is exacerbated in the populous arid and semi-arid regions of the world including Arizona, in the southwestern United States. Arizona is the United States' second fastest growing state. Arizona grew from 3.6 million to 5.1 million inhabitants, a 40% increase, in the decade from 1990 to 2000. Although the annual growth rate has recently slowed to about 2%, by July 2009, Arizona's population had increased by another 1.58 million people, a 30.3% increase since the 2000 census (ADOC, 2009). The principal challenge facing Arizona water managers is sustainable water use in light of the rapid population growth of its cities and the increasing competition for water both inside and outside of the state (Colby and Jacobs, 2007). While there is keen interest in finding water to fuel future growth, this interest is increasingly tempered by an acknowledgement of the importance of Arizona's rivers and groundwater resources to the natural environment. This paper describes an effort by the Arizona Department of Water Resources (ADWR) to evaluate the sustainability of Arizona's water supplies through an assessment of current and future water resource vulnerability in the state's 51 groundwater basins.

Characteristics of Arizona's Water Resources and their Use

Precipitation in Arizona is characterized by two distinct seasons: the summer "monsoon" season, generally from July to mid-September and a winter season from November through mid-April. Winter precipitation is more hydrologically effective than summer precipitation because it is more widespread, is generally of low intensity and long duration, coincides with cooler temperatures and lower evaporation rates and, when stored as snow, is released gradually, resulting in greater infiltration. Summer rainfall is more localized, of higher intensity and short duration and subject to high evaporation rates. Arizona can be divided into three water resource provinces, basin and range lowlands, plateau uplands and central highlands. (Figure 1) Each province has groundwater supplies, but the type and productivity of their aquifers vary. Surface water supplies are also variable across the state with perennial supplies occurring mostly at higher elevations and within the central highlands province. Surface water from this province is an important water supply for the Phoenix area, Arizona's largest metropolitan area, with 60% of the state's population. Renewable surface water supplies in the state are largely developed, and there remains little opportunity for further enhancement of this supply. The most significant source of surface water for the state is the Colorado River, which runs across northwestern Arizona and then south forming the state boundary with California and Nevada. Large metropolitan areas in the center of the state, Phoenix and Tucson, depend upon water from the Colorado River that is pumped from the river and transported to them via the Central Arizona Project (CAP) canal as well as other surface water supplies from in-state rivers in the central highlands province. (Anderson et al, 2007) In 2001-2005 on average, 54% of the statewide water demand was met by surface water, 43% by groundwater and 3% by reclaimed wastewater. (ADWR, 2010) (Figure 2)

Figure 1: Arizona Water Resource Provinces

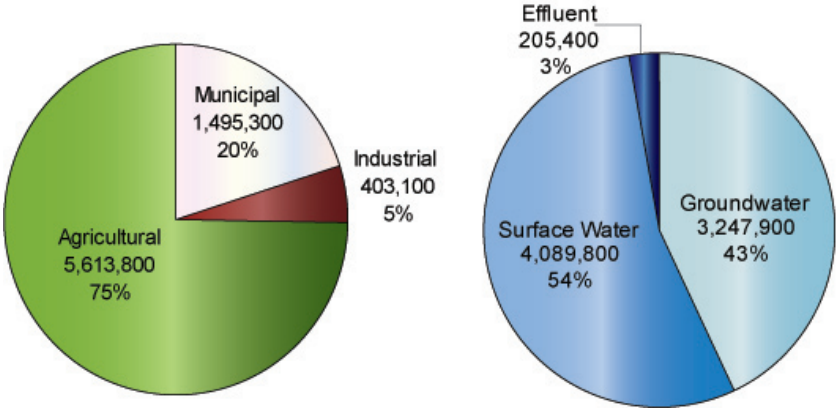

Figure 2: 2001-2005 Average Annual Water Demand in Acre-Feet by Water Supply Sector (Left) and Water Type (Right) (ADWR, 2010)

While the population of Arizona has increased significantly, water demand statewide has declined or remained stable due to retirement of agricultural lands, increased water use efficiency and effluent reuse. (Figure 3) In addition, use of non-groundwater supplies (CAP,

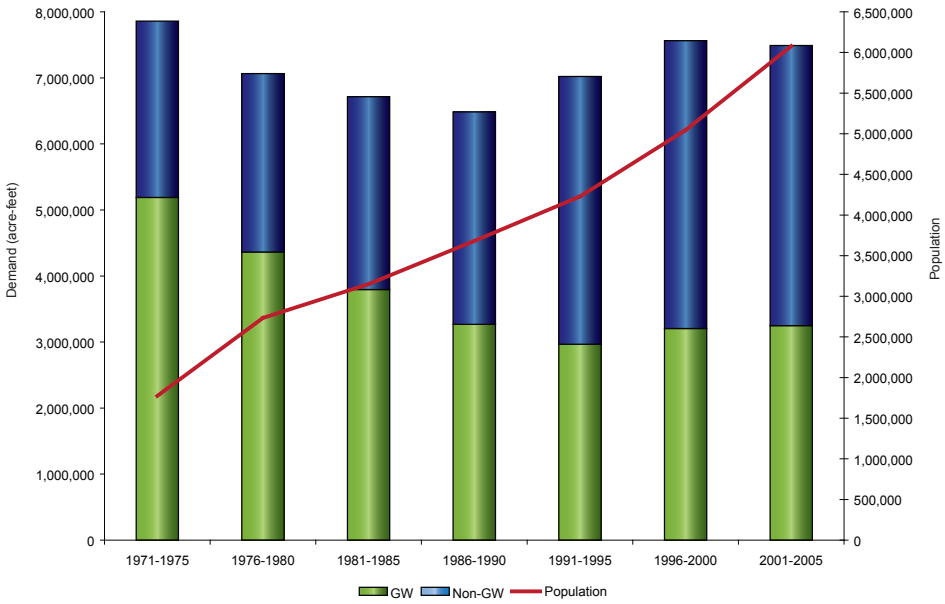

Figure 3: Comparison of Average Annual Water Demand in Arizona to Arizona Population, 1971-2005 (ADWR, 2010)

other surface water and effluent) has increased substantially compared to pre-1990 levels, primarily due to importation of CAP water to central Arizona. For water planning Arizona uses an organizational concept called planning areas that provide a regional perspective on water supply, demand and issues. (Figure 4) Figure 5 shows the demand and water supply use trends Arizona's seven planning areas. The majority of the population in Arizona is within the Active Management Area (AMA) Planning Area. Recent (2001-2005) AMA water demand is comparable to that in the early 1980s despite the doubling of population between the 1980 and 2000 census while the use of non-groundwater supplies increased by 52%. By contrast, demand in the Lower Colorado River, Upper Colorado River and Southeastern Arizona planning areas has increased from the early 1980s.

Water demand in the planning areas varies significantly by volume, water source and demand sector. Approximately half of the state's total water demand occurs in the AMAs where non-groundwater supplies such as CAP and in-state surface water account for most of the municipal and agricultural water supply. Agriculture continues to be the largest water demand sector in the state, accounting for 75% of water demand (not counting return flow) from 2001-2005 (Figure 2) and is the largest demand sector in every planning area except the Eastern Plateau. (Figure 4)

Water Management in Arizona

The laws and policies that govern water use in Arizona are quite variable. As a western state, surface waters are subject to the doctrine of prior appropriation, whereby the first in time to divert the waters is the first to receive their allocation. However, there is a legal divide between surface water and groundwater, and only in select river systems is the hydrological connection between surface water and groundwater recognized and incorporated into management. The largest metropolitan areas in Arizona are regulated by a relatively strict groundwater code established in 1980. This code sets a target for achieving "safe-yield" of the aquifers by 2025 through the use of renewable supplies and demand management. There are five of these areas, called Active Management Areas (AMAs) in the state (Prescott, Phoenix, Pinal, Tucson and Santa Cruz). (Figure 4) Outside of the AMAs there is little restriction on withdrawing groundwater as long as it is put to reasonable and beneficial use, such as domestic, agricultural or industrial uses. The only excep-

Figure 4: Arizona Planning Areas and Groundwater Basins

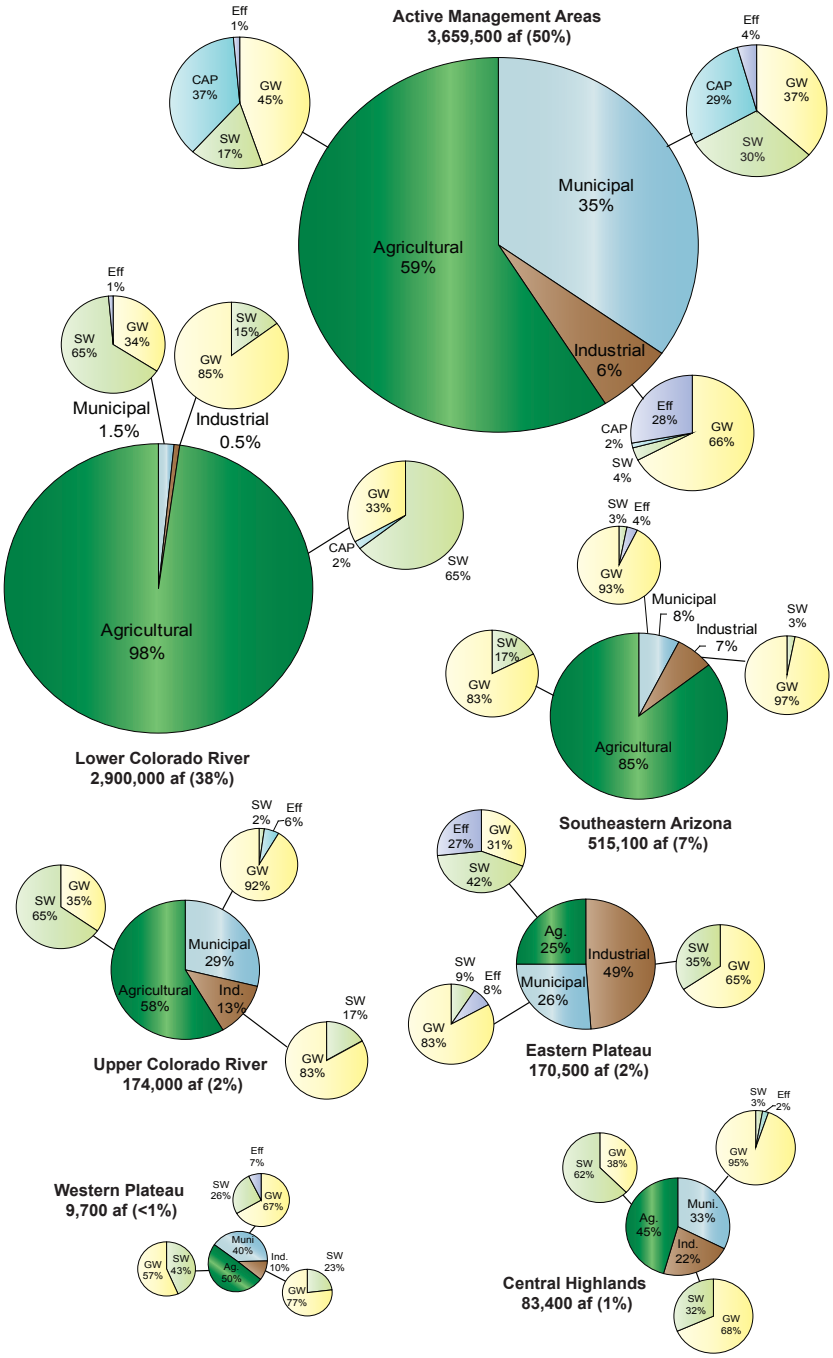

Figure 5: Average Annual Planning Area Water Demand by Sector and Water Source During 2001-2005 (ADWR, 2010)

tion to this beneficial use doctrine outside the AMAs occurs within three areas designated as Irrigation Non-Expansion Areas (INAs), where irrigation of new agricultural lands is restricted to prevent further groundwater declines.

Within the AMAs, mandatory water metering and reporting requirements for groundwater right holders has resulted in the systematic collection of water use data, which is compiled in AMA management plans. The management plans contain conservation requirements for the agricultural, municipal and industrial water use sectors and provide the framework for the day-to-day implementation of Code mandates and Department policies for each AMA. Management of water resources outside the AMAs is not regulated by the state, however, a number of statewide efforts have supported water resource planning, information needs and management efforts in these areas. These include establishment of the Rural Watershed Initiative Program (1998); adoption of the 2004 Arizona Drought Plan and associated legislation (H.B. 2277); initiation of the Statewide Water Conservation and Drought Program; establishment of a Rural Water Legislative Study Committee (2005-2007); and formation of a Statewide Water Advisory Group (SWAG) focused on programs for water resources development and management programs outside of AMAs (2006). In August 2009, a Governor's Blue Ribbon Panel on Water Sustainability was convened to improve the long-term sustainability of Arizona's water supplies through increased conservation and recycling statewide with a focus on challenges to increasing wastewater reuse. Legislation passed in 2010 (H.B. 2661) established the Water Resource Development Commission (WRDC), tasked with assessing current and future water needs in Arizona including identification of future supplies and financing mechanisms for water supply acquisition and infrastructure. The WRDC will prepare a report including recommendations and suggested legislation by October 2011.

Arizona Water Atlas

In an effort to further support water resource management and planning on a statewide level, over the last seven years the Arizona Department of Water Resources (ADWR) has collected and synthesized water-related information for Arizona into a "water atlas" organized by regional planning areas. The Water Atlas brings together over 80 unique water resource datasets containing both spatial and tabular information. Water Atlas data were collected both from within ADWR as well as from other state, federal and local resources. The Arizona Water Atlas consists of nine volumes. Volume 1 is an executive summary, Volumes 2 through 8 address each of the regional planning areas and Volume 9 is a water resource sustainability evaluation. The seven regional planning area volumes include data and information on groundwater and surface water hydrology and conditions (e.g. water level changes), climate, water supply availability and demand, population growth, environmental conditions, water quality and water resource issues. The first eight volumes of the Water Atlas were finalized by ADWR in September 2010 and are available in both pdf and web format on the Department's webpage (www.azwater.gov)

The final volume of the Atlas is intended to interpret and evaluate water resource sustainability conditions in Arizona using

the extensive data contained in the seven regional planning area volumes. The goal of Volume 9 is to answer the most common question ADWR receives from the public: "Does my community have enough water?" ADWR began this effort hoping to support and improve water planning and management decisions at the state, regional and local level in order to reduce system vulnerability and support development of sustainable water supplies. To assess the sustainability of each groundwater basin ADWR has developed a series of vulnerability categories, criteria and metrics designed to provide a uniform, statewide evaluation of both current and future (20-, 35- and 50-year) water supplies. The ADWR Water Atlas team evaluated sustainability through a vulnerability assessment because most planning efforts and datasets are based on discrete time periods, whereas sustainable or sustainability generally implies a perpetual condition or "in perpetuity", and can be defined in multiple ways depending on regional water management goals.

Although the sustainability evaluation was conceived at the beginning of the Arizona Water Atlas project in 2004, recent budget cuts to ADWR have caused the project to be funded by an external source, the Arizona Water Infrastructure Finance Authority (WIFA), a division of the Arizona Department of Environmental Quality. In May 2010 WIFA provided ADWR a one-year contract to complete Volume 9 of the Arizona Water Atlas. As of May 2011, the project team has completed both the criteria for assessing current and future water resource vulnerability and the methodology for determining the relative importance of each criterion to the vulnerability of a groundwater basin. The criteria have undergone an extensive review both internally at ADWR and by external stakeholder focus groups. The initial completion date for the project was June 2011, however, staffing and the project's relationship to the WRDC process and outcome have delayed the project's completion to January 2012. The remainder of this paper discusses the development of the water resource vulnerability criteria, the methodology ADWR will use to evaluate each of the 51 groundwater basins, lessons learned from the project to date and avenues for future research.

2. Methods

Creating the Categories, Criteria and Metrics

To assess a basin's vulnerability the Water Atlas team first attempted to answer the fundamental question, "What would we need to know to determine if a groundwater basin's water resources are vulnerable now and into the future?" From initial Water Atlas team meetings six vulnerability categories emerged: 1) Limited physical supply, 2) Projected demand diminishes supply, 3) Sensitivity to drought or shortage, 4) Potential for environmental impacts, 5) Legal constraints and 6) Water quality conditions. Existing data within the Arizona Water Atlas were then identified to provide the information necessary to support an assessment of each category and the questions these data sources answered became criteria and the data themselves the metrics. (Figure 6) The project team then designed a decision matrix to determine the basin's vulnerability, with four designations possible: severe, moderate, minimum or none. (See Figure 7)

The original categories, criteria and metrics were initially reviewed through a series of internal meetings at ADWR. Five meetings were held with each focusing on a different aspect of overall vulnerability related to the participant's expertise: physical supply and water quality, water demand, drought and shortage, legal constraints and environmental concerns. During each of these meetings staff were guided through the relevant criteria, asked to contribute new criteria where

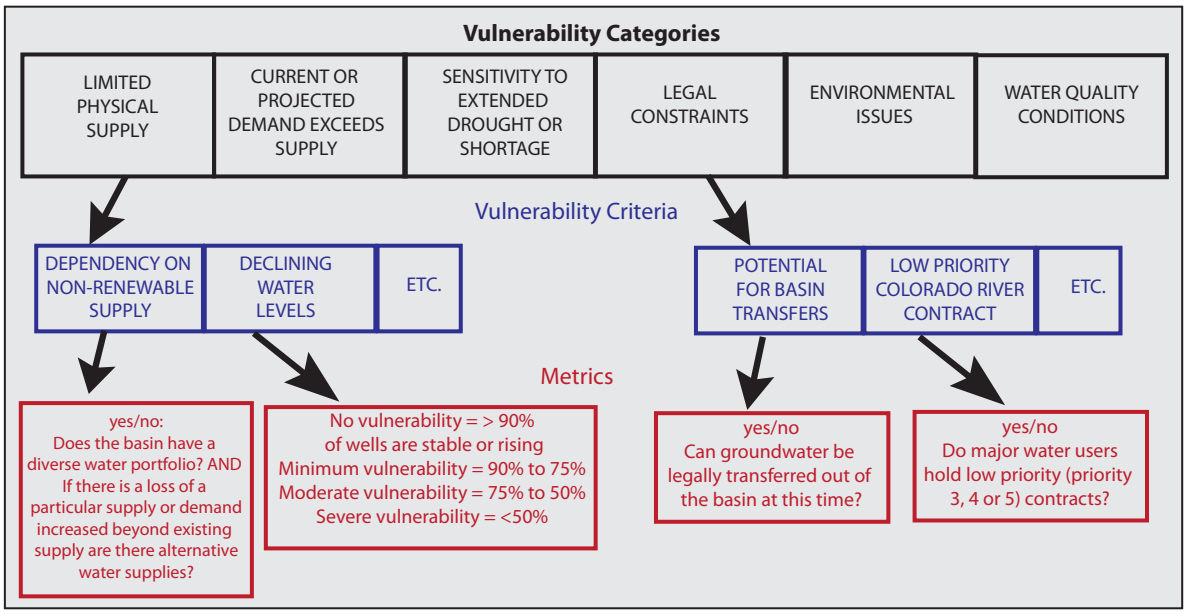

Figure 6: Flow Chart of Initial Vulnerability Categories, Criteria and Metrics.

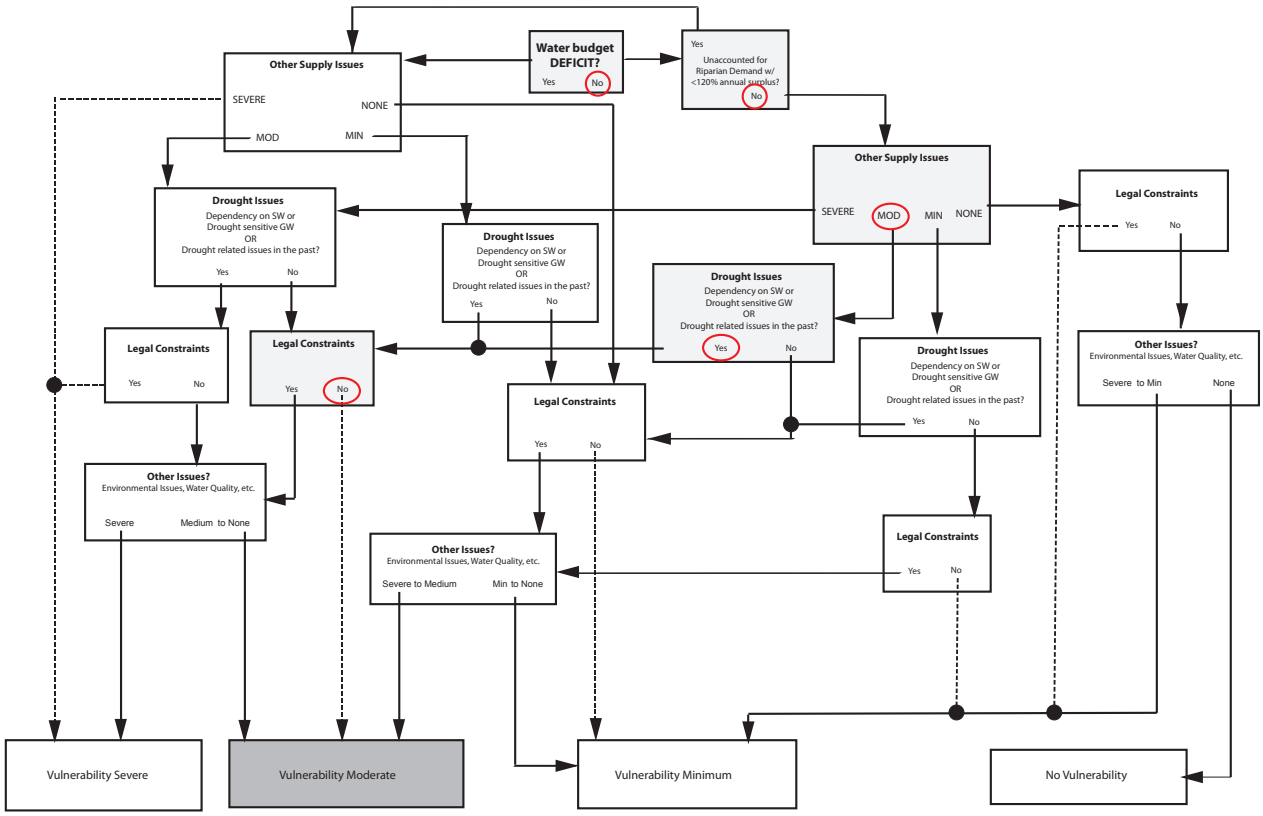

Figure 7: Initial Vulnerability Assessment Decision Matrix

needed and provide insight into data sources to evaluate the criteria where necessary. Significant changes to our approach occurred during the internal review. Principal among the changes were: the elimination of a "no vulnerability" ranking; incorporating the water quality category into the limited physical supply category and elimination of the decision matrix in favor of a weighting point system for each criteria resulting in a total vulnerability "score" for each basin.

The weighting point system was created to reflect the relative importance of the criteria to the overall vulnerability of a basin, as well as allow for flexibility within the criteria. For example, a significant criteria such as water level declines would receive more weight, or points, than a less critical criteria such as aquifer characteristics. Furthermore, within the water level decline criteria an increasing number of points would be assigned to increasing water level declines, e.g., less than 0.5 feet per year = 10 points, 0.5 to 2 feet per year = 20 points and greater than 2 feet per year = 30 points. The use of the weighting system also allowed for consideration of the robustness of the data behind the criteria. For example, the criterion "Meeting current demand has been identified as a problem" appears to be a very critical component of determining water resource vulnerability. The dataset behind this criterion, however, is from surveys that are now eight years old and include only those water providers who elected to answer the survey. Once the weights, or range of weights, were assigned to each criterion a total number of points for high, moderate and low vulnerability were determined. (Figure 8) The ability of this method to produce reasonable results was tested by selecting four "calibration" groundwater basins. Two of these groundwater basins were areas with well recognized high vulnerability and two with low vulnerability based on previous studies and reports.

Following completion of revisions to the weighting system and the categories, criteria and metrics according to the comments received during the internal review process an external stakeholder review process was initiated. External stakeholders were identified using a snowball technique where initial contacts were identified during the internal review process by ADWR experts and these individuals were asked to identify others in the field or region that would have an interest in reviewing and discussing the project. The external review was intended to function as a series of focus groups and not a public participation process per se. The goal of the external review focus groups was to further refine the categories, criteria and metrics; determine which criteria were more important, and should therefore receive more weight toward vulnerability; and obtain additional local knowledge and expertise on water supply and demand characteristics. Over the course of five months, 16 meetings were held with almost 90 different stakeholders representing 60 distinct interest groups ranging from federal agencies to citizen water advisory groups. Meetings were conducted in 6 of the 7 planning areas (the exception being the Western Plateau which has minimal population and water demand) and 10 of the 15 counties in Arizona. The meetings began with a brief overview of the Arizona Water Atlas project and the majority of the two hour meeting was spent reviewing the categories, criteria and metrics. During the meetings participants were encouraged to ask clarifying questions, add new criteria and modify existing criteria. At the end of each meeting participants were asked to list the five criteria

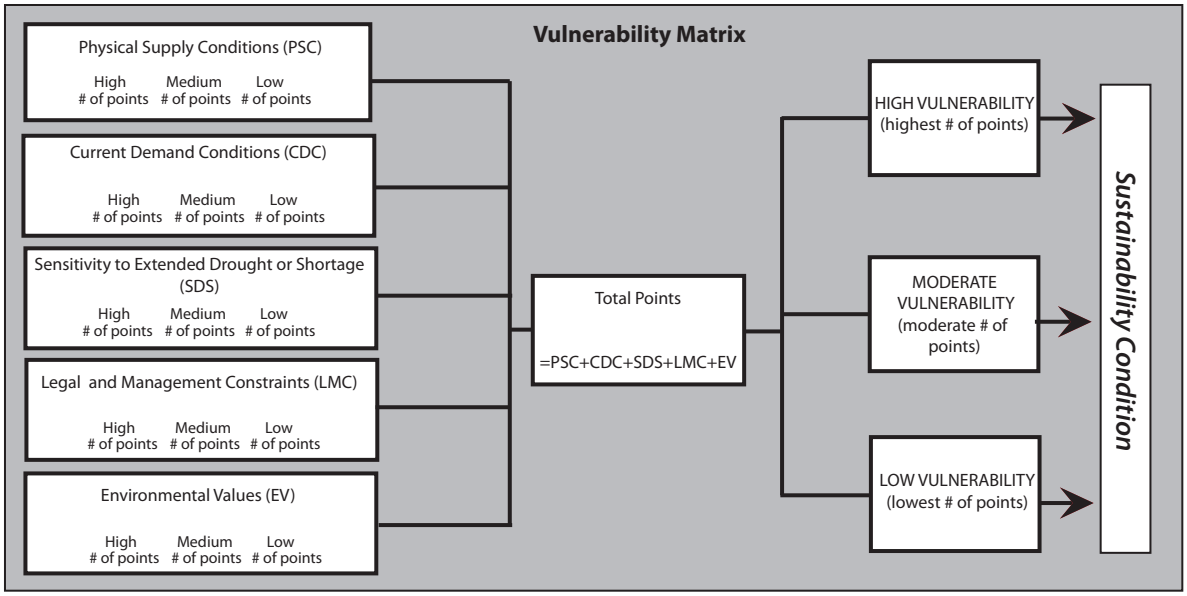

Figure 8: Revised (and Final) Vulnerability Assessment Decision Matrix Based on Criteria Weighting

that they believed were the most important for determining water resource vulnerability. The Atlas team did not reveal the weights that we had previously assigned to the criteria during these meetings, preferring instead to solicit their unbiased feedback on which criteria should be given the most weight.

Upon completion of the external review process the comments and questions from each meeting were assembled, and the criteria were revised and clarified to reflect these comments. Due to data and time constraints not all additional criteria or adjustments to existing criteria could be incorporated into the final vulnerability criteria and metrics. A document was created to address every suggested change to the criteria and metrics as well as answer any questions that arose during the meetings. This document also includes any comments on the overall vulnerability assessment process or the criteria gathered during the external review process. A matrix was created listing the top five criteria identified by each participant and criteria identified by the largest number of stakeholders as most important was used to guide the revision of the weights for each criterion.

Data

The sustainability evaluation was designed as the final volume of the Arizona Water Atlas, therefore, the primary data source are the datasets contained within the Water Atlas planning area volumes. Data from the Water Atlas used in the assessment include:

- Water supply and demand estimates for each groundwater basin for each demand sector (i.e., agricultural, municipal and industrial) and by water type (surface water or groundwater) for 1991-2008.
- Water level declines in wells between 1988-2010.
- Perennial, intermittent or effluent dependent streams and springs in each groundwater basin.
- Results from two ADWR water system surveys conducted in 2003 and 2004. Among other questions, these surveys asked water system managers about infrastructure, water quality concerns and water supply concerns both at that time and into the future.
- Water quality exceedences in wells or springs for total dissolved solids, nitrates, arsenic and fluoride from 1971-2005, impaired stream reaches and areas with point-source contamination that restricts use of drinking water supplies such as Superfund (National Priority List) sites.
- Population growth by basin between 1971-2050.
- Estimated groundwater in storage in aquifers and natural and artificial recharge estimates to those aquifers.
- Determinations of “inadequate” water supply in the basins outside of the AMAs.
- Legal access to water, including Colorado River contracts, in-state surface water adjudications and other surface water right claims.
- Presence of an endangered species in the basin.

Additional data, not included in the original Arizona Water Atlas, was also incorporated into the analysis. Examples of these data include:

- Local information on water resources and water resource management gained through the stakeholder review process.
- Anlaysis of Arizona Community Water System’s Water Plans to determine individual system vulnerability.
- Demand and supply projections for 20, 35 and 50 years into the future created by the Arizona Water Resources

Development Commission.
- Arizona Department of Environmental Quality database on water users that rely on hauled water.
- Data on unsafe dams and dams in need of substantial improvement.

3. Findings

The nearly year-long process of review and revision of the vulnerability categories, criteria and metrics resulted in a set of well-defined elements to assess water resource vulnerability in Arizona. Although there were multiple adjustments to the methodology through the internal and external stakeholder meetings, both the topic areas assessed and the process of assessment fundamentally remained the same. This section will highlight some of the final criteria, how they changed, why they were chosen and discuss the results of the weighting preference exercise from the external focus groups.

Examples of Final Criteria

During the internal and external review, much time was spent on the physical supply characteristics category. Although the metrics used for the assessment in every category are both quantitative and qualitative the physical supply characteristics category contains the majority of the quantitative metrics. Within the physical supply category there were two critical criteria that benefited from significant review and revision: dependency on a single water source and groundwater level declines. A brief discussion of how these two criteria were improved during the course of review highlights the benefits of the process.

	Criteria Name	Metric(s)
Sample Criterion 1		
Original Criterion	Dependency on a limited water source	1) Reported crises
		2) Available supply is <120% of current demand
Criterion after Internal Review	Dependency on a non-renewable supply	1) Is more than 50% of demand is met by one supply type?
		2) If there is a loss of existing supply or demand increases beyond existing supply are there alternative water supplies?
Final Criterion	Dependency on a water supply that is non-renewable and/or drought sensitive	1) How dependent is the basin on a non-renewable water supply?
		High: 80%-100%
		Medium: 50% -79%
		Low: <49%
		2) How dependent is the basin on a drought sensitive water supply?
		High: 80%-100%
		Medium: 50% -79%
		Low: <49%
Sample Criterion 2		
Original Criteria	Declining Water Levels	1) What percent of wells are stable (-5 ft to + 5 ft) or rising over the 15 yr period between 1990-2005?
		Severe vulnerability: 50% or less
		Moderate vulnerability: 51% to 75%
		Minimum vulnerability: 76% to 90%
		No Vulnerability: >90%
Criteria after Internal Review	Declining Water Levels in Demand Centers	1) What is the mean negative water level change rate?
		High: 2.1 ft./yr to -4.3 ft/yr
		Medium: -0.5 ft./yr to -2.0 ft./yr
		Low: -0.1ft./yr to -0.5 ft./yr
Final Criteria	Declining Water Levels in Demand Centers	1) What is the mean negative water level change rate?
		High: > 2.0 ft./yr
		Medium: -0.5 ft./yr to -2.0 ft./yr
		Low: < -0.5 ft./yr
		2) Where there are high and medium declines, is the groundwater geologically limited?
		3) Is there active subsidence in the basin due to groundwater overdraft?
		4) Do the water users in the basin need to maintain drainage in order to use supply?

Table 1: Changes to Physical Water Supply Criteria through Internal and External Review

Dependency on a single water source was initially identified as a criteria because it was believed that if a basin was dependent on a single water supply that represented a significant vulnerability. During internal review it was recognized that there would be situations where a basin dependent on just one water supply was not highly vulnerable because that supply was either very large, the demand very small or the water supply was annually replenished either through stream flow or groundwater recharge. Any of these three factors would provide a “false” vulnerability to a basin that depended on a single water source. Because of this shortcoming, it was determined that the criteria should be changed to “Dependency on a non-renewable water supply” With this adjustment the emphasis was placed on the amount of water supply more so than the diversity of water supply sources per se. During the external focus group review, however, many discussions highlighted that even this approach was not adequate to capture the vulnerability of the water resource. The criteria was inadequate because those basins that have multiple sources, i.e., groundwater and surface water, could have a more dependable water supply because should one type of supply be interrupted, e.g., surface water due to drought, the other may still be available. This observation led to the incorporation of drought sensitivity to the metric in addition to an examination of the dependency upon a non-renewable supply. (Table 1)

The collection of groundwater level change data was a key effort in the Arizona Water Atlas project. The original time period for this data, as published in the final volumes of the Arizona Water Atlas, was 1992-1995 to 2002-2005 with the ten year period examined varying based on the data available in the

basin. During the internal review process it was determined that this criteria, because of its importance to determining water resource vulnerability, should be updated and expanded. Additional analysis was conducted by ADWR's chief hydrologist that focused on the period from 1988 to 2010. Data were selected based on a review of available water level measurements for each groundwater basin in the state. Because of variability between basins in the time period available for analysis the mean annual negative change rate was calculated by dividing the basin's mean negative water level change by the number of years of data available. During the external review this criteria was further refined through adding metrics on the aquifer characteristics and subsidence. (Table 1)

Historically, in analysis of water demand in Arizona the water resource needs of the environment have not been considered. This omission is gradually changing, both in management practice and policy, and therefore it was determined that to the extent possible the Volume 9 analysis would assess vulnerability to water supply for the environment as well as vulnerability to water supply for human use. In contrast to the Physical Supply Characteristics category, which contains many quantitative criteria, the Environmental Values category contains only qualitative data. The paucity of statewide data for this category posed a significant challenge to its design. Suggestions during the external review process in particular were invaluable to improving the capacity of this category to capture water resource vulnerability. For example, initially the metric for the Environmental Water Need criterion was the presence of a perennial or intermittent stream in the basin. This simple metric was refined during external review to include springs as well as a ratio of basin size to stream miles. This ratio will allow us to approximate the importance of the water source to the basin, i.e., a single stream in a large basin is more likely to provide a critical water supply for the environment than a small basin with many surface water resources. This criterion was further improved with an additional metric based on data from an ecoregional assessment by The Nature Conservancy (TNC). The TNC assessment identified areas across Arizona as targets for conservation based on an extensive analysis of the flora and fauna of the area. Through using TNC analysis we are able to highlight habitat aspects of environmental water demand not previously available.

Determining Criteria Weights

Key to the success of this approach is the relative weight provided to the criteria. The importance of any given criteria can be very subjective and difficult to determine accurately. In an effort to make these weights less of a subjective decision by a few ADWR professionals, we requested feedback from each of the external focus group participants on what they perceived to be the most important criteria for determining vulnerability. Initially we requested participants to provide a score or weight for each criterion, however, after the first meeting with only one participant completing the exercise it was decided to approach the request more simply. In an effort to understand what criteria the participants perceived as most important they were requested to examine all of the criteria and indicate the five that would, regardless of the presence of any other factors, make the water resources of a groundwater basin highly vulnerable. The five criteria were not ranked, and participants were allowed to include new criteria suggested during the meetings as well as combinations of criteria discussed during the meeting.

Overall 87 participants provided their top five criteria. One focus group decided to determine their top five based on consensus, however, all others were based on individual opinions determined independently and then reported back to the group after their determinations were made. Two important elements emerged from this exercise: 1) there were two criteria that many participants felt to be more important to determining vulnerability than others and 2) the top five criteria varied based on geography and affiliation of the participants. The most frequently cited criteria by the participants was Dependency on a Non-Renewable Water Supply Source with 54% including it in their top five. During the course of the external review process many recommended that this criterion be merged with the Dependency on a Drought Sensitive Supply criterion. For the final criterion these two were combined, and if we take into consideration the votes for both of these criteria a total of 63% of the participants included this criterion amongst their top five. The other criterion included by a significant number of the participants, 43%, was Water Budget Deficit/Water Deficit Assessment.

Also notable were a number of criteria that very few participants identified in their top five. Criteria that 5% or fewer participants identified included: Contamination Restricts Use as Drinking Water Supplies, Instream Flow Rights, Subsidence and Quality of the Water System Drought Preparedness Plan. Although participants were not specifically asked which criteria were least important, some insight into why three of these four received so little attention can be discovered through a review of participant comments. The first criterion, Contamination Restricts Use as Drinking Water Supplies refers to areas of the state where the water supply is either unusable or must be extensively treated prior to use because of contamination by industrial pollutants such as Tetrachlroethene (PCE) and Volatile Organic Compounds (VOCs). Participants commented that this criterion does not apply to most basins in the state and where it does it is a vulnerability that can be addressed through adequate finances for cleanup. The second criterion, Instream Flow Rights, refers to basins where a water right certificate has been issued for an instream flow, i.e., the water right is for maintenance of flow within the river for recreation and wildlife and not a use that requires a diversion. The instream flow water right is a relatively new type of water rights claim in Arizona, and therefore most instream flow claims are junior to other rights on the river. The junior status of these rights was cited by a number of participants as making these claims a relatively weak protection for maintaining stream flow.

The third criterion, subsidence, is an indicator of over pumping of the aquifer. A few participants indicated that this criterion was implied within the criterion measuring groundwater level declines. Others indicated that this is also an issue that can be resolved with adequate funding, i.e., affected infrastructure can be relocated, and therefore not a critically important criterion for determining water resource vulnerability. Finally, it is unclear from the comments received why the fourth criterion, Quality of the Water System Drought Preparedness Plan was not frequently selected as a top five criteria.

Variation in the selection of the top five criteria is also apparent based on the region and by the participant's affiliation. For example, the Upper San Pedro and the Verde Valley areas are two groundwater basins where the health of perennial streams are a major concern. In these focus groups the criteria for an Environmental Water Need and Potential for Pumping to Impact Streams or Springs both were individualy ranked in the top five by 55% of the participants as compared to 14% and 36% respectively of the total number of participants. The criterion, Potential for Pumping to Impact Streams or Springs, was also more frequently chosen by participants with a statewide perspective, with 54% of these participants including this criterion in their top five. Participants representing cities and towns were more likely to include Dependency on a Water Supply that is Non-Renewable or Drought Sensitive, 67% compared to the overall total of 53%, and less likely to consider the Potential for Pumping to Impact Streams or Springs a top five criteria.

4. Conclusions

As of May 2011 the Arizona Water Sustainability Evaluation project has completed perhaps the most extensive phase of its development: creation and subsequent finalization of the categories, criteria and metrics to assess vulnerability and a mechanism for determining how to value each criterion. Although the project is far from complete, a number of lessons learned and avenues for further investigation beyond this project are already apparent.

Principal among these lessons learned is the value of review by multiple individuals representing diverse geographies and interests. Although the Water Atlas team included water managers with several decades of combined experience, we found that there were ideas and metrics proposed during review that previously had not been considered. Furthermore, a discussion of the vulnerability categories, criteria and metrics with external groups allowed ADWR a unique opportunity to reach out to the larger community concerned about water resources, and solicit their opinions before decisions were made. This effort to incorporate a larger audience in our very preliminary planning efforts was received very positively by the stakeholders and we were thanked multiple times for the opportunity to review and comment on the project given the sensitive nature of assessing vulnerabiity and potential consequences. Creating a sense of ownership of the project amongst a diverse set of interests may contribute to its ultimate utility, however, at this time it is premature to determine if this will indeed occur.

Although the review process was a success overall, there are aspects that would change should we begin the project again. All of the internal and external stakeholder meetings were conducted by the first two authors of this paper. Although difficult for two individuals to organize the entire stakeholder process, it was very beneficial because it allowed us to both keep the meeting format consistent and facilitated analysis of reviewer comments. Until April 2011 we worked under the assumption that the project must be finished by June 2011, and therefore we conducted fewer meetings than might have been optimal. This caused an under representation of some interest groups, most significantly Indian tribes. Furthermore, it was dfficult to engage some interest groups, such as industrial water users, therefore their perspective is not necessarily captured in the final categories, criteria and metrics.

The delay in the project's completion is also a source of concern. At this time most of the original Arizona Water Atlas team have left ADWR and have not been replaced. The loss of both the institutional knowledge and technical skills make successful completion of the project difficult. The project's delay is not, however, due only to resource constraints.

The project is currently running parallel to another statewide water resource assessment effort, the Water Resources Development Commission (WRDC). The goal of this legislatively created body is to provide recommendations on areas of the state that currently have unmet water demands or will have unmet demands in the next 100 years. Members of the WRDC were appointed by the Director of ADWR, and include those knowledgeable about various water resource and water management issues across Arizona. Many of the stakeholders that we met with during our project are also involved in the WRDC. Although the ultimate goal of the Volume 9 Water Sustainability Evaluation project is to identify water resource vulnerability, not unmet demand per se, there is considerable overlap between these two efforts. In many ways this overlap has been beneficial to this project. Through the WRDC we have received future demand and supply projections as well as refined criteria for assessing environmental values. The Volume 9 project has also influenced the WRDC and many of the techniques that are being used to examine current and future water supplies are based on our physical supply conditions criteria. Concern about results of the Volume 9 project being contradictory to the WRDC conclusions are, however, the overarching reason for the project's delay. The intention is to allow the WRDC to complete their analysis and present their recommendations in October 2011 and then for ADWR to release Volume 9 in January 2012.

The ultimate outcome of the Volume 9 project notwithstanding, both the categories, criteria and metrics identified within the analysis and those identified by stakeholders that could not be incorporated, provide a rich source of information for further research and data gathering. For example, a suggested criterion that was not included because of a lack of readily available data, was to measure the economic capacity to develop additional water supplies and/or improve infrastructure. Participants suggested that this capacity could be measured through an evaluation of median income or assessed property value in each groundwater basin because doing so might reflect an area's ability to raise funds through taxes. Another suggested crterion was to examine change in riparian areas as an indicator of vulnerability under the environmental values category. To date, however, there has been very little comprehensive mapping of riparian areas in Arizona and their relative health, making this sort of analysis impossible at this time.

The final categories, criteria and metrics presented in Appendix A were designed to be applied across Arizona, and therefore are considered to be relatively general. Would it be possible then to use these criteria to evaluate the water resource vulnerability of other western states as well? Or are they too tailored to both the data available to and legal situation of Arizona. Or are there elements of this analysis that could be applied beyond the West to other semi-arid areas of the world? Although the general applicability of these criteria as well as the ultimate fate of this analysis is unknown at this time, based on stakeholder feedback the attempt to create a list of vulnerability factors is a valuable exercise in thinking about the elements critical to a more sustainable water resource future for Arizona.

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Appendix A:
Final Vulnerability Assessment Categories, Criteria and Metrics
for *Current Conditions*

Categories

A) Physical Supply Characteristics
B) Current Demand Characteristics
C) Sensitivity to Extended Drought or Shortage
D) Legal and Management Considerations
E) Environmental Values

Criteria and Metrics

A) Physical Supply Characteristics

A1 Dependency on a water supply that is non-renewable and/or drought sensitive

- How dependent is the basin on a water supply that is non-renewable?
  - High dependency = 80%-100%
  - Moderate dependency = 50%-79%
  - Low dependency = 30%-49%
- How dependent is the basin on a drought sensitive water supply?
  - High dependency = 80%-100%
  - Moderate dependency = 50%-79%
  - Low dependency = 30%-49%
- *Non-renewable – a water supply that is not replenished annually, i.e., groundwater mining in excess of natural recharge or surface water use in excess of allocation.*
- *Drought sensitive groundwater – areas where it is well established that groundwater supplies are reliant on regular precipitation for recharge.*
- *Drought sensitive surface water - in-state rivers and water supply along the Colorado River that is priority 2 or lower.*

A2 Declining water levels in demand centers

- What is the mean annual negative water level change rate in the basin?
  - High = -2.1 feet/year or greater
  - Medium = -0.5 feet/year to -2.0 feet/year
  - Low = -0.4 feet/year or less
- In those areas with high and medium declines, is the groundwater geologically limited? (yes/no)
- Is there active subsidence in the basin due to groundwater overdraft? (yes/no)
- Do water users in the basin need to maintain drainage in order to maintain supply? (yes/no)
- *Demand center –area where most of the water demand occurs in the basin. Demand center is used because wells are not evenly or randomly distributed in basins and most monitored wells are located in demand centers.*

A3 Insufficient municipal infrastructure to deliver currently available supply

- Percent of population served by a water provider with insufficient municipal infrastructure
  - High = >50%
  - Medium = 25%-50%
  - Low = <25%
- *Infrastructure – the pipes, storage and other aspects necessary for a water provider to supply currently available supply to their customers during all seasons and at all times.*

A4 Regional water quality exceedences

- TDS (> 3,000 mg/l) (yes/no)
- Nitrate (yes/no)
- Arsenic
  - Percent of population served by a water provider not meeting Arizona Dept. of Environmental Quality's arsenic standards
    - High = >50%
    - Medium = 25%-50%
    - Low = <25%
- Meeting Safe Drinking Water (SDW) standards identified as a problem in surveys
  - Percent of population served by a water provider that has identified meeting SDW standards as a problem
    - High = >50%
    - Medium = 25%-50%

- Low = <25%

A5 Contamination restricts use as drinking water supplies
- Areas where contamination restricts pumpage and impaired reaches with contamination relevant to suitability for drinking water supplies (yes/no)
- Areas with mercury advisories for reservoirs used as water supply (yes/no)

A6 Groundwater or Surface Water data needs
- No data available (High uncertainty)
  - Groundwater and Surface Water - no/very limited data specific to the basin exist.
- Data exist but are old and/or unreliable (Moderate uncertainty)
  - Groundwater - most components of the water budget are unknown; significant studies/models necessary to update and understand basin conditions.
  - Surface Water - Presence of a perennial or intermittent stream in the basin with few stream gages or multiple discontinued stream gages.
- Minimal concerns (Low uncertainty)
  - Groundwater - multiple studies or models over time that will need updating in the future OR multiple studies exist but do not cover entire geographic area or not all components of the water budget have been studied.
  - Surface Water – Presence of a perennial or intermittent stream in the basin with multiple currently operating stream gages.

B) Current Demand Characteristics

B1 Current rate of annual growth
- High = 2% or higher per year (from Growing Smarter)
- Medium = 1.9% to 1 % medium
- Low = Less than 1%

B2 Meeting current demand has been identified as a problem
- Based on studies and surveys
  - High = >50%
  - Medium = 25%-50%
  - Low = <25%
- Include Indian, environmental, industrial and agricultural demand as well as municipal demand

B3 Water Budget Deficit or Water Deficit Assessment
- Use existing water budgets where available
  - Very High = demand > 20% larger than annual supply
  - High = demand 1% - 20% larger than annual supply
  - Moderate = demand equal (100%) to or 80% of annual supply
  - Low = demand less than 80% of annual supply
- Where no budget available use:
  - What is the ratio of natural, artificial and incidental recharge to demand
    - Very High = demand > 20% larger than recharge
    - High = demand 1% - 20% larger than recharge
    - Moderate = demand equal (100%) to or 80% recharge
    - Low = demand less than 80% recharge
  - If ratio is very high or high:
  - What is the ratio of demand to water in storage?
    - Very High = 1:1 - 1:200
    - High = 1:200 – 1:500
    - Moderate = 1:500 – 1:1,000
    - Low = >1:1,000

B4 Characteristics of Water Demand
- What percent of water demand in the basin committed to municipal use?
  - High vulnerability = > 50%
  - Moderate vulnerability = 25%-50%
  - Low vulnerability = < 25%
- What percent of municipal water demand is met by water providers with CAGRD contracts?
  - High vulnerability = > 50%
  - Moderate vulnerability = 25%-50%
  - Low vulnerability = < 25%

B5 Number of inadequacy determinations (outside AMAs; all reasons; by number of lots)
- High vulnerability = < 50% of lots in the basin are adequate

- Moderate vulnerability = 75% to 50% of lots in the basin are adequate
- Minimum vulnerability = > 75% of lots in the basin are adequate

B6 International or interstate water demand uncertainty
- Does the basin share a border or boundary with Mexico or another state where their water demand could effect the water supply of the basin? (yes/no)

B7 Access to dependable water supply infrastructure
- What percent of the water demand in the basin is met by hauled water?
  - High vulnerability = > 25%
  - Moderate vulnerability = 10%-25%
  - Low vulnerability = < 10%
- What percent of the water demand in the basin is met by exempt wells?
  - High vulnerability = > 50%
  - Moderate vulnerability = 25%-50%
  - Low vulnerability = < 25%

B8 Demand data are lacking in any given sector
- Municipal (yes/no)
- Industrial (yes/no)
- Agricultural (yes/no)
- Environmental (yes/no)

C) Sensitivity to Extended Drought or Shortage

C1 Drought-caused supply problems in the recent past
- Water shortage due to drought identified in surveys, drought plan, emergency transfers or rural watershed initiative tables from Water Atlas Volumes 2-7 (yes/no)

C2 Insufficient long-term storage (dams, recharge)
- In the recent past have water levels declined below “usable” levels in surface water reservoirs used for water supply? (yes/no)
- Does the basin contain reservoirs that are used for water supply that are unsafe or in need of repair? (yes/no)
- Are there sufficient artificial recharge credits to address shortage? (yes/no)
- *Sufficient – enough supply to meet your current demand*

C3 Quality of Drought Preparedness Plan (Community Water Systems)
- Five factors will determine if a plan is fair
  1. Emergency backup supply
  2. Drought stages
  3. Conservation plan
  4. System Metering
  5. Communication plan
  6. Amount of storage
- High vulnerability = > 50%
- Moderate vulnerability = 25%-50%
- Low vulnerability - < 25%

C4 Basin Average Annual Precipitation is Less than Evaporation
- Is the basin, on average, in a precipitation deficit, i.e., does evaporation exceed precipitation? (yes/no)

D) Legal and Management Considerations

D1 Low priority Colorado River rights
- Is basin located along Colorado River and Priority 4, 5 or 6 contractors are major water users? (yes/no)
- Is the basin an AMA that utilizes substantial quantities of CAP water for non-Indian agriculture? (yes/no)
- If the basin uses CAP, is there a substitute for this water supply available? (yes/no)
- *Substantial or major – More than 50% of water demand.*

D2 Unquantified Water Right Claims
- Does the basin contain Indian water right claims that have not been settled or decreed? (yes/no)
- Does the basin contain non-Indian federal or state lands (e.g., military bases, national forest, wilderness, national parks, monuments etc.) with water right claims that have not been decreed or settled? (yes/no)

D3 Threatened, Endangered or Candidate Species
- Does the basin have aquatic obligate endangered, threatened or candidate species (yes/no)
- If so, does the basin have a Habitat Conservation Plan in place? (yes/no)

D4 Surface Water Adjudications
- Is the basin within an area where surface water rights have not been adjudicated? (yes/no)

D5 Lack of a regional or local water resource management, planning or regulation

- Are there enforceable regulations?
    - High vulnerability = no enforceable regulations
    - Medium vulnerability = enforceable regulations in some portions of the basin and/ or enforceable regulations exist but are difficult to implement
    - Low vulnerability = enforceable regulations exist in entire basin and are actively enforced
- Are there basin or regional water planning efforts? (yes/no)
- Are there established management institutions? (yes/no)

E) Environmental Values

E1 Environmental Water Need

- Presence of a perennial, intermittent, or effluent-dependent stream or major or minor in the basin indicates an environmental water need. (yes/no)
- Ratio of perennial stream miles to basin size
    - High vulnerability = > 1:50
    - Medium vulnerability = 1:10 to 1:50
    - Low vulnerability = < 1:10
- Basin contains an area identified as a conservation area/target by The Nature Conservancy Ecoregional Assessment (yes/no) (http://azconservation.org/downloads/category/ecoregional_assessment/)

E2 Potential for pumping to impact surface water resources

- Is there a known connection between surface water and groundwater in the basin? (yes/no)

E3 Instream Flow rights

- Are there certificated instream flow rights in the basin? (yes/no)

E4 Impaired waters affect use for environment or recreation

- Impaired waters with contamination relevant to suitability for fish and wildlife or recreation (yes/no)

E5 Environmental water needs identified as a value in policy

- Does the local community have a policy or regulation relating to protection of environmental flows? (yes/no)
- Does the basin contain an Arizona Heritage Water? (yes/no) (http://www.azheritagewaters.nau.edu/designated_w.html)
- Does the basin contain a Unique Water? (yes/no)
- Does the basin contain and Wild and Scenic River or a nominated wild and scenic river? (yes/no)

E6 Unknown vulnerability

- It is unknown what the impacts of existing demand in the basin will be on the environment in a basin (yes/no)