VULNERABILITY OF WATER SYSTEMS: A COMPREHENSIVE FRAMEWORK FOR ITS ASSESSMENT AND IDENTIFICATION OF ADAPTATION STRATEGIES

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Abstract

Most climate projections predict that average surface temperature and precipitation variability will increase at the global scale, triggering hydrological variations and alterations in river flows and groundwater table levels. Climate change impacts on freshwater resources are likely to affect freshwater availability and quality and by extension the ability of water systems to support natural processes and ensure population needs. As a result, the vulnerability of water systems to adverse conditions (e.g. water shortages, overexploitation, and quality deterioration) is intensified; hence, methods and tools for vulnerability assessment and identification of adaptation measures are necessary. This paper proposes a comprehensive framework for the assessment of water systems' vulnerability to adverse water related conditions and the identification of potential adaptation strategies. The proposed methodology is applied in the four Study Site areas of the FP7 COROADO project (selected River Basins in Argentina, Brazil, Chile, and Mexico), and an indicator-based framework is adopted, expressing natural, physical, socio-economic and institutional attributes of the examined areas. The vulnerability assessment was conducted following a disaggregated analysis (use of proxy indicators). The vulnerability profiles of the four Study Sites were formulated, describing the factors shaping vulnerability and the aspects that need improvement. Additionally, the anticipated contribution of alternative strategies to vulnerability mitigation was assessed. The systems' response to alternative strategies (what-if scenarios) was analyzed following an aggregated analysis (development of an overall vulnerability index).

Keywords: vulnerability, water systems, adaptation strategies, water recycling and reuse, Latin America

1 Introduction

Climate change is expected to significantly affect freshwater systems and their management. Limited freshwater availability and degraded water quality, due to climate change impacts, may pose serious challenges to ecosystems' preservation, human health and well-being. The pressures that non-climatic factors, such as population increase, rapid economic development and land-use changes, exert on water systems, will further aggravate the impacts of climate change on freshwater resources [1]. The ability of water systems to meet basic requirements for environmental protection and to cover demand for all legitimate water uses will be jeopardized, and their vulnerability to adverse conditions will be intensified. The use of methods and tools to assess and monitor water systems' vulnerability and to identify potential adaptation strategies is thus necessary, and can contribute substantially towards Integrated Water Resources Management [2].

Vulnerability is defined as the degree to which a system is susceptible to, and unable to cope with, injury, damage, or harm [3]. It is a function of the system's exposure to hazards, its sensitivity and its adaptive capacity. In the present work, exposure, sensitivity and adaptive capacity, are considered the three aspects of vulnerability and, based on the definitions provided by the Intergovernmental Panel on Climate Change (IPCC) [4] and Gallopín [5], have been defined as follows:

- *Exposure:* the nature, degree, duration and/or extent to which the system is in contact with, or subject to perturbations;
- *Sensitivity*: the degree to which a system can be modified or affected (adversely or beneficially, directly or indirectly) by a disturbance or set of disturbances;
- *Adaptive capacity:* the ability of a system to adjust to disturbances, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences of transformations that occur.

The exposure and sensitivity aspects are linked, and together express the potential impacts on the analyzed systems, being positively associated with vulnerability. On the contrary, adaptive capacity expresses the

potential of the systems to effectively cope with the impacts and associated risks and is negatively associated with vulnerability. Consequently, the functional form of vulnerability could be:

$$V = \mathrm{f}\left(PI - AC\right) \quad (1)$$

where V is vulnerability, PI is potential impact (=exposure + sensitivity), and AC is adaptive capacity. Higher adaptive capacity is associated with lower vulnerability, while higher potential impact is associated with higher vulnerability [6, 7].

Adaptive capacity, and by extension vulnerability, includes both hydro-physical and socio-economic attributes, e.g. technological development, access to water supply and sanitation, governance of the water sector, as the way in which society adapts to changes in water supply may be more critical than freshwater availability [1, 2, 7]. The vulnerability of water systems can be defined as the degree to which the analyzed systems may be unable to function under environmental and socio-economic changes, specifically changes either arising from or bringing about adverse water related conditions (i.e. water scarcity, water shortages, water resources variation, and water quality deterioration). A comprehensive framework is needed to assess its multifaceted nature, considering the different vulnerability dimensions, i.e. natural, physical, economic, social, and institutional [8].

Such a framework is proposed in this paper, and is applied in four River Basins: the Suquía River Basin (Argentina), the Upper Tiête River Basin (São Paulo, Brazil); the Copiapó River Basin (Chile); and the Lower Rio Bravo/Rio Grande Basin (Mexico). All four River Basins (Study Sites) are facing water scarcity or stress conditions due to hydrologic variations, water quality issues, increased water demand, and/or lack of adequate infrastructure and proper governance mechanisms. The proposed framework is used to assess the degree to which the water systems (i.e. water resources, water uses, and water users) are vulnerable to adverse water related conditions, and to identify potential adaptation Water Recycling and Reuse (WR&R) strategies for vulnerability mitigation. The adopted framework enables the comprehensive vulnerability assessment of the water systems, as well as the analysis of the systems' potential for improvement through the assessment of different adaptation strategies.

2 Methodological framework

Vulnerability assessment is a challenging task with ingrained difficulties in defining quantification criteria and methods [2, 9]. Different assessment frameworks exist with their own advantages and drawbacks. Indicator-based frameworks are the most common and widely used, expressing vulnerability through a number of proxy indicators or through composite indices.

It is widely considered that the use of a composite index to assess the vulnerability of water resources could result into loss of information, when compared to the use of numerous indicators which allow for a more detailed and comprehensive analysis [10, 11]. Experts [12, 13] have suggested building vulnerability profiles through the consideration of a number of proxy indicators. However, composite indices provide condensed information and allow for a broad variety of issues to be addressed through a single value. Composite indices can also easily communicate assessments to decision makers [2], and vulnerability indices have been adopted in a number of water-related studies [14-16]. Regardless of the adopted approach, particular attention should be given to avoiding misleading interpretation of the assessment results [2].

In this work, an indicator-based framework was adopted for the assessment of vulnerability as a function of exposure, sensitivity and adaptive capacity (see Section 1). The comprehensive analysis of the vulnerability status of the examined River Basins comprises two complementary methodological steps (Figure 1) involving both the selection of proxy indicators (for the vulnerability assessment) and the development of a composite index (for the vulnerability mitigation). Proxy indicators, expressing the different vulnerability dimensions, were used to formulate the vulnerability profiles of the examined areas, i.e. the significant water resources pressures that each area faces, the status of adaptive capacity and the aspects that need to be improved. In addition, an Overall Vulnerability Index (VI) was estimated, using the Principal Components Analysis (PCA), to analyze the responses of the systems under alternative adaptation strategies. Taking into account the significance of certain indicators in the developed VI, alternative WR&R adaptation strategies were formulated and were then assessed based on their anticipated contribution to vulnerability mitigation.

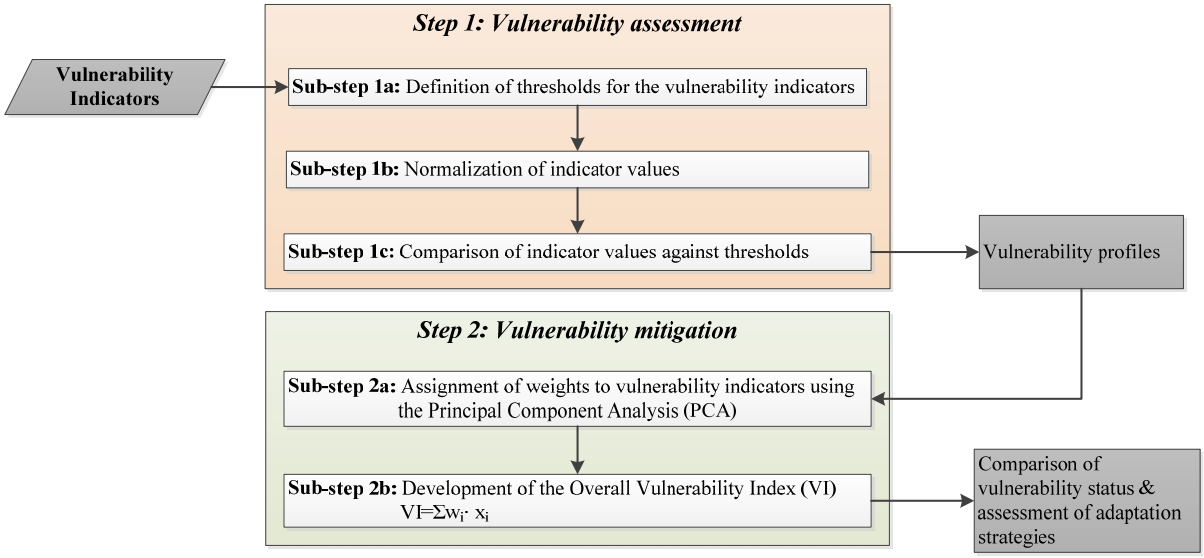

Figure 1: The methodological framework of the analysis [2]

The selected vulnerability indicators and the two methodological steps used for the River Basin vulnerability analysis are presented in detail in the following Sections.

2.1 The Vulnerability Indicator Scheme

The proxy indicators were selected after a broad review of literature on vulnerability and water resources management, in order to identify the most widely used and accepted indicators and indices. Specific criteria were considered for selecting the vulnerability indicators:

- *Relevance to the Study Sites' context:* only the quantitative and qualitative indicators which were likely to be critical and applicable to the analyzed areas were considered;
- *Data availability*: only indicators for which data were readily available or accessible through national or regional reports and publications, were used for the assessment;
- *Avoidance of overlapping:* special attention was paid to ensure that the analysis does not include different indicators which express similar parameters of the analyzed systems, to avoid double counting and overemphasizing of specific issues.

A non-exhaustive list of 20 indicators was developed, which is flexible for use in other study areas as well. Each one of the selected indicators falls under a vulnerability aspect, i.e. exposure, sensitivity and adaptive capacity (Tables 1, 2 and 3 respectively), providing insight on the characteristics of the water related pressures and the prevailing conditions of water use.

Table 1: The selected exposure indicators

Parameter	Indicator	Proxy for	Threshold
Water resources variation	Coefficient of variation of rainfall (CV)	Variation of water resources over the years	0.3 [15]
Water resources scarcity	Per capita water availability / Falkenmark Indicator (WRS)	Population pressure on available water resources	1,700 m³/capita/yr [17]
Water resources exploitation	Total water use with respect to available water / Water Exploitation Index (WEI)	Increased water demand as stress on available water resources	40% [18]
Water pollution	Wastewater discharge as percentage (%) of available water resources (WRP)	Pollution to water environment by anthropogenic activities	10% [15]

Table 2: The selected sensitivity indicators

Parameter	Indicator	Proxy for	Threshold
Prevailing development conditions	Population density (PD)	Localized stress on water systems	55 inh/km^2 [19]
	Population growth (PG)	Growth of water demand & generation of wastewater	1.2% [19]
	Percentage (%) of the total cultivated area dependent on irrigation (ID)	Water dependence of agricultural production	38% [19]

Table 3: The selected adaptive capacity indicators

Parameter	Indicator	Proxy for	Threshold
Natural capacity	Vegetation cover of the area (VC)	Capacity in improving land cover & reducing flood & erosion risk	30% [19]
Physical capacity	Losses in the water supply network (WSL)	Efficiency of technology & infrastructure	20% [20]
	Irrigation water use efficiency (IE)	Efficiency of technology & infrastructure	40% [19]
	Domestic, agricultural & industrial supply with reclaimed water (DWR, AWR, IWR)	Use of alternative water resources to cope with demand	10% (estimate based on prevailing conditions)
Socio-economic capacity	Economically active population (EP)	Social capital with access to technology & financial resources	60% [19]
	Gross Regional Domestic Product per capita (GRDP)		$10,000 [19]
	Population below poverty line (PP)		34% [19]
Legal & institutional capacity	Governance of water supply & wastewater treatment sectors (GW, GWW)	Management of water supply & wastewater treatment	Qualitative score = 3 (estimate based on a scale from 1 to 5)
	Legal & institutional WR&R framework (LF, IF)	Capacity to support WR&R implementation	Qualitative score = 3 (estimate based on a scale from 1 to 5)

2.2 Step 1: Vulnerability assessment

For the vulnerability assessment a disaggregated approach is used, to provide a detailed analysis of the vulnerability profiles of the analyzed areas. The vulnerability assessment comprises the following sub-steps (Figure 1):

Sub-step 1a: Definition of thresholds for vulnerability indicators

For all vulnerability indicators, thresholds were defined, i.e. benchmark values indicating acceptable conditions and standards, to provide a measure on whether or not the indicators contribute significantly to vulnerability. The threshold values for the vulnerability indicators are presented in Tables 1, 2, and 3, and were defined as follows:

1. For some indicators critical values have already been proposed in the literature, above or below which the systems are considered as not operating properly;
2. World mean values, retrieved from the World Bank's online database on World Development Indicators [19], were considered the thresholds of the indicators for which critical values have not been proposed;

3. For the indicators concerning WR&R interventions (not available in the World Bank online database), thresholds were estimated on the basis of prevailing conditions in the Study Site areas. The threshold in this case was defined as the desired minimum penetration of WR&R in water supply.

Sub-step 1b: Normalization of indicator values

All indicators were expressed in such a way that higher indicator values would indicate higher contribution to the exposure, sensitivity or adaptive capacity of the system; some indicator values are inverted so that an increase in the indicator value leads also to an increase in the corresponding aspect. The indicator values were further normalized as ratios of their respective thresholds. After normalization, threshold values were equal to 1 and the indicator values ranged from 0 to 5 (the cut-off value of 5 was used to facilitate graphic presentation).

The qualitative indicators, which express the legal and institutional aspects of the systems' adaptive capacity (Table 3), were considered separately and were not normalized. Their values were based on expert judgment using a scale ranging from 1 (absent/non-existent) to 5 (good), and 3 was considered the respective threshold. In the graphical display of results (Section 4) the threshold value of qualitative indicators is 3 and not 1.

Sub-step 1c: Comparison of indicator values against thresholds

The indicator values were compared against their respective thresholds, in order to identify the underlying vulnerability factors. Exposure and sensitivity indicators with values above the threshold of 1, and adaptive capacity indicators with values below the threshold (1 for quantitative and 3 for qualitative indicators), express the parameters which contribute to the vulnerability of the analyzed systems.

2.3 Step 2: Vulnerability mitigation

To identify suitable strategies for vulnerability mitigation, an aggregated analysis is followed. A composite Overall Vulnerability Index (VI) is developed, aiming to provide a useful metric to benchmark River Basins in terms of vulnerability, and to assess alternative adaptation strategies (analysis of what-if scenarios). The sub-steps of the aggregated analysis are (Figure 1):

Sub-step 2a: Assignment of weights to vulnerability indicators using the PCA

PCA is a technique used in statistical analysis aiming to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as much as possible of the variation present in the data set. This is achieved by identifying a new set of uncorrelated proxy variables (Principal Components) which are orthogonal linear transformations of the original variables. The generated Principal Components (PCs) are ordered so that the first few retain most of the variation present in all of the original variables; the first PC accounts for as much of the total variation as possible, and each succeeding PC accounts for as much of the remaining variation as possible [21].

The weight for each indicator was assumed to be the sum of products of the coefficients of the most significant PCs, with the corresponding percentages of total variation explained. The most significant PCs are those that account for most of the variation of the data set. In the present analysis, the Kaiser criterion [22] was used to decide how many of the generated PCs (which are as many as the original variables) would be considered significant.

Step 2b: Development of the Overall Vulnerability Index (VI)

The VI was expressed as the weighted sum of the indicator values in the following way:

$$VI = \varepsilon \left(w_i X x_i \right) \qquad (2)$$

where w_i corresponds to the calculated weights through PCA, and x_i to the standardized indicator values.

Only exposure and sensitivity indicators with positive weights and adaptive capacity indicators with negative weights were considered for the construction of the VI, as exposure and sensitivity were defined as positively associated with vulnerability, and adaptive capacity was defined as negatively associated with the vulnerability of water systems (Section 1, Equation 1). The weights of indicators in the developed VI point to possible interventions/strategies that may be suitable at the local level and the degree to which these interventions could contribute to vulnerability mitigation.

3 The Study Site Areas

The four Study Site areas, located in different regions of Northern, Western, Eastern and Southern Latin America (Figure 2), capture a broad range of hydrological and socio-economic conditions (Table 4) and face significant water related issues, such as overexploitation of available resources, imbalance between water supply and demand, increased pollution of water bodies, and insufficient management of the water sector.

Figure 2: The Study Site Areas (Google Earth image)

The *Suquía River Basin*, which is located in a semi-arid region of the province of Córdoba (Argentina), has been subjected to prolonged droughts and floods during recent decades. In addition, uncontrolled urban expansion, land-use changes, insufficient infrastructure capacity and strong population growth have resulted in limited freshwater availability and water quality deterioration [23].

In the *Upper Tietê River Basin* (Brazil), which roughly corresponds to the São Paulo Metropolitan Region (SPMR), rapid urban sprawl and industrial growth, coupled with unregulated land use, have generated intense water demand and severe contamination of water bodies. Although an extensive network of water infrastructure has been implemented over the years (including hydropower plants, inter-basin transfers and pumping stations), water availability remains extremely low in the area, resulting in water scarcity conditions [23].

Water scarcity conditions are also apparent in the *Copiapó River Basin*, which is located in the Atacama Desert of Chile. The uncontrolled trade of water rights, combined with the increased demand of the agricultural and mining sectors have led to the overexploitation of available water resources. The rapid development of the mining industry and the anticipated population increase are expected to further compound limited water availability, and intensify the competition over water supply [23].

The Study Site area of the *Lower Rio Bravo/Grande Basin* is located in the easternmost part of the USA-Mexico border, and faces complex water management and distribution issues, due to overlapping management jurisdictions and frequent conflicts between the agricultural sector and the rapidly growing industry. The drought events experienced during the last decades further aggravated water shortage and resulted in the reduction of agricultural irrigated areas due to limited water availability [23].

Table 4: Main characteristics of the Study Site areas [23]

Parameter	Suquía, AR	SPMR, BR	Copiapó, CL	Rio Bravo, MX
Area (km^2)	6,000	7,947	18,538	10,162
Population (inh.)	1,329,604 (census 2010)	19,867,456 (census 2010)	188,015 (census 2012)	1,279,313 (census 2010)
Population density (inh./km^2)	220	2,500	10	126
Mean annual rainfall (mm)	800	1,400	28	596
Main land use	Agricultural	Urban	Agricultural	Agricultural
Most water consuming sector	Urban/domestic	Urban/domestic	Agriculture	Agriculture
Main economic activities	Services & industrial sectors	Services & industrial sectors	Agriculture & mining	Agriculture & livestock
GRDP (US$ per capita)	9,120	14,790	26,587	16,626

4 Results & Discussion

4.1 Vulnerability profiles

The vulnerability profiles of the four Study Sites were formulated by comparing the normalized values of the exposure, sensitivity and adaptive capacity indicators against their respective thresholds.

As shown in Figure 3, the Copiapó River Basin is characterized by high temporal variation of rainfall, as the area frequently faces long dry periods with no rainfall, indicating the low reliability of available resources. All four areas struggle with water scarcity, with the Upper Tietê River Basin facing severe shortage, as the annual available freshwater resources in the area are about 135 m³ per capita, which is far below the respective threshold (water availability below 500 m³/capita/year is a main constraint to quality of life [17]). Overexploitation of the limited available resources is a commonly faced challenge in the analyzed areas, expressed by the extremely high values of the WEI, which exceeds the warning threshold of 40% [18] in all cases, indicating strong competition for water. Particularly in the Upper Tietê and Copiapó River Basins, the water used exceeds the locally available resources by 30%. Moreover, in the Upper Tietê River Basin (SPMR) the great amount of untreated wastewater discharge, which represents 45% of available water resources, triggers severe contamination of the receiving water bodies.

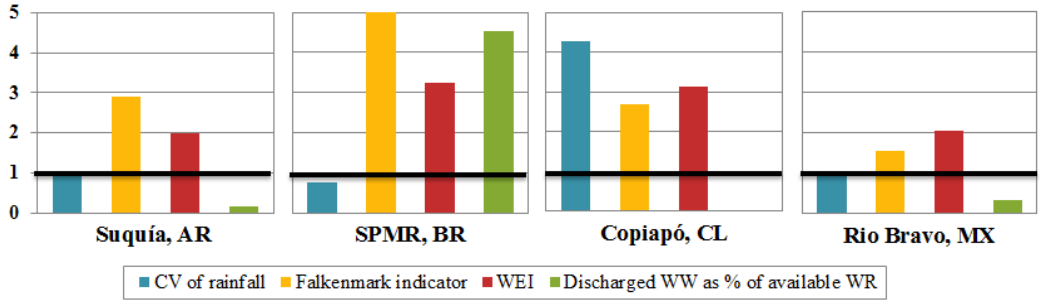

Figure 3: Comparison of exposure indicators against their respective thresholds (black line)

Furthermore, economic development and rapid population growth resulted in high population densities in the Suquía (about 220 inh/km^2), the Upper Tietê (about 2,500 inh/km^2), and the Lower Rio Bravo Basins (about 126 inh/km^2), exerting localized pressures on water systems (Figure 4). Increased water demands for irrigation in the Copiapó and the Lower Rio Bravo Basins further exacerbate water scarcity conditions, particularly given the high dependence of the agricultural production to irrigation (100% and 53% of cultivated land is irrigated in Copiapó and Lower Rio Bravo respectively). Agricultural production is also highly dependent on irrigation in the Upper Tietê River Basin, yet the amount of water consumed by the agricultural sector in the area is negligible when compared to urban and industrial water uses.

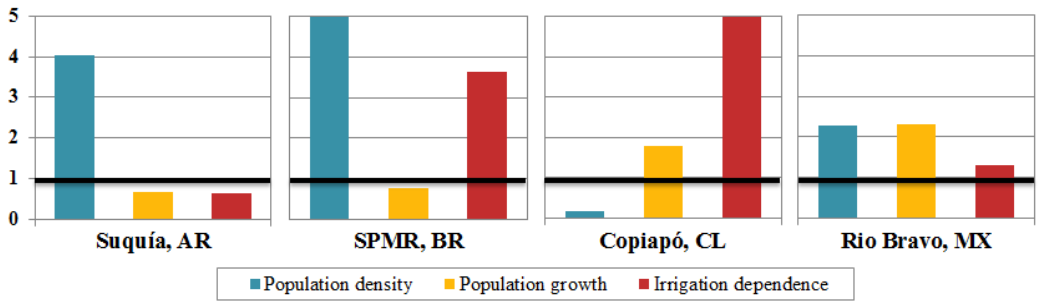

Figure 4: Comparison of sensitivity indicators against their respective thresholds (black line)

The poor performance of the Study Site areas' adaptive capacity aggravates the described water related pressures (Table 5).

Table 5: Comparison of adaptive capacity indicators against their respective thresholds*

Adaptive Capacity indicators	Threshold	Suquía, AR	SPMR, BR	Copiapó, CL	Rio Bravo, MX
Vegetation cover of the area	**1**	0.90	1.00	0.00	1.53
Losses in the water supply network	**1**	0.63	0.53	0.59	0.87
Irrigation efficiency	**1**	0.75	3.00	4.00	1.20
Domestic supply with reclaimed water	**1**	0.00	0.00	0.00	0.00
Agricultural supply with reclaimed water	**1**	0.00	0.00	0.30	0.00
Industrial supply with reclaimed water	**1**	0.50	0.14	4.86	0.02
Economically active population	**1**	0.91	1.23	0.93	0.69
GRDP per capita	**1**	0.91	1.48	2.66	1.66
Population below poverty line	**1**	3.54	0.94	3.33	0.86
Governance of water supply sector	**3**	2.30	3.40	1.00	3.80
Governance of WW treatment sector	**3**	2.90	2.60	2.20	4.27
Legal WR&R framework	**3**	3.00	3.00	3.00	3.71
Institutional WR&R framework	**3**	1.50	3.00	3.00	3.71

**Red color: value below threshold/low capacity; yellow color: value equal or near to threshold/marginal capacity; green color: value above threshold/adequate capacity.*

The natural capacity of the examined areas is very poor, as vegetation cover is limited (with the exception of the Lower Rio Bravo Basin in Mexico, where about 46% of land is covered by vegetation). The same applies to the physical aspect of adaptive capacity, mainly due to the very high water distribution losses and the limited WR&R applications (except for the Copiapó River Basin, where about 48% of the mining sector's demand is covered by treated wastewater). In addition, the low efficiency of the irrigation methods used in the Suquía and the Lower Rio Bravo Basin indicates the low physical capacity of the systems. The socio-economic capacity of the areas is moderate, with the exception of the Copiapó River Basin where it is relatively good, expressed by a high GRDP (about US$ 26,580 per capita, in 2011) and a low poverty rate (about 10% in 2009). The percentages of economically active population are below or close to thresholds in all cases, while the Upper Tietê and the Lower Rio Bravo Basins have high poverty rates (about 36% and 40%, respectively in 2010). Additionally, the legal and institutional capacity of the examined systems is weak, as the governance of water supply and wastewater treatment sectors is insufficient and the existing legal and institutional frameworks do not promote the implementation of WR&R schemes. Unlike the other areas, the Lower Rio Bravo Basin has good legal and institutional capacity; improvements are still needed though, especially regarding the legal and institutional frameworks related to WR&R.

4.2 The Overall Vulnerability Index

The values considered in the development of the VI for the four Study Sites are presented in Figures 3, 4, and in Table 5. The VI was estimated as the weighted sum:

$$VI = 0.056 \times CV + 0.194 \times WRS + 0.207 \times WEI + 0.162 \times WRP + 0.082 \times PD + 0.182 \times ID - (0.07 \times VC + 0.171 \times WSL + 0.121 \times DWR + 0.104 \times AWR + 0.017 \times PP + 0.018 \times GW + 0.105 \times GWW + 0.049 \times LF) \quad (3)$$

As shown in Equation 3, only fourteen indicators[1] were considered for the construction of the VI (six exposure and sensitivity indicators with positive weights, and eight adaptive capacity indicators with negative weights). A threshold for the VI was also calculated on the basis of the threshold values of the indicators considered. The VIs of the four Study Sites were normalized to a range from 0 to 100, using the min-max normalization process, in which the threshold value of the VI is set to zero (Figure 5).

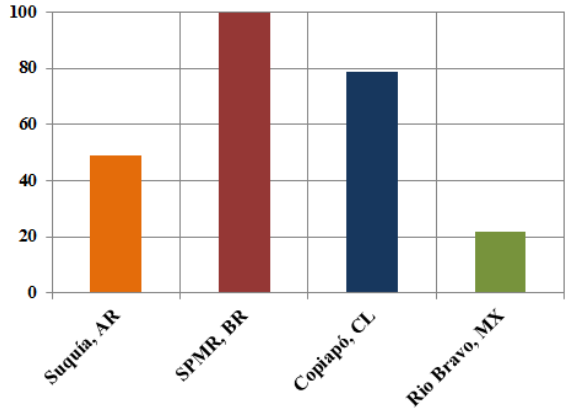

Figure 5: The Overall Vulnerability Index for the four Study Sites

As shown in Figure 5, the Upper Tietê River Basin (SPMR, BR) is the most vulnerable area followed by the Copiapó River Basin, while the Lower Rio Bravo/Grande Basin (Rio Bravo, MX) is the least vulnerable area among the four Study Sites. This, however, does not indicate that the water system conditions in the Lower Rio Bravo/Grande Basin are satisfactory, as the vulnerability status of the area surpasses the VI threshold significantly (~ 22%). The different vulnerability levels of the four areas are due to different combinations of exposure, sensitivity and adaptive capacity aspects, which in all cases exceed the acceptable thresholds. As a result, all four areas are vulnerable to adverse water related conditions to a smaller or greater extent, and are in need of intervention measures to improve their status and to support natural and societal needs.

4.2.1 Assessment of alternative WR&R adaptation strategies

In order to develop WR&R strategies for mitigating vulnerability, the critical vulnerability indicators, i.e. those having higher weights in the equation of the VI (Equation 3), should be considered and their values should be decreased.

Based on the indicators retained for the development of the VI and their respective weights, alternative WR&R vulnerability mitigation strategies can be formulated for the urban/domestic and agricultural sectors. Industrial WR&R strategies were not considered as the relevant indicator was excluded from the equation of the VI (its weight did not meet the defined specifications). The industrial water uses are the least water consumptive uses and do not contribute significantly to the vulnerability of the examined water systems, with the exception of the Upper Tietê River Basin.

WR&R strategies for urban/domestic and agricultural applications would directly affect the indicators related to the use of reclaimed water for the domestic and agricultural supply, as well as the legal framework related to WR&R. Recycling of treated wastewater for domestic purposes would potentially lead to the reduction of the

[1] The abbreviated names of the indicators in Equation 3 are given in Tables 1, 2 and 3.

generated wastewater and would enhance the governance of the wastewater treatment sector. The WEI, which is the most significant indicator, would be also affected by the implementation of different WR&R applications, as alternative water resources would be used instead of freshwater resources.

WR&R adaptation strategies can be combined with additional interventions for vulnerability mitigation, which will affect indicators with high weights in Equation 3, such as the irrigation dependence and losses in the urban distribution network. The identified adaptation strategies are presented in Table 6.

Table 6: The identified WR&R adaptation strategies*

Strategy	Description
1. Domestic WR&R applications	
Strategy #1a: Reuse of treated WW in domestic water uses	• Supplying 10% of domestic water uses with reclaimed water (corresponding reduction of the WEI); • Appropriate arrangements for the enhancement of the existing legal framework related to WR&R; • 10% reduction of water losses in the urban water distribution network.
Strategy #1b: Recycling of domestic wastewater	• Supplying 10% of domestic water uses through the recycling of domestic wastewater (corresponding reduction of the WEI and of the untreated wastewater discharge); • Appropriate arrangements for the enhancement of the governance of wastewater treatment sector; • All other aspects are the same as in Strategy #1a.
2. Agricultural WR&R applications	
Strategy #2a: Reuse of treated wastewater for irrigation	• Supplying 10% of agricultural water uses with reclaimed water (corresponding reduction of the WEI) • Appropriate arrangements for the enhancement of the existing legal framework related to WR&R
Strategy #2b: Reuse of treated wastewater for irrigation, and change in crop patterns	• 10% reduction of the irrigation dependence, through the substitution of irrigated crops by rainfed crops • All other aspects are the same as in Strategy #2a

**10% supply with reclaimed water was suggested, in order to reach the threshold values of the corresponding indicators*

The vulnerability mitigation, expressed as the percent reduction in the VI, which can be achieved through each strategy is presented in Table 7.

Table 7: The percentage of vulnerability mitigation achieved through each strategy

Study Sites	Strategy #1a	Strategy #1b	Strategy #2a	Strategy #2b
Suquía, AR	52%	59%	31%	31%
SPMR, BR	34%	38%	15%	19%
Copiapó, CL	36%	41%	21%	21%
Rio Bravo, MX	22%	28%	55%	57%

As shown in Table 7, the strategies for domestic WR&R applications are the most effective in terms of vulnerability mitigation in the cases of Suquía, Upper Tietê (SPMR) and Copiapó River Basins, while in the Lower Rio Bravo Basin the strategies which concern agricultural WR&R applications are the most effective. This is mainly due to share of the WEI attributed to the different water uses in each case; hence the reduction of the water use with the highest contribution to the WEI affects the final results respectively. In addition, strategies which include indicators with higher weights have a greater contribution to vulnerability mitigation.

5 Conclusions

Through the water systems vulnerability analysis, great insight was gained regarding the water related pressures and the areas that need improvement in the four Study Sites. Limited availability and overexploitation of freshwater resources are common challenges in the areas. All four areas are vulnerable to adverse water related conditions to a smaller (Lower Rio Bravo/Grande Basin) or greater extent (Upper Tietê River Basin), and

intervention measures are needed. More specifically, in the Suquía River Basin the significant water related pressures are further exacerbated by the poor capacity of the natural and anthropogenic environment, while in the Upper Tietê River Basin the interplay of the urban socio-economic setting combined with the inadequate capacity to adapt, has led to the high vulnerability of water systems. In the Copiapó and Lower Rio Bravo/Grande Basins the ability of water systems to meet increased demand is limited, due to the poor management of the water sector, the rapid population increase and economic development. Implementation of domestic WR&R applications can have an essential contribution in the mitigation of vulnerability in the Suquía, Upper Tietê and Copiapó River Basins, while agricultural WR&R applications would significantly reduce the vulnerability of water systems in the Lower Rio Bravo/Grande Basin.

The adopted methodological framework facilitates the comparison of the vulnerability status and the identification of appropriate and targeted interventions that are needed at the local level. The selected group of indicators reflects the complexity of water resources systems and the multifaceted context of vulnerability. The indicator scheme can be further reviewed and adjusted to support the development of adaptation strategies in different areas. Additionally, the developed VI can be used to compare and rank areas, as well as to benchmark areas as to their vulnerability threshold.

The assessment results can provide useful input in the identification of adaptation strategies to mitigate vulnerability, and can support decision making and planning processes in order to enable the implementation of suitable interventions, if combined with other analytical/assessment tools (e.g. cost-benefit analysis, MCDA, etc.).

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