# VULNERABILITY OF WATER SYSTEMS:

## A COMPREHENSIVE FRAMEWORK FOR ITS ASSESSMENT & IDENTIFICATION OF ADAPTATION STRATEGIES

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# The Need for Vulnerability Assessment & Adaptation

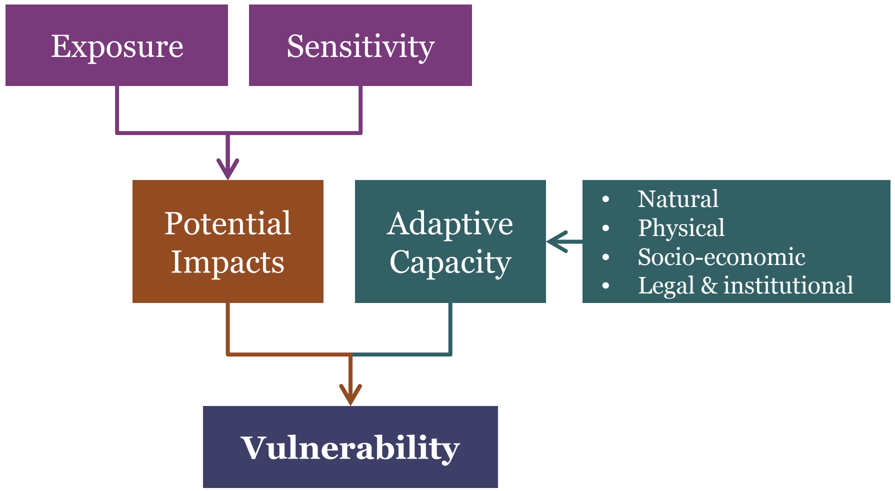
- **Climatic projections**
  - Increase in average surface temperature
  - Hydrologic variations
- **Climate Change impacts** on freshwater resources
  - Limited availability
  - Degraded quality
- **Jeopardized ability of water systems** to support natural processes & ensure population needs
- **Vulnerable water systems** to adverse water related conditions due to climate change

- Analysis of **water systems' vulnerability to adverse water related conditions**
  - Water scarcity & shortages
  - Water resources variation
  - Water quality deterioration
- Identification of **adaptation strategies** for vulnerability mitigation
  - Potential WR&R interventions/responses

# Defining Vulnerability

*"the degree to which a system is susceptible to, and unable to cope with, injury, damage, or harm" (EEA, Glossary of Terms)*

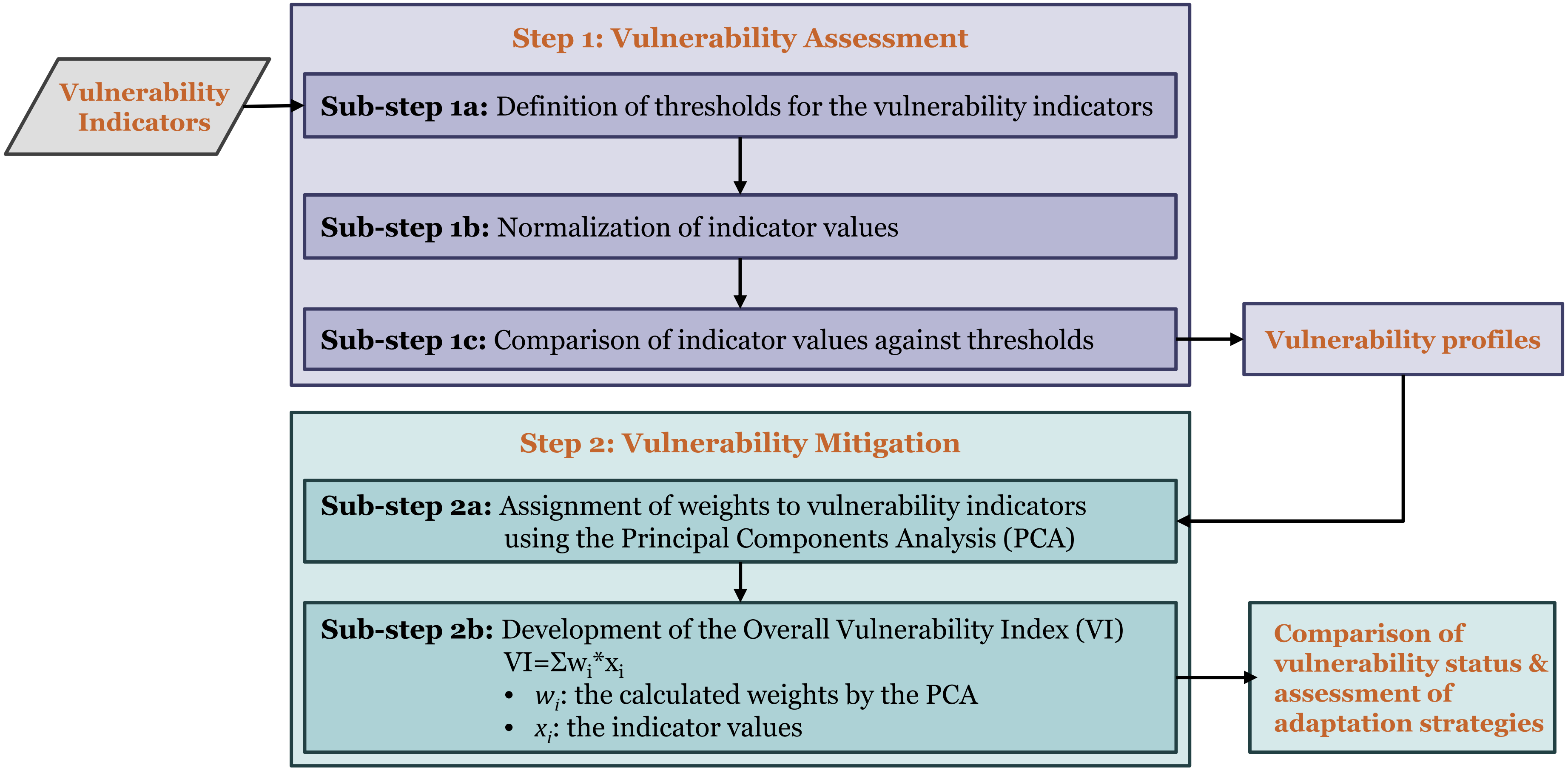
- **Three Vulnerability Aspects**
  - **Exposure**
    - The nature, degree, duration and/or extent to which the system is in contact with, or subject to perturbations
  - **Sensitivity**
    - The degree to which a system can be modified or affected (adversely or beneficially, directly or indirectly) 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




**V=(Exposure + Sensitivity) - Adaptive Capacity**

*Sources: Babel, 2011; Füssel and Klein, 2006; Gallopín, 2006; IPCC, 2001*

# Methodological Framework



# The Vulnerability Indicator Scheme (1/2)

## Exposure & Sensitivity Indicators

| Parameter | Indicator | Proxy for | Threshold |
|---|---|---|---|
| **Exposure Indicators** | | | |
| Water resources variation | Coefficient of variation of rainfall (CV) | Variation of water resources over the years | 0.3 (Huang & Cai, 2009) |
| Water resources scarcity | Per capita water availability / Falkenmark Indicator (WRS) | Population pressure on available water resources | 1,700 $m^3$/cap/yr. (Falkenmark, 1989) |
| 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% (UN-CSD, 1997) |
| Water pollution | Wastewater discharge as percentage (%) of available water resources (WRP) | Pollution to water environment by anthropogenic activities | 10% (Huang & Cai, 2009) |
| **Sensitivity Indicators** | | | |
| Prevailing development conditions | Population density (PD) | Localized stress on water systems | 55 inh/$km^2$ (World mean *) |
| | Population growth (PG) | Growth of water demand & generation of wastewater | 1.2 % (World mean *) |
| | Percentage (%) of the total cultivated area dependent on irrigation (ID) | Water dependence of agricultural production | 35% (World mean - AQUASTAT, 2006; Hamouda et al., 2009) |

**Values derived from World Bank, World Development Indicators – online database*

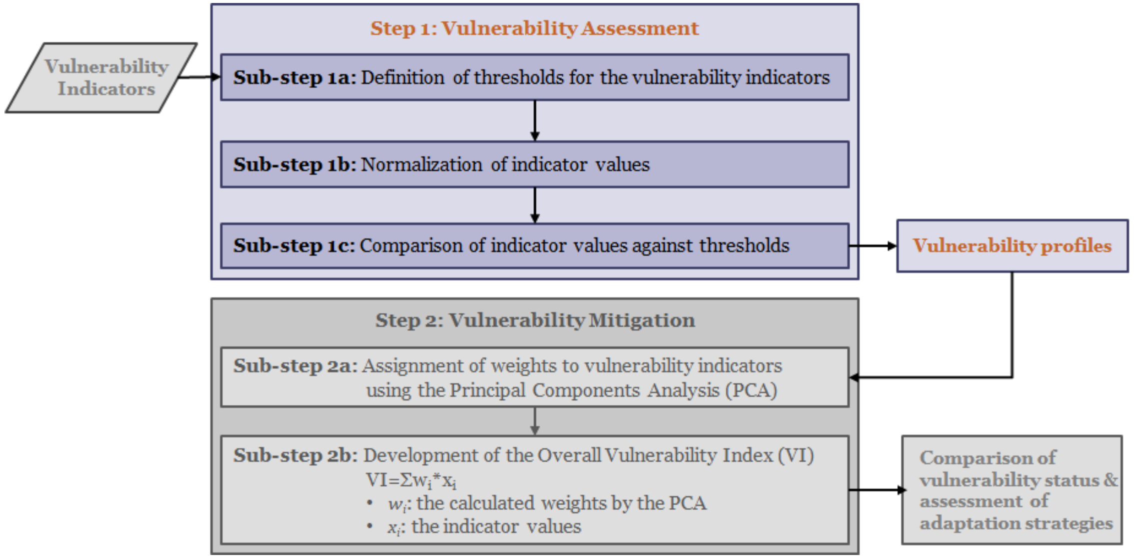
# The Vulnerability Indicator Scheme (2/2)

## 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%<br>(World mean *) |
| **Physical capacity** | Losses in the water supply network (WSL) | Efficiency of technology & infrastructure | 20 %<br>(Sharma, 2008) |
| | Irrigation water use efficiency (IE) | Efficiency of technology & infrastructure | 40%<br>(World mean – Revenga et al., 2000) |
| | Domestic, agricultural & industrial supply with reclaimed water (DWR, AWR, IWR) | Use of alternative water resources to cope with demand | 10%<br>(Estimate based on prevailing conditions) |
| **Socio-economic capacity** | Economically active population (EP) | Social capital with access to technology & financial resources | 60%<br>(World mean *) |
| | Gross Regional Domestic Product per capita (GRDP) | | $10,000<br>(World mean *) |
| | Population below poverty line (PP) | | 34%<br>(World mean – World Bank, 2010) |
| **Legal & institutional capacity** | Governance of water supply & wastewater treatment sectors (GW, GWW) | Management of water supply & wastewater treatment | Qualitative score=3<br>(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<br>(Estimate based on a scale from 1 to 5) |

**Values derived from World Bank, World Development Indicators – online database*

# Step 1: Vulnerability Assessment




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

- Benchmark values indicating acceptable conditions & standards

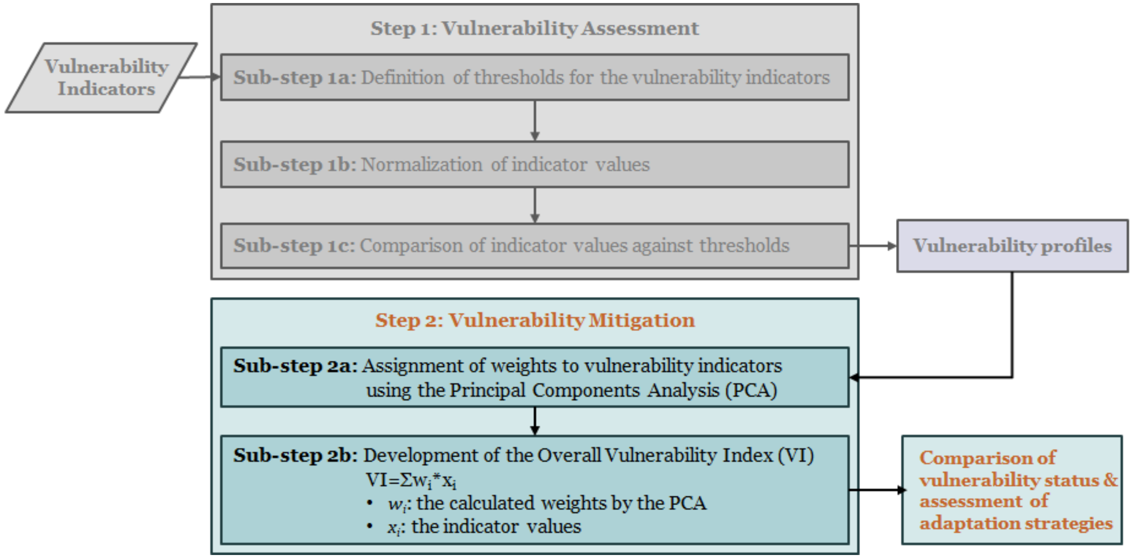
**Sub-step 1b: Normalization of indicator values**

- High indicator values should indicate higher exposure, sensitivity or adaptive capacity aspects
- Different approach for the **quantitative** & **qualitative** indicators
  - Values were normalized as ratios of their respective thresholds: threshold values equal to 1
  - Based on expert judgment using a scale from 1 to 5: threshold values equal to 3

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

- Identification of the indicators which contribute to vulnerability
  - Exposure & sensitivity indicators with values above the threshold of 1
  - Adaptive capacity indicators with values below the thresholds (1 for quantitative & 3 for qualitative indicators)

# Step 2: Vulnerability Mitigation




**Sub-step 2a: Assignment of weights to vulnerability indicators**

- Weighting scheme: **Principal Component Analysis (PCA)**
  - Indicator weights were assumed to be the sum of products of the coefficients of the most significant PCs
    - PCs with eigenvalues greater than one (Kaiser criterion)

**Sub-step 2b: Development of the Overall Vulnerability Index (VI)**

- Expressed as the weighted sum of the indicator values
  - $\boldsymbol{V} = \sum \boldsymbol{w_i} \times \boldsymbol{x_i}$
  - Retention of:
    - Exposure & sensitivity indicators with positive weights
    - Adaptive capacity indicators with negative weights

- Threshold VI calculated based on the threshold values

# The Study Site Areas (1/2)

- ***The Suquía River Basin (Argentina)***
  - Semi-arid region of the Córdoba province
  - Limited freshwater availability & water quality deterioration
- ***The Upper Tietê River Basin (Brazil)***
  - São Paulo Metropolitan Region (SPMR)
  - Intense water demand & severe contamination of water bodies
- ***The Copiapó River Basin (Chile)***
  - Atacama Desert of Chile
  - Water scarcity conditions & competition over water supply
- ***The Lower Rio Bravo/Grande Basin (Mexico)***
  - Easternmost part of the USA-Mexico border
  - Complex water management & distribution issues

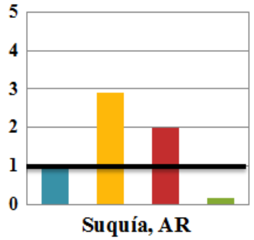
# The Study Site Areas (2/2)

## A broad range of hydrological & socio-economic characteristics

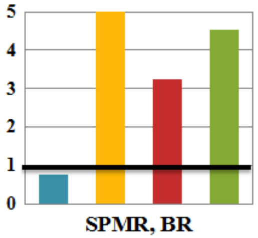
| Parameter | Suquía , AR | SPMR, BR | Copiapó , CL | Rio Bravo, MX |
|---|---|---|---|---|
| Area ($km^2$) | 6,000 | 7,947 | 18,538 | 10,162 |
| Population (inh.) | 1,329,604 (census 2010) | 19,867,456 (census 2010) | 188,015 (census 2012) | 1,279,313 (census 2010) |
| Population density ($inh/km^2$) | 221 | 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 |

# Results

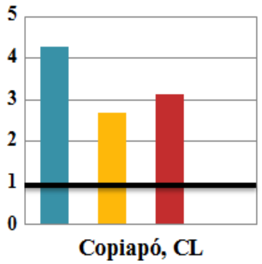
## Vulnerability Profiles – Exposure Indicators



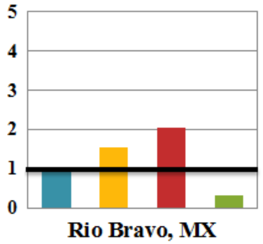

- **Suquía River Basin, Argentina**
    - Intense water scarcity conditions (584 m³/cap/yr.)
    - Overexploitation of available resources (WEI 79%)




- **Upper Tietê River Basin, Brazil**
    - Absolute water scarcity (135 m³/cap/yr.)
    - Water used exceeds locally available resources by 30%
    - Severe contamination (untreated WW discharge 45% of available resources)




- **Copiapó River Basin, Chile**
    - High temporal variation of rainfall – low reliability of available resources
    - Water stress conditions & strong competition for water (WEI 125%)

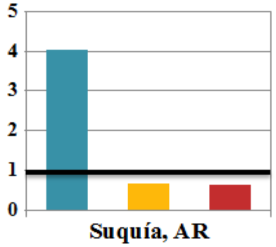



- **Lower Rio Bravo/Grande Basin, Mexico**
    - Water stress conditions (1,094 m³ /cap/yr.)
    - Overexploitation of available resources (WEI=82%)

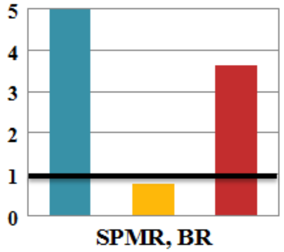
■ CV of rainfall ■ Falkenmark indicator ■ WEI ■ Discharged WW as % of available WR

# Results

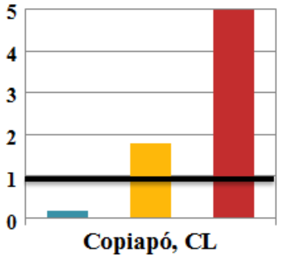
## Vulnerability Profiles – Sensitivity Indicators



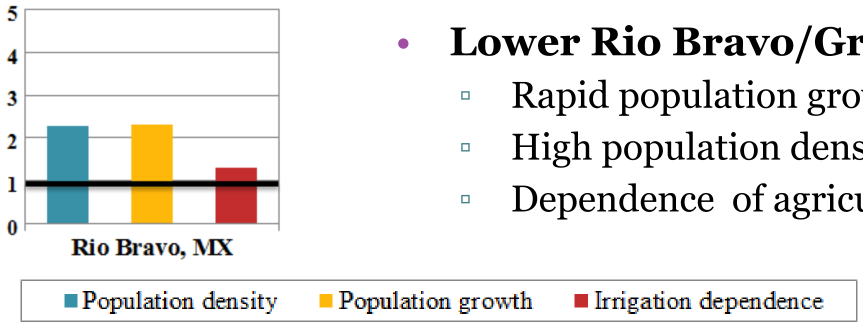

- **Suquía River Basin, Argentina**
  - High population density (221 inh/km²)




- **Upper Tietê River Basin, Brazil**
  - Extremely high population density (2500 inh/km²)
  - Agricultural production is highly dependent on irrigation (83%)
    - Negligible amount of water consumed by the agricultural sector when compared to urban and industrial water uses




- **Copiapó River Basin, Chile**
  - Significant population growth (2.14% for the period 2002-2012)
  - Absolute irrigation dependence (100% of cultivated land is irrigated)




- **Lower Rio Bravo/Grande Basin, Mexico**
  - Rapid population growth (~ 2.3% annual growth rate, 2000-2010)
  - High population density (126 inh/km²)
  - Dependence of agricultural production to irrigation (53% irrigated land)

# Results

## Vulnerability Profiles – Adaptive Capacity Indicators

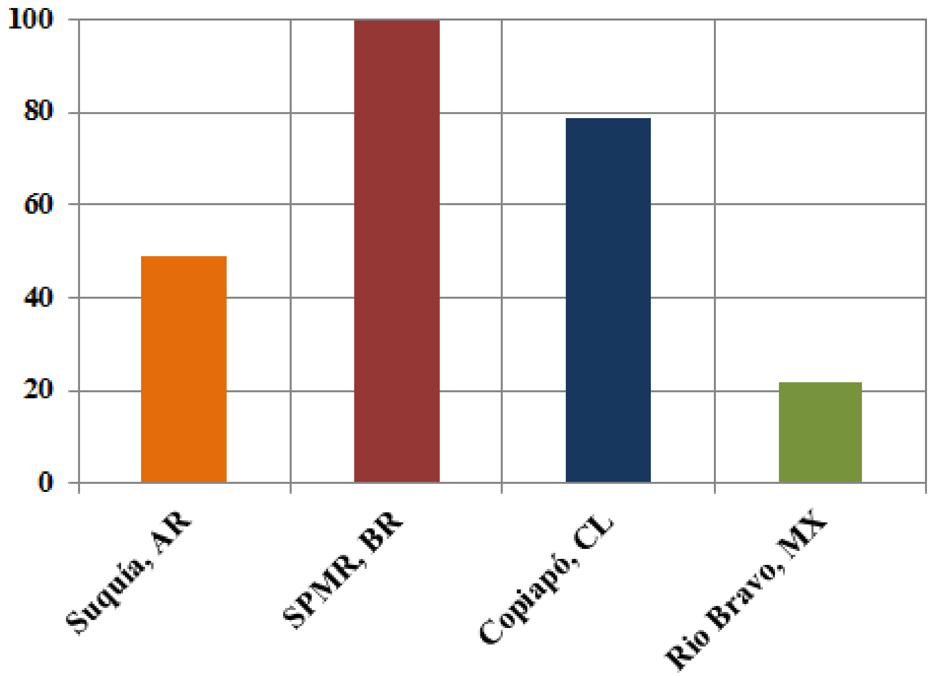
- Poor natural capacity
  - Limited vegetation cover
    - Exception: Rio Bravo, 46% of land is covered by vegetation
- Poor physical capacity
  - High distribution losses
  - Limited WR&R penetration
    - Exception: Copiapó, 48% of the mining sector's demand is covered by WR&R
- Moderate socio-economic capacity
  - Percentages of economically active population below or close to thresholds
  - High poverty rates
    - Upper Tietê (36%) & Rio Bravo (40%)
- Weak legal & institutional capacity
  - Insufficient governance mechanisms & WR&R related frameworks
    - Exception: Rio Bravo, good status

| Adaptive Capacity Indicators | THR. | Suquía, AR | SPMR, BR | Copiapó, CL | Rio Bravo, MX |
|---|---|---|---|---|---|
| Vegetation cover | 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 |

# Results

## The Overall Vulnerability Index

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




*Normalized VIs to a range from 0-100*

- *Min-max normalization process*
- *Threshold VI is set to 0*

- The Vulnerability status of the 4 areas
  - Most vulnerable area
    - Upper Tietê River Basin (SPMR, BR)
  - Least vulnerable area
    - Lower Rio Bravo Basin, MX
    - *But*
      - Water system conditions in the Lower Rio Bravo Basin are not satisfactory
        - The vulnerability status of the area surpasses the VI threshold significantly (~22%)

# Results

## Identification of WR&R Adaptation Strategies

- **Focus** on urban/domestic & agricultural WR&R applications
  - Affected indicators & *suggested changes*
    - Supply with reclaimed water
      - *10% supply was suggested*
    - *Legal framework related to WR&R*
      - *Appropriate arrangements for enhancement*
    - Treated WW as % of the available resources
      - *10% reduction in case of domestic recycling*
    - Governance of the WW treatment sector
      - *Appropriate arrangements for enhancement in case of domestic recycling*
    - WEI
      - *10% reduction*

- Combination of WR&R strategies with **additional interventions** to affect critical vulnerability indicators
  - Indicators with high weights in the VI equation & *suggested changes*
    - Water losses in the urban water distribution network
      - *10% reduction*
    - Irrigation dependence
      - *10% reduction the substitution of irrigated crops by rainfed crops*

# Results

## Assessment of WR&R Adaptation Strategies

| Percent reduction in the VI achieved through each strategy | | | | |
|---|---|---|---|---|
| **Study Sites** | **Strategy #1a**<br>Reuse of treated WW in domestic water uses & reduction of water losses | **Strategy #1b**<br>Recycling of domestic WW & reduction of water losses | **Strategy #2a**<br>Reuse of treated WW for irrigation | **Strategy #2b**<br>Reuse of treated WW for irrigation & change in crop patterns |
| **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%** |

# Conclusions

## The Study Site Areas

- All four areas are vulnerable
  - To a smaller or greater extent
    - Lower Rio Bravo RB, MX
    - Upper Tietê (SPMR) RB, BR
- *Suquía RB*
  - Poor capacity of natural & anthropogenic environment
- *Upper Tietê RB (SPMR)*
  - Interplay of the urban socio-economic setting & inadequate capacity to adapt
- *Copiapó RB*
  - Increased demand & poor management
- *Lower Rio Bravo RB*
  - Limited availability & rapid economic development

- Commonly faced challenges
  - Limited freshwater resources & overexploitation
- Intervention measures are needed for vulnerability mitigation
  - Strategies involving *domestic WR&R applications*
    - Suquía, Upper Tietê (SPMR) & Copiapó River Basins
  - Strategies involving *agricultural WR&R applications*
    - Lower Rio Bravo Basin

# Conclusions

## The Methodological Framework

- The **developed VI** facilitates
  - Comparison of the vulnerability status
  - Ranking & benchmarking of areas as to vulnerability threshold
  - Identification of appropriate & targeted interventions at the local level
- The selected **indicator scheme**
  - Reflects the complexity of the water resources systems & the multifaceted context of vulnerability
  - Can be further reviewed & adjusted to analyze different areas
- **Assessment results** are indicative & are used to illustrate the proposed method
  - Data gathering is still ongoing
  - The final result is dynamic & data-dependent
  - Results just provide input for further research
- The **adopted framework** can support decision making & planning processes to enable the implementation of suitable interventions
  - Combination with other analytical tools
    - Cost-benefit analysis, MCDA, etc.

# Acknowledgments

Data were provided by the Study Site partners of the

**EU-funded FP7 project COROADO:** "*Technologies for Water Recycling and Reuse in Latin American Context: Assessment, Decision Tools and Implementable Strategies under an Uncertain Future*" (Grant agreement No: 283025)

Thank you for your attention!

# Back-up slides

# Step 1: Vulnerability Assessment

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

- Benchmark values indicating acceptable conditions & standards
  - Critical values already proposed in the literature
  - World mean values
  - Estimates based on prevailing conditions (indicators concerning WR&R interventions)

**Sub-step 1b: Normalization of indicator values**

- High indicator values should indicate higher exposure, sensitivity or adaptive capacity aspects
- Quantitative indicators
  - Values were normalized as ratios of their respective thresholds
    - Threshold values equal to 1
    - Indicator values range from 0 to 5 (5: cut-off value)
- Qualitative indicators
  - Based on expert judgment using a scale from 1 to 5
    - Threshold values equal to 3
    - Indicator values range from 1 to 5

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

- Identification of the indicators which contribute to vulnerability
  - Exposure & sensitivity indicators with values above the threshold of 1
  - Adaptive capacity indicators with values below the thresholds (1 for quantitative & 3 for qualitative indicators)

# Step 2: Vulnerability Mitigation

**Sub-step 2a: Assignment of weights to vulnerability indicators**

- Weighting scheme: **Principal Component Analysis (PCA)**
  - Indicator weights were assumed to be the sum of products of the coefficients of the most significant PCs
    - PCs with eigenvalues greater than one (Kaiser criterion)
      - In essence this is like saying that, unless a component extracts at least as much as the equivalent of one original variable, we drop it. This criterion was proposed by Kaiser (1960), and is probably the one most widely used.

**Sub-step 2b: Development of the Overall Vulnerability Index (VI)**

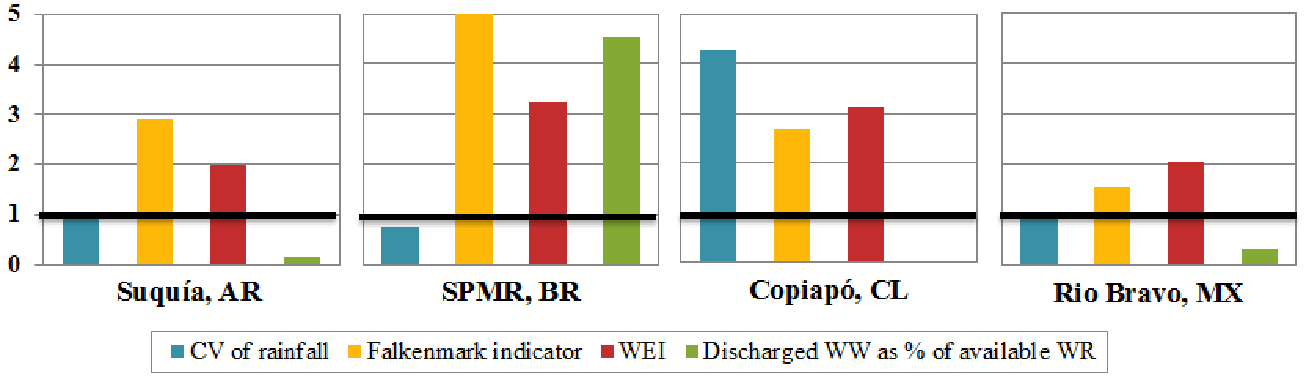
- Expressed as the weighted sum of the indicator values
  - $\boldsymbol{V = \sum w_i \times x_i}$
    - $w_i$: the calculated weights by the PCA
    - $x_i$: the standardized indicator values
  - Retention of:
    - Exposure & sensitivity indicators with positive weights
    - Adaptive capacity indicators with negative weights
- Threshold VI calculated based on the threshold values

# The Study Site Areas (1/2)

- ***The Suquía River Basin (Argentina)***
  - Semi-arid region of the Córdoba province
  - Limited freshwater availability & water quality deterioration
    - Prolonged droughts & floods, uncontrolled urban expansion, land-use changes, insufficient infrastructure capacity, strong population growth
- ***The Upper Tietê River Basin (Brazil)***
  - São Paulo Metropolitan Region (SPMR)
  - Intense water demand & severe contamination of water bodies
    - Rapid urban sprawl, industrial growth, unregulated land use
- ***The Copiapó River Basin (Chile)***
  - Atacama Desert of Chile
  - Water scarcity conditions & competition over water supply
    - Uncontrolled trade of water rights, increased demand of the agricultural & mining sectors
- ***The Lower Rio Bravo/Grande Basin (Mexico)***
  - Easternmost part of the USA-Mexico border
  - Complex water management & distribution issues
    - Drought events, overlapping jurisdictions & frequent conflicts between the agricultural sector and the rapidly growing industry

# Results

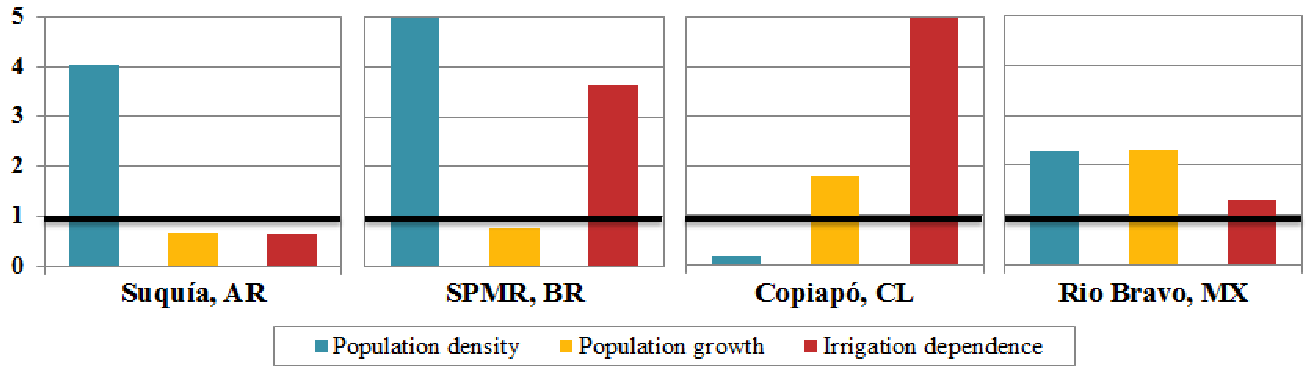
## Vulnerability Profiles – Exposure Indicators




- **Suquía River Basin, Argentina**
  - Intense water scarcity conditions (584 $m^3$/cap/yr.)
  - Overexploitation of available resources (WEI 79%)
- **Upper Tietê River Basin, Brazil**
  - Absolute water scarcity – critical conditions of water resources in the area (135 $m^3$/cap/yr.)
  - Water used exceeds locally available resources by 30%
  - Severe contamination of receiving water bodies (untreated WW discharge 45% of available water resources)
- **Copiapó River Basin, Chile**
  - High temporal variation of rainfall – low reliability of available resources
  - Water stress conditions & strong competition for water (WEI 125%)
- **Lower Rio Bravo/Grande Basin, Mexico**
  - Water stress conditions (1,094 $m^3$ /cap/yr.)
  - Overexploitation of available resources (WEI=82%)

# Results

## Vulnerability Profiles – Sensitivity Indicators




- **Suquía River Basin, Argentina**
  - High population density (221 inh/km²)
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  - Dependence of agricultural production to irrigation (53% of cultivated land is irrigated)

# Results

## Assessment of WR&R Adaptation Strategies

| Strategy | Description |
|---|---|
| ***1. Domestic WR&R applications*** | |
| Strategy #1a: Reuse of treated WW in domestic water uses | • 10% supply with reclaimed water (corresponding reduction of WEI)<br>• Enhancement of legal framework related to WR&R<br>• 10% reduction of water losses in the urban water distribution network |
| Strategy #1b: Recycling of domestic wastewater | • 10% supply of domestic uses through the recycling of domestic WW (corresponding reduction of WEI & of the untreated WW discharge);<br>• Enhancement of the governance of WW treatment sector;<br>• All other aspects as in Strategy #1a. |
| ***2. Agricultural WR&R applications*** | |
| Strategy #2a: Reuse of treated WW for irrigation | • 10% supply with reclaimed water (corresponding reduction of the WEI)<br>• Enhancement of legal framework related to WR&R |
| Strategy #2b: Reuse of treated WW for irrigation & change in crop patterns | • 10% reduction of the irrigation dependence (substitution of irrigated crops by rainfed crops)<br>• All other aspects as in Strategy #2a |

| **Percent reduction in the VI achieved through each strategy** | | | | |
|---|---|---|---|---|
| **Study Sites** | Strategy #1a | Strategy #1b | Strategy #2a | Strategy #2b |
| | Strategy #1a: Reuse of treated WW in domestic water uses | Strategy #1b: Recycling of domestic wastewater | Strategy #2a: Reuse of treated WW for irrigation | Strategy #2b: Reuse of treated WW for irrigation & change in crop patterns |
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