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Megan C. Marcellin, University of Virginia

Risk and Systems Analysis for Renewable Power Generation with Environmental and Other Stressors

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The opinions expressed herein are of the authors alone, and not necessarily the opinions of any government agency.

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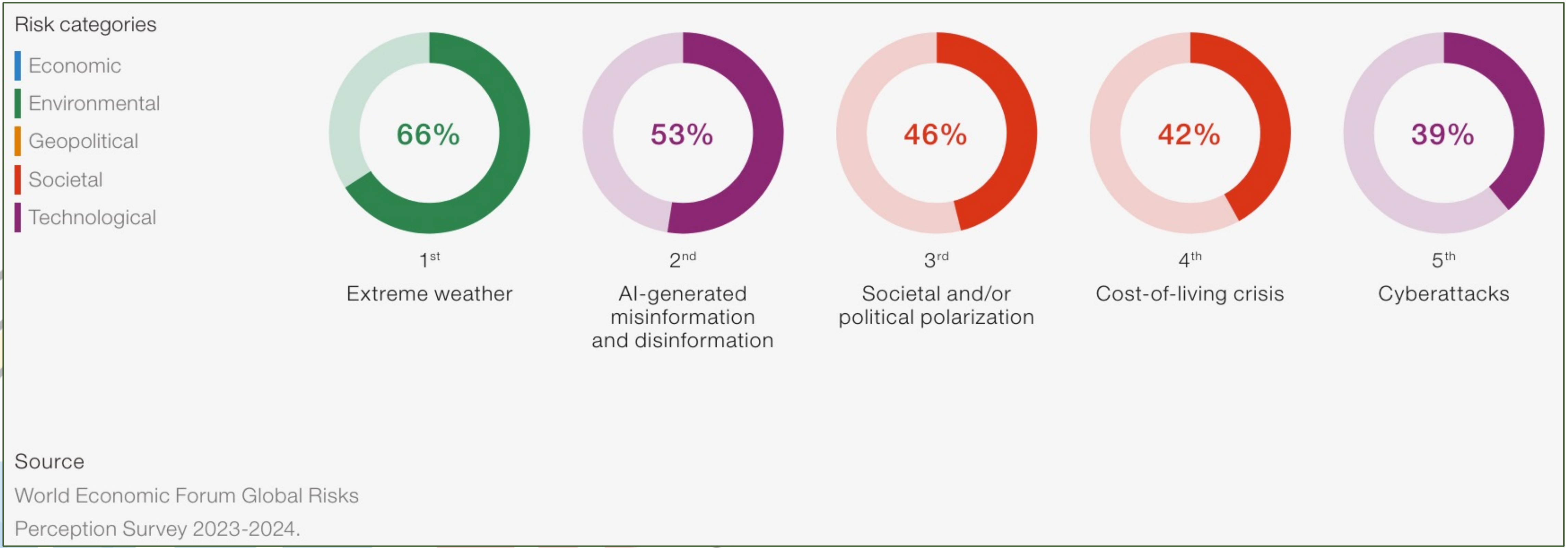
Introduction and Motivation

Current risk landscape,
World Economic Forum 2024

"Please select up to five risks that you believe are most likely to present a material crisis on a global scale in 2024."



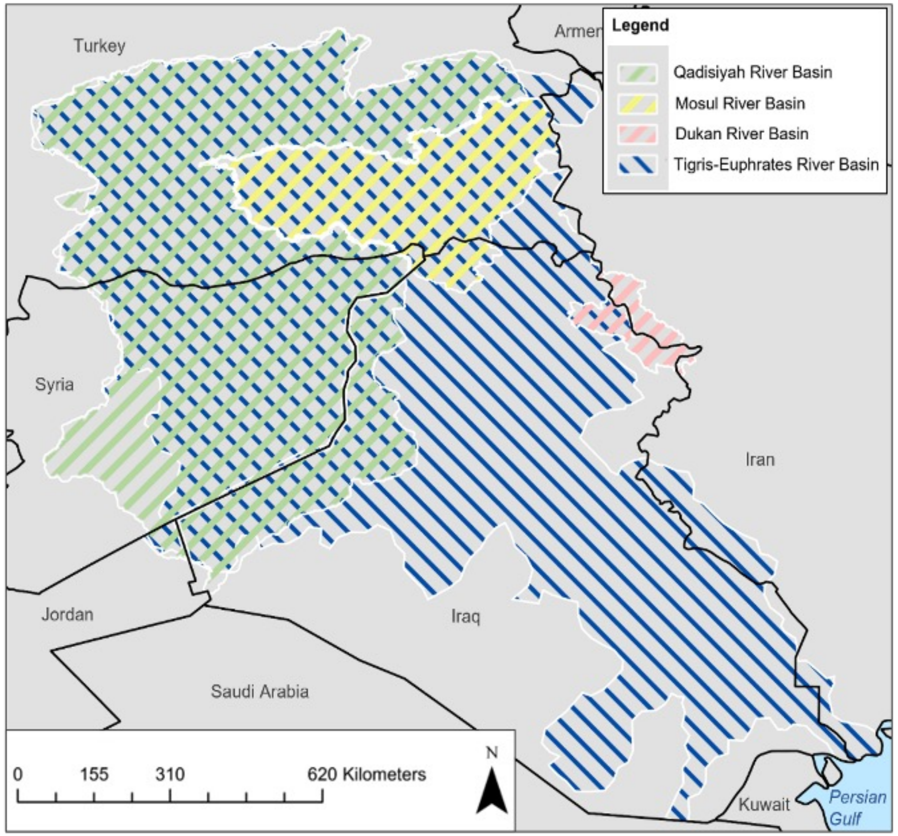
Long-term expected severity, World Economic Forum 2024

10 years

1st	Extreme weather events
2nd	Critical change to Earth systems
3rd	Biodiversity loss and ecosystem collapse
4th	Natural resource shortages
5th	Misinformation and disinformation
6th	Adverse outcomes of AI technologies
7th	Involuntary migration
8th	Cyber insecurity
9th	Societal polarization
10th	Pollution

Water insecurity in arid climates

- Water scarcity is endemic globally (UN 2023)
- Growing water crisis is fueled by climate change and socio-technical factors
  - Diminished precipitation, excessive heat, poor water quality, population increase, old and damaged infrastructure
- Iraq: 5th most vulnerable country to water, climate, and environmental insecurity (IOM 2022)
- Shortages are exacerbated by transboundary river reliance
  - Dam building and increased storage by upstream neighbors (Turkey GAP project)
  - 40% reduction in Euphrates River levels post-2000



Oil production and water resources

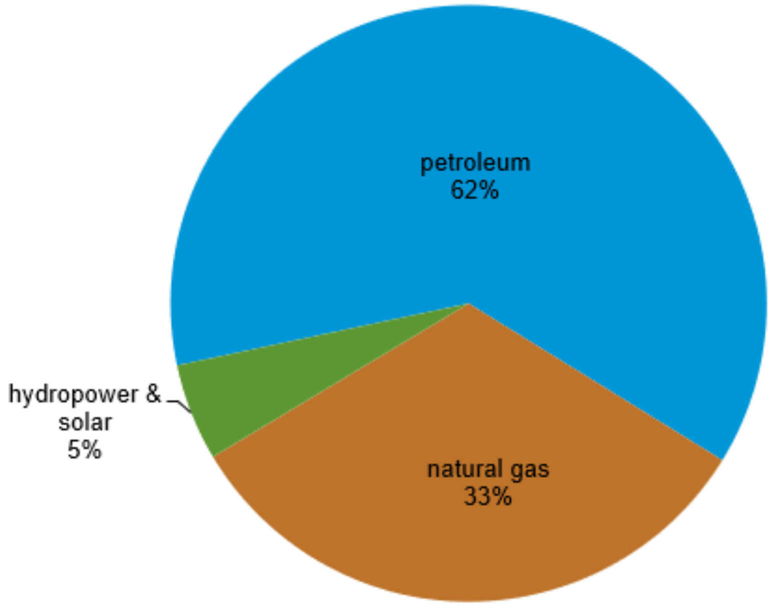
- Many MENA nations rely on oil production and export revenues
- Oil production is water intensive – 1.5 barrels of water per barrel of oil
- Oil production contributes to environmental deterioration and natural resource scarcity

Iraq's oil boom blamed for worsening water crisis in drought-hit south, The Guardian UK (2023)

Shifts towards renewable energy

- Investments in renewable energy (hydro, solar)in the region have been slow due to COVID-19 pandemic and lack of funding
  - Decrease in oil price during pandemic reduced government revenue
- Hydropower and solar are not immune to climate change effects – investment planning should be climate risk-informed

Figure 2. Iraq's total primary energy consumption, share by fuel, 2021



Data source: U.S. Energy Information Administration, *International Energy Statistics*
Note: Chart does not include traditional biomass and waste, such as burning firewood and waste.

Research goals

- **Motivation**:
  - Evaluate climate and natural resource risks to renewable energy system investment and growth

- **Methodology**:
  - Prioritize assets using a multi-criteria analysis framework
  - Score assets against markers of hydrological health, in addition to traditional criteria
  - Assess scenario impacts on assets, projects, and policies to quantify risk and identify opportunities to build resilience

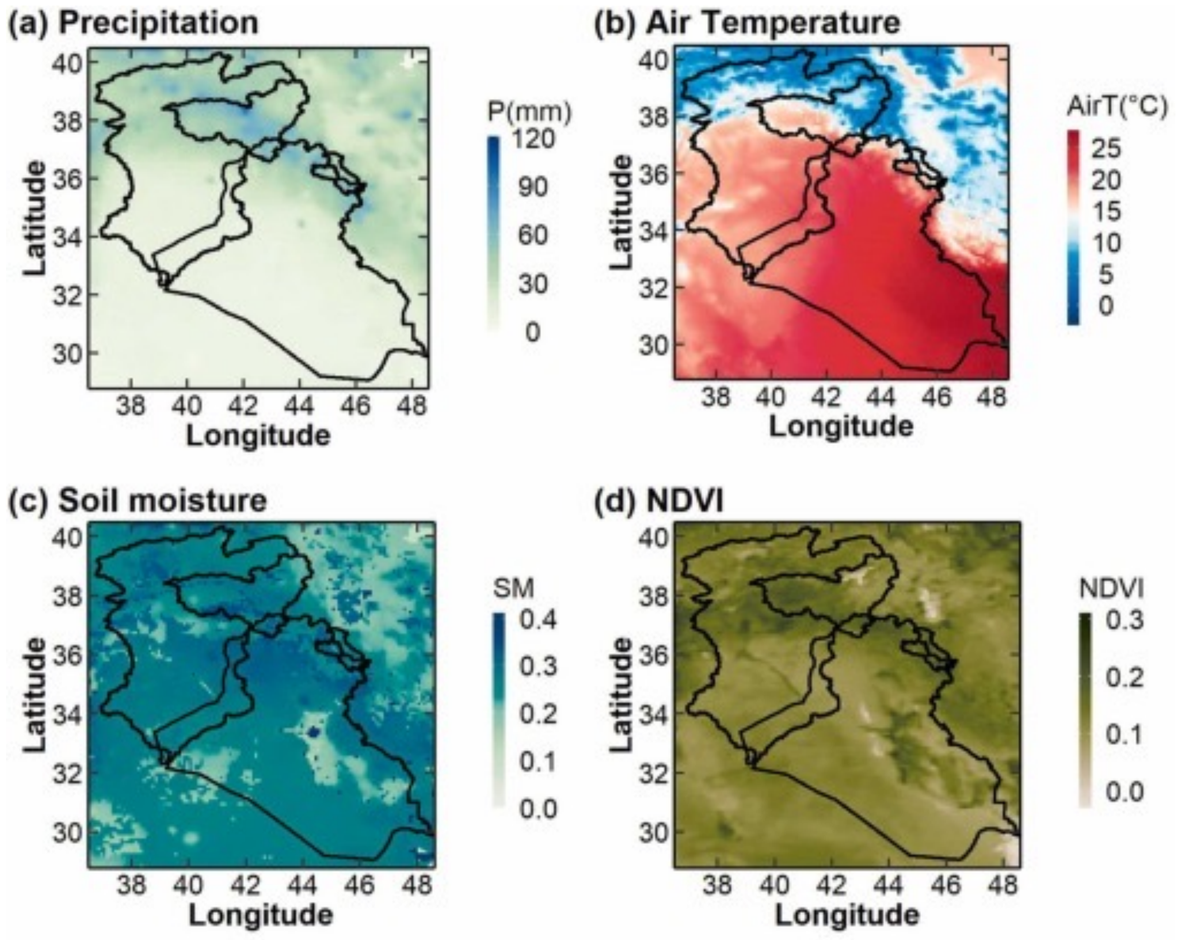
- **Outcomes:**
  - Identify the most disruptive scenarios to system priorities
  - Highlight infrastructure investments resilient to climate and other stressors
  - Build Microsoft Excel software tool for on-the-ground users

Hydrology Analysis

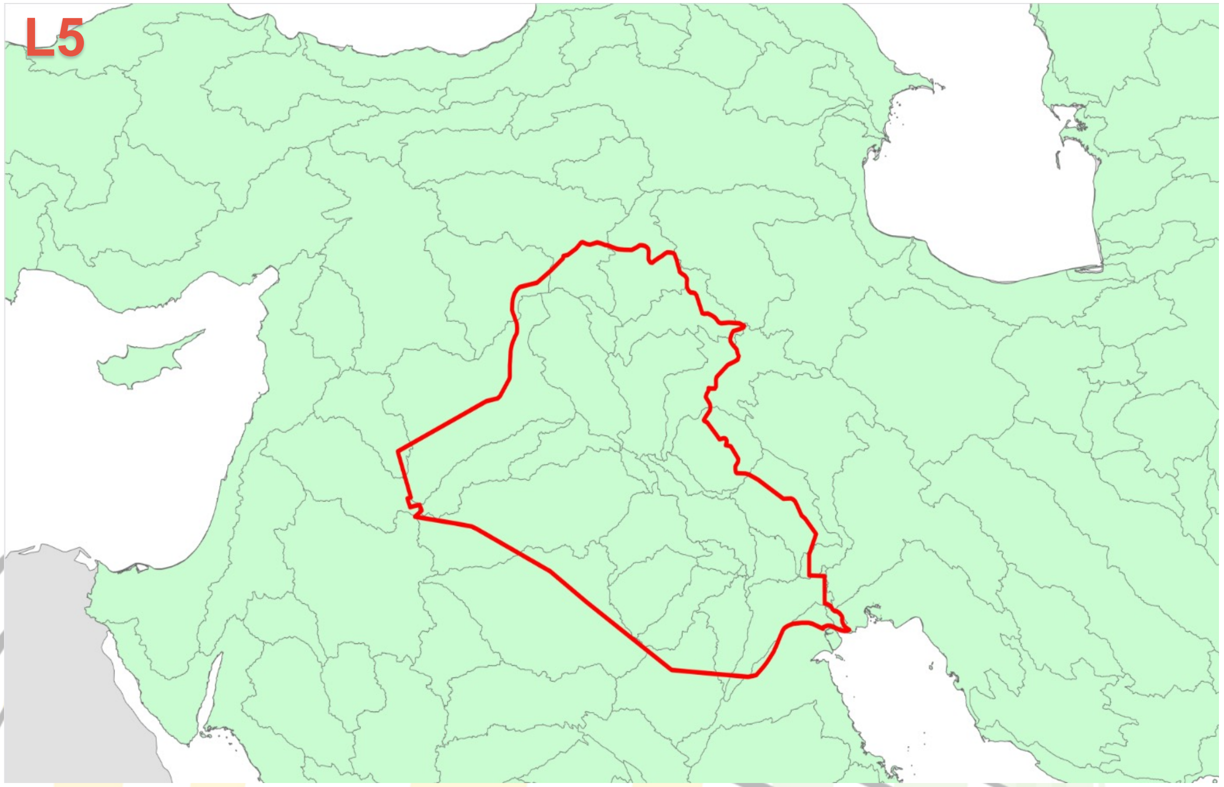
Satellite remote-sensing hydrology

- **Motivation**:
  - What: Spatial and temporal metrics
  - Where: Iraq and contributing basins
  - When: 2001 – 2022
  - Why: in-situ observations unavailable/unreliable

- **Methodology**:
  - Satellite observations and model outputs for:
    - 1. Precipitation
    - 2. Air Temperature
    - 3. Root Zone Soil Moisture (0 – 2 m)
    - 4. NDVI
    - 5. Etc…



HydroBASINS

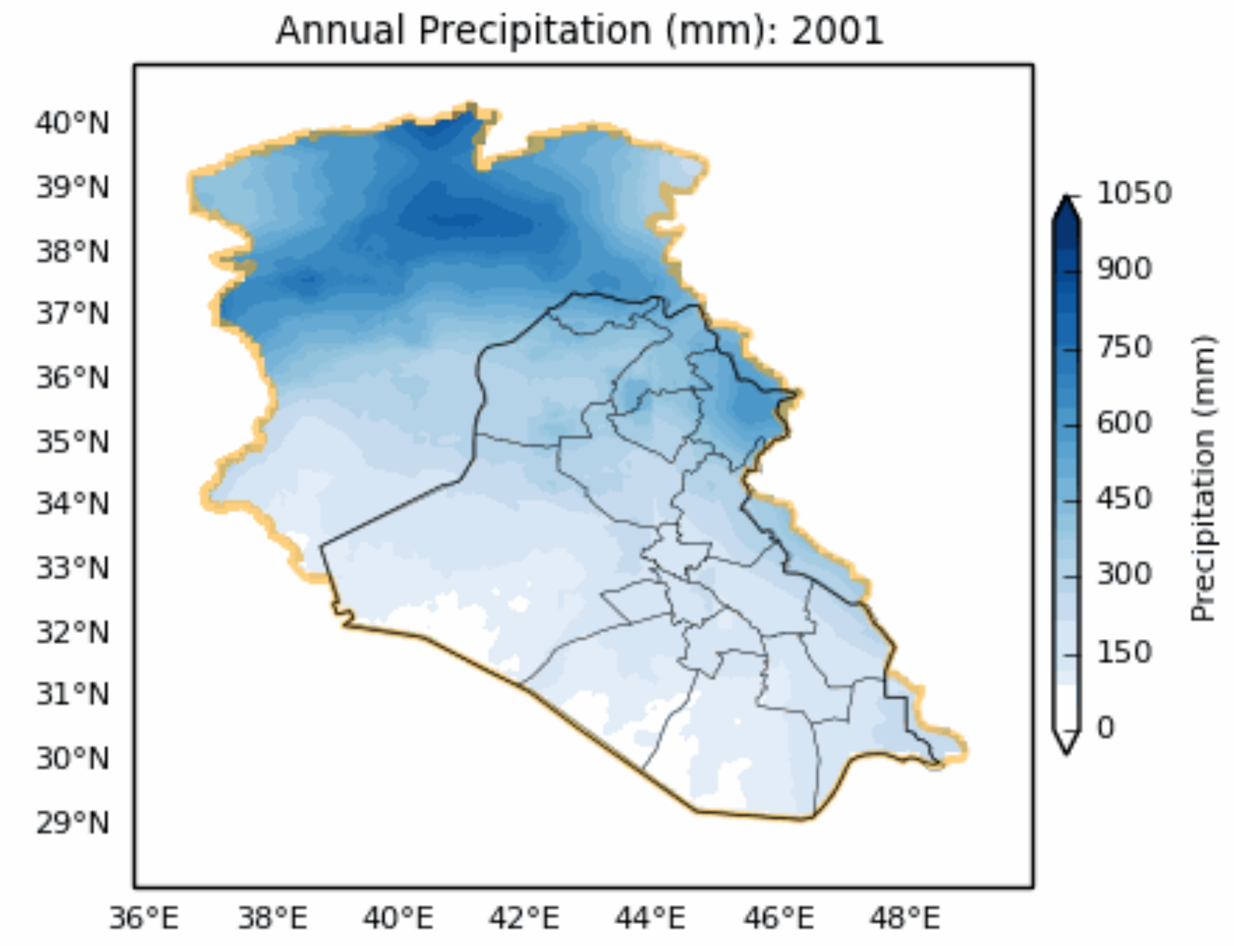


Number of divisions in Iraq	31
Max. area (sq. km)	99750.9
Min area (sq. km)	16.2
Avg. area (sq. km)	27564.6
Median area (sq. km)	20562.2
Max GPM pixels per boundary	997.509
Min GPM pixels per boundary	0.162
Avg. GPM pixels per boundary	275.646
Median GPM pixels	205.622
max NDVI modis pixels	199501.8
min NDVI modis pixels	32.4
avg. NDVI modis pixels	55129.2
median NDVI modis pixels	41124.4
max GLDAS pixels	159.6014
min GLDAS pixels	0.02592
avg. GLDAS pixels	44.10336
median GLDAS pixels	32.89952

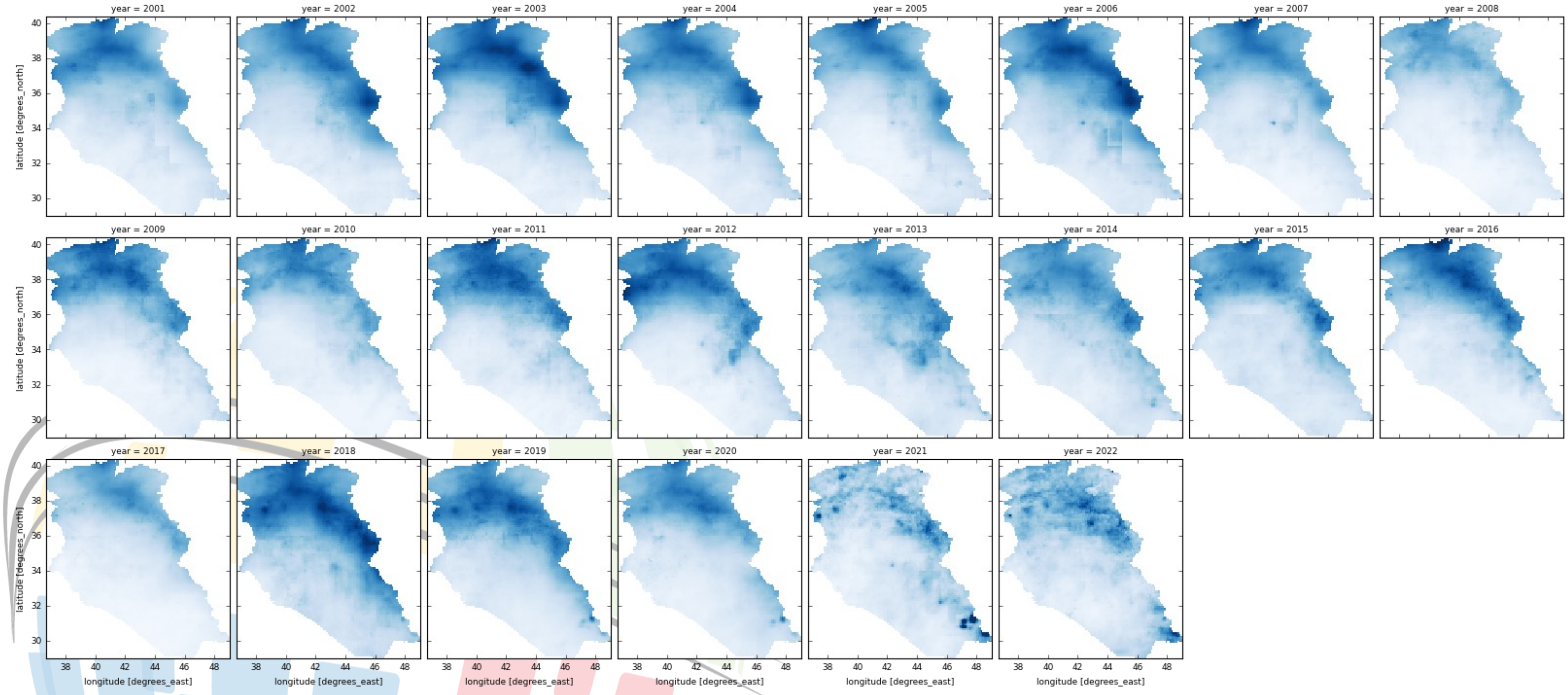
HydroBASINS Source: https://www.hydrosheds.org/products/hydrobasins#:~:text=HydroBASINS%20represents%20a%20series%20of,boundaries%20at%20a%20global%20scale.

Spatial plots: annual average precipitation

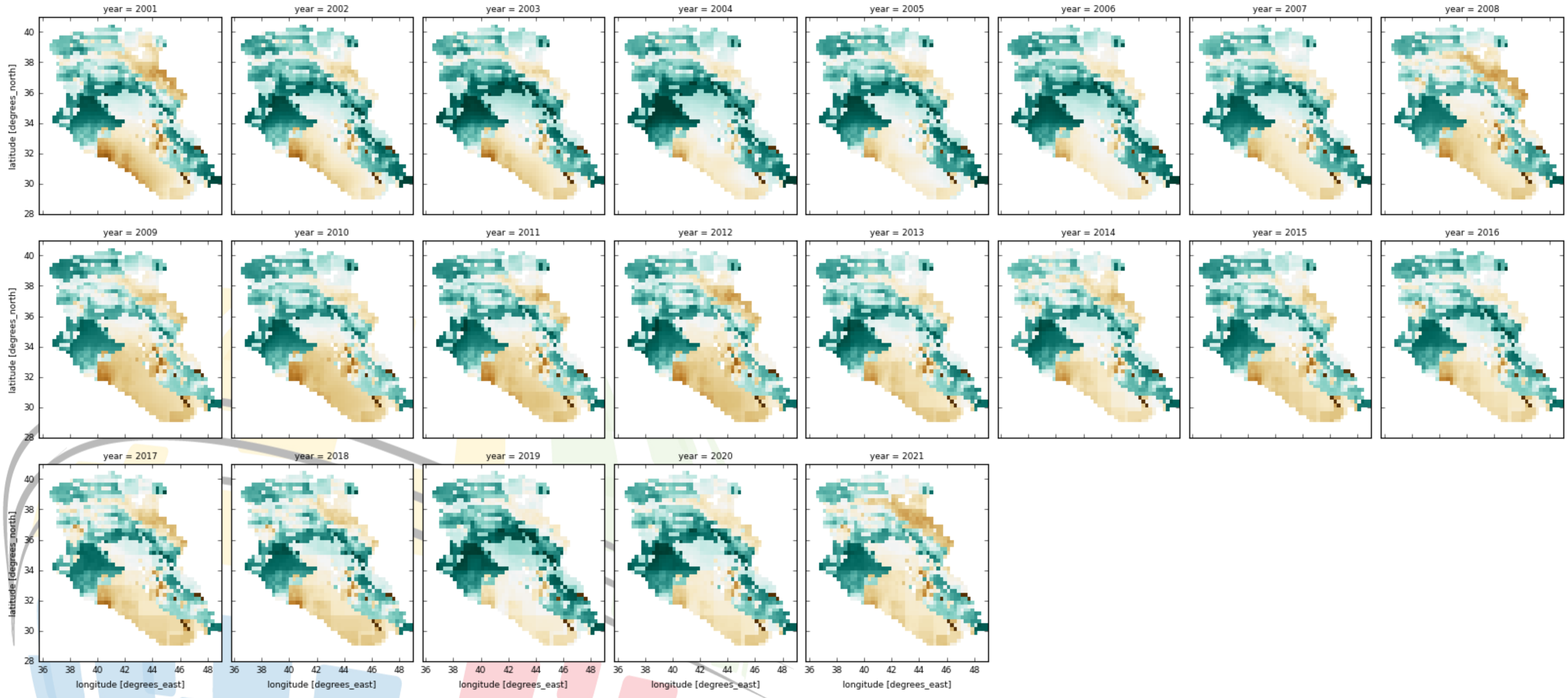
- Study Area
- Iraq Border
- Iraq Province Borders



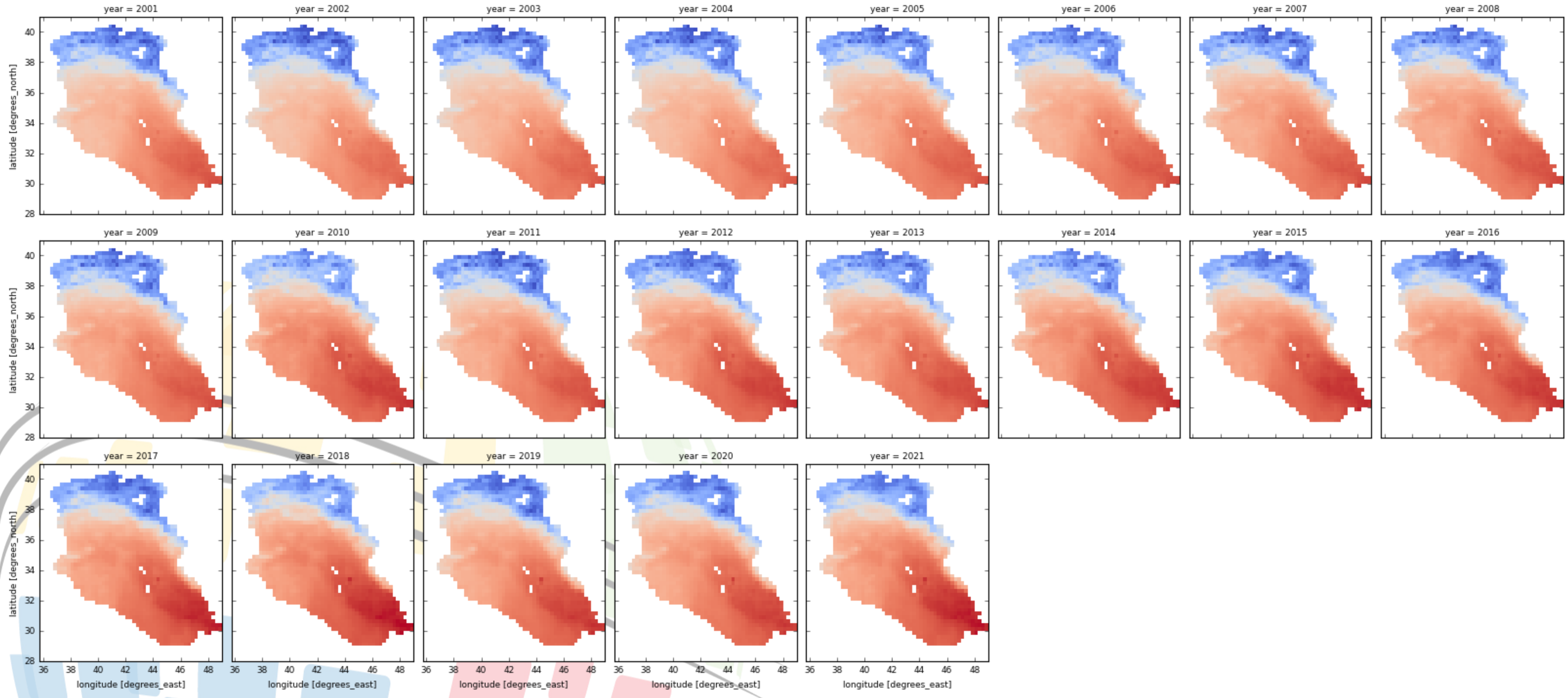
Spatial plots: annual average precipitation



Spatial plots: soil moisture



Spatial plots: annual average air temperature



Risk and Systems Analysis Methods

How do we define risk to a system?

The influence of scenarios to *system orders*

Lambert et al. (2024, 2023, 2021, 2019), Marcellin et al. (2024), Moghadasi et al. (2024, 2023), Loose et al. (2022)

The effect of uncertainty on objectives

ISO 31000 (2018)

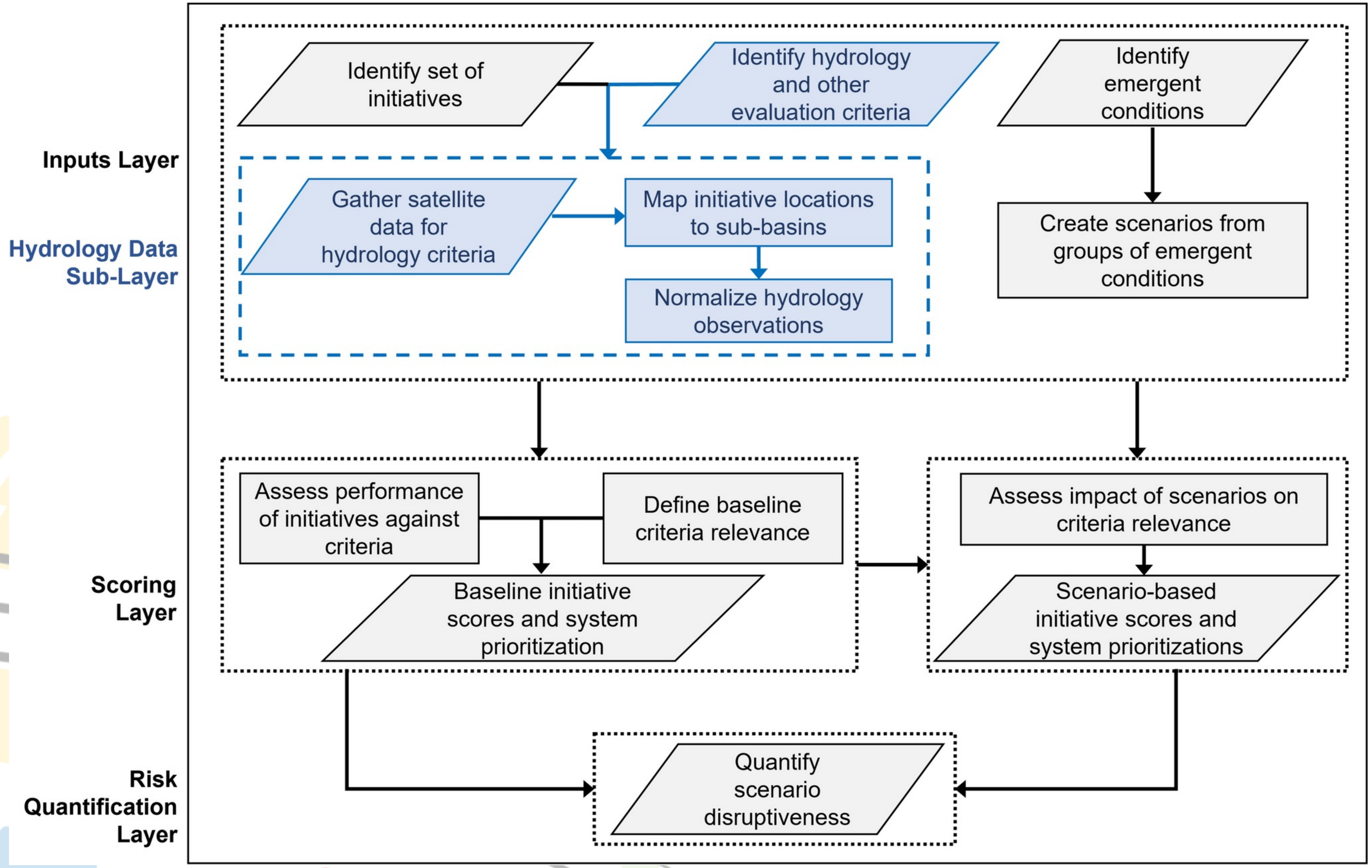
What can go wrong, what are the likelihoods, what are the consequences

Kaplan and Garrick (1981)

Measure of the probability and severity of adverse effects

Lowrance, *Of Acceptable Risk* (1976)

Scenario-based preferences model for risk analysis



Marcellin, M.C., Pavur, G., Loose, D.C. et al. Systems analysis for energy assets of Iraq influenced by water scarcity. Environ Syst Decis (2024). https://doi.org/10.1007/s10669-024-09967-w

Model input sets

- Success criteria (system goals, success metrics)
  - Including hydrological measures

- Initiatives (system assets, projects)

- Potential conditions → Scenarios (potential threats, opportunities)

Model scoring methods

1. Determine relative importance of each system success criterion
2. Assess the extent to which each initiative achieves or promotes each criterion
3. Baseline initiative scores: weighted sum of criteria weights and initiative scores
4. Assess how each scenario shifts the relative importance of each criterion
5. Scenario-based initiative scores: weighted sum of shifted criteria weights and initiative scores

Model outputs

- Baseline ordering of system initiatives (1, 2, …, n)
- Scenario-based orderings of system initiatives
- Scenario risk scores: level of disruption to system order induced by each scenario

Case Study of Renewable Energy Investment for Iraq

Demonstration

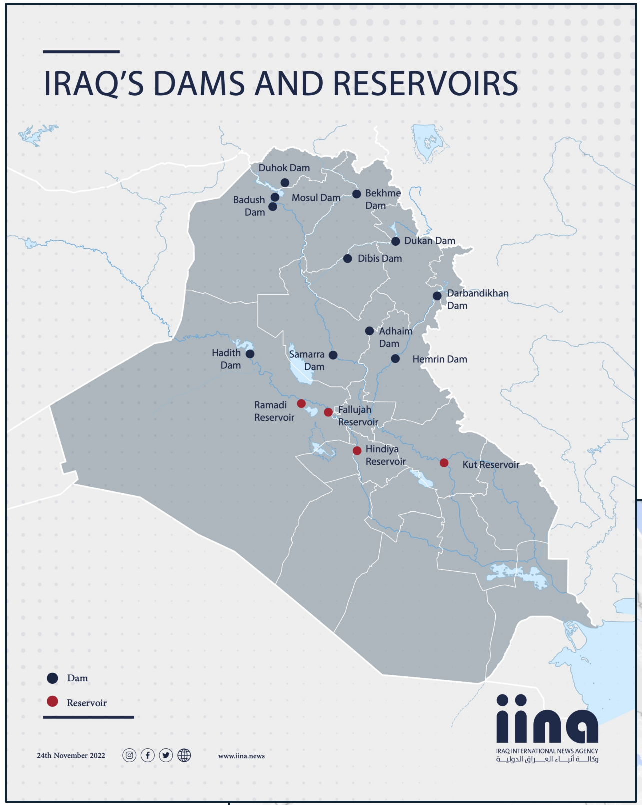
System success criteria

- Represent goals, values, or features of a successful system
- Criteria are gathered from national development goals, agency reports, and expert feedback
- Hydrology criteria assess hydrological health at system asset locations
- Numerical weights (1: low, 2: medium, 4: high) represent relative criteria importance

Criterion	Baseline Weight
Sustainability	4
Social Equity	4
Adaptability	2
Mitigation	2
Manage Transitions	4
Affordability	2
Harm Reduction	2
Economic Development	2
Annual Precipitation	1
Soil Moisture	1
Air Temperature	1
Vegetative Health	1
Monthly Low Precipitation	1

System initiatives

- Assets, projects, technologies, or policies comprising the system
- Renewable energy production:
  - Hydropower dams
  - Solar PV investments
- Initiatives are scored and ordered based on their relationship to performance criteria



Images: IINA, Global Energy Monitor

Criteria-initiative assessment

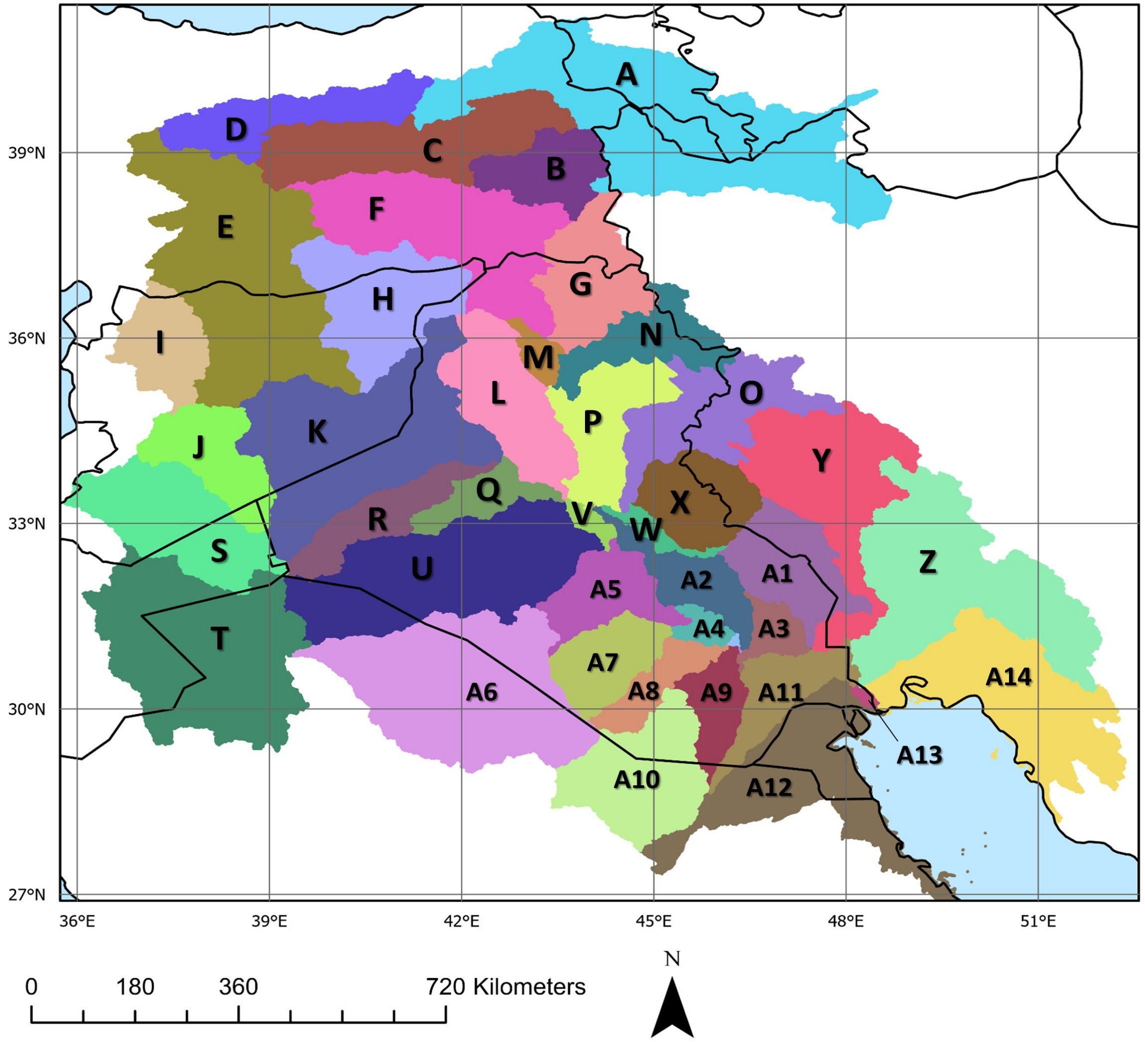
	c.01 – Sustainability	c.02 - Social Equity	c.03 - Adaptability	c.04 - Mitigation	c.05 - Manage Transitions	c.06 - Affordability	c.07 - Harm Reduction	c.08 - Economic Development	c.09 - Annual Precipitation	c.10 - Soil Moisture	c.11 - Air Temperature	c.12 - Vegetative Health	c.13 - Monthly Low Precipitation
x.01 - Mosul Dam Hydropower	○	○	○	◐	○	○	○	●	●	○	●	●	
x.02 - Mosul Regulation Dam	○	○	○	◐	○	○	○	○	●	○	●	●	
x.03 - Mosul Pumped Storage	○	○	○	◐	○	○	○	◐	●	○	●	●	
x.04 - Samarra Barrage Hydropower	◐	○	○	◐	○	◐	◐	○	○	○	○	◐	◐
x.05 - Haditha Dam Hydropower	◐	○	○	◐	○	◐	◐	●		●	○		
x.06 - Hemrin Dam Hydropower	◐	○	○	◐	○	◐	◐	○	◐	○	◐	●	●
x.07 - Kufa Hydropower	◐	○	○	◐	○	◐	◐					◐	
x.08 - Al-Hindyia Old Barrage Hydropower	◐	○	○	◐	○	◐	◐					◐	
x.09 - Badush Dam Hydropower	◐	○	○	◐	○		◐	◐	●	○	●	●	
x.10 - Masdar Ramadi Solar Project	●	◐		●	●	◐	●	●			○	○	

Symbolic Scoring

How well does the initiative achieve or promote the goal of each criterion?

***Very well:* ● (score = 1)**
***Well:* ◐ (2/3)**
***Somewhat:* ○ (1/3)**
***Not at all: (blank)* (0)**

Hydrology criteria-initiative assessment



Basin Identification Numbers:

A	2050643500	U	2050785890
B	2050085990	V	2050785900
C	2050668200	W	2050784800
D	2050668190	X	2050784690
E	2050737850	Y	2050816870
F	2050723850	Z	2050828790
G	2050723860	A1	2050816320
H	2050737750	A2	2050784800
I	2050086110	A3	2050816390
J	2050086070	A4	2050816600
K	2050759640	A5	2050810010
L	2050770040	A6	2050085850
M	2050735750	A7	2050810230
N	2050735780	A8	2050815450
O	2050773470	A9	2050816590
P	2050773460	A10	2050086550
Q	2050770120	A11	2050828780
R	2050759680	A12	2050073580
S	2050085860	A13	2050073570
T	2050085900	A14	2050072930

Hydrology criteria-initiative assessment

			Annual Precipitation mm/year (2018-2022 average)	Annual Precipitation Scaled Score	Annual Precipitation Scaled Score Bin (1, 2, 3, 4)
	Max Value of initiative set:		639.88		
	Min Value of initiative set:		142.38		
Index	**Initiative**	**L5 Basin Number**			
1	Mosul Dam Hydropower	2050723850	639.88	100	4
2	Mosul Regulation Dam	2050723850	639.88	100	4
3	Mosul Pumped Storage	2050723850	639.88	100	4
4	Samarra Barrage Hydropower	2050773460	349.00	42	2
5	Haditha Dam Hydropower	2050759640	197.15	11	1
6	Hemrin Dam Hydropower	2050773470	468.30	66	3
7	Kufa Hydropower	2050810010	163.66	4	1
8	Al-Hindyia Old Barrage Hydropower	2050785900	215.42	15	1
9	Badush Dam Hydropower (unfinished)	20507238			4
10	Masdar Ramadi Solar Project	20507701			1
11	Masdar Dhi Qar Solar Project	20508176			1
12	Masdar Mosul Solar Project	20507238			4
13	Masdar Amarah Solar Project	20508163			3
14	PowerChina Al-Muthanna Solar Project	2050815450			1
15	Al-Bilal Iskandariya Solar Project	2050785900			1
16	Al-Bilal Karbala Solar Project	2050785890			1
17	Jissan Solar Project (bidded)	2050784800	282.40	28	2
18	Khidir Solar Project (bidded)	2050815340	190.34	10	1
19	Sawa Solar Project (bidded)	2050815340	190.34	10	1
20	Al Diwaniyah Solar Project (bidded)	2050817690	252.14	22	1
21	ACWA Najaf Solar Project	2050810010	163.66	4	1
22	TotalEnergies SE Artawi Solar Project	2050828780	260.80	24	1
23	United Energy Group Siba Solar Project	2050073570	408.93	54	3
24	Adhaim Dam Hydropower (unfinished)	2050773460	349.00	42	2
25	Government building rooftop solar (Baghdad)	2050773460	349.00	42	2

Map initiative location to basin number

Collect hydrology observation

Normalize set of observations on 0 (“worst”)-100 (“best”) scale

$$= 100 \times \frac{x - x_{min}}{x_{max} - x_{min}}$$

Assign “bin” 1 (lowest) to 4 (highest)

Bin-Score Mapping
4: ●
3: ◐
2: ○
1: *(blank)*

Baseline system order

$$V(x_i)_b = \sum_{j=1}^{a} w_{jb} x_{ij}\,, \forall i \in X$$

where w_{jb} is the baseline weight of criterion c_j,
and x_{ij} is the criteria-initiative assessment score of initiative x_i for criterion c_j

If $V(x_i)_b > V(x_j)_b$ then $x_i \succ x_j$

Risk scenarios

Index	Scenario
s.01	*Drought and desertification*
s.02	*Prolonged heatwave*
s.03	*Decrease in transboundary flows*
s.04	*Increase in electricity demand*
s.05	*Sociotechnical disruption*
s.06	*Economic stress*
s.07	*Infrastructure damage or failure*

Climate and other scenarios identified for risk analysis of renewable power system

Criteria-scenario assessment

- Risk is the influence of scenarios on priorities…how do scenarios affect stakeholder values (criteria weights)?
  - Increase, decrease, remain the same?

Criteria-scenario assessment

- Adjust criteria weights up (multiplier > 1), down (multiplier between 0 and 1), or none (no change)

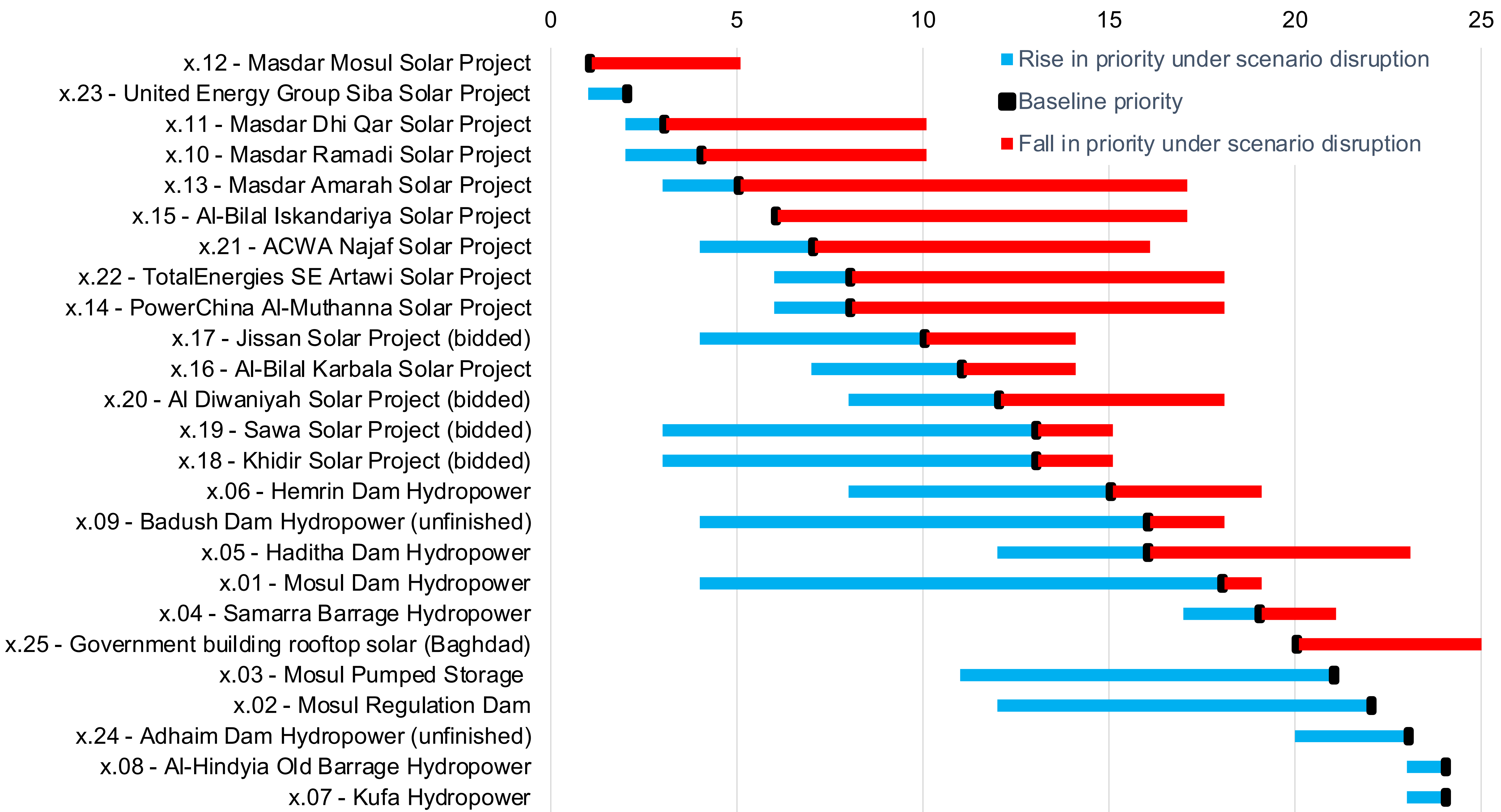
p.01 Iraqi Stakeholders	s.01 - Drought and desertification	s.02 - Prolonged heatwave	s.03 - Decrease in transboundary inflows	s.04 - Increase in electricity demand	s.05 - Sociotechnical disruption	s.06 - Economic stress	s.07 - Infrastructure damage or failure
c.01 - Sustainability	Increases Slightly	-	Increases Slightly	Increases Slightly	-	-	-
c.02 - Social Equity	Increases	Increases Slightly	Increases	Increases Slightly	Increases Slightly	-	Increases
c.03 - Adaptability	Increases	Increases Slightly	Increases	-	Increases Slightly	-	Increases Slightly
c.04 - Mitigation	Increases Slightly	-	-	Increases	Decreases Slightly	Decreases Slightly	Decreases
c.05 - Manage Transitions	-	-	Increases Slightly	Increases	Increases	Increases Slightly	-
c.06 - Affordability	Decreases Slightly	-	-	Decreases Slightly	Decreases Slightly	Increases Slightly	Decreases
c.07 - Harm Reduction	Increases Slightly	Increases Slightly	Increases Slightly	-	-	-	Increases
c.08 - Economic Development	-	-	Increases Slightly	Increases	Increases Slightly	Increases	-
c.09 - Annual Precipitation	Increases	Increases Slightly	Increases	Increases	Increases	Increases Slightly	Increases Slightly
c.10 - Soil Moisture	Increases	Increases Slightly	Increases Slightly	Increases Slightly	-	-	Increases Slightly
c.11 - Air Temperature	-	Increases	-	Increases	Increases Slightly	Increases	Increases
c.12 - Vegetative Health	Increases Slightly	-	Increases Slightly	-	-	-	-
c.13 - Monthly Low Precipitation	Increases	-	Increases	Increases Slightly	Increases Slightly	Increases Slightly	Increases Slightly

Scenario-disrupted system orders

$$V(x_i)_k = \sum_{j=1}^{a} w_{jk} x_{ij} \, , \forall i \in X, k \in S$$

where w_{jk} is the weight of criterion c_j for scenario s_k,
and x_{ij} is the criteria-initiative assessment score of initiative x_i for criterion c_j

If $V(x_i)_k > V(x_j)_k$ then $x_i \succ x_j$


0
5
10
15
20
25
x.12 - Masdar Mosul Solar Project
x.23 - United Energy Group Siba Solar Project
x.11 - Masdar Dhi Qar Solar Project
x.10 - Masdar Ramadi Solar Project
x.13 - Masdar Amarah Solar Project
x.15 - Al-Bilal Iskandariya Solar Project
x.21 - ACWA Najaf Solar Project
x.22 - TotalEnergies SE Artawi Solar Project
x.14 - PowerChina Al-Muthanna Solar Project
x.17 - Jissan Solar Project (bidded)
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x.01 - Mosul Dam Hydropower
x.04 - Samarra Barrage Hydropower
x.25 - Government building rooftop solar (Baghdad)
x.03 - Mosul Pumped Storage
x.02 - Mosul Regulation Dam
x.24 - Adhaim Dam Hydropower (unfinished)
x.08 - Al-Hindyia Old Barrage Hydropower
x.07 - Kufa Hydropower
Rise in priority under scenario disruption
Baseline priority
Fall in priority under scenario disruption

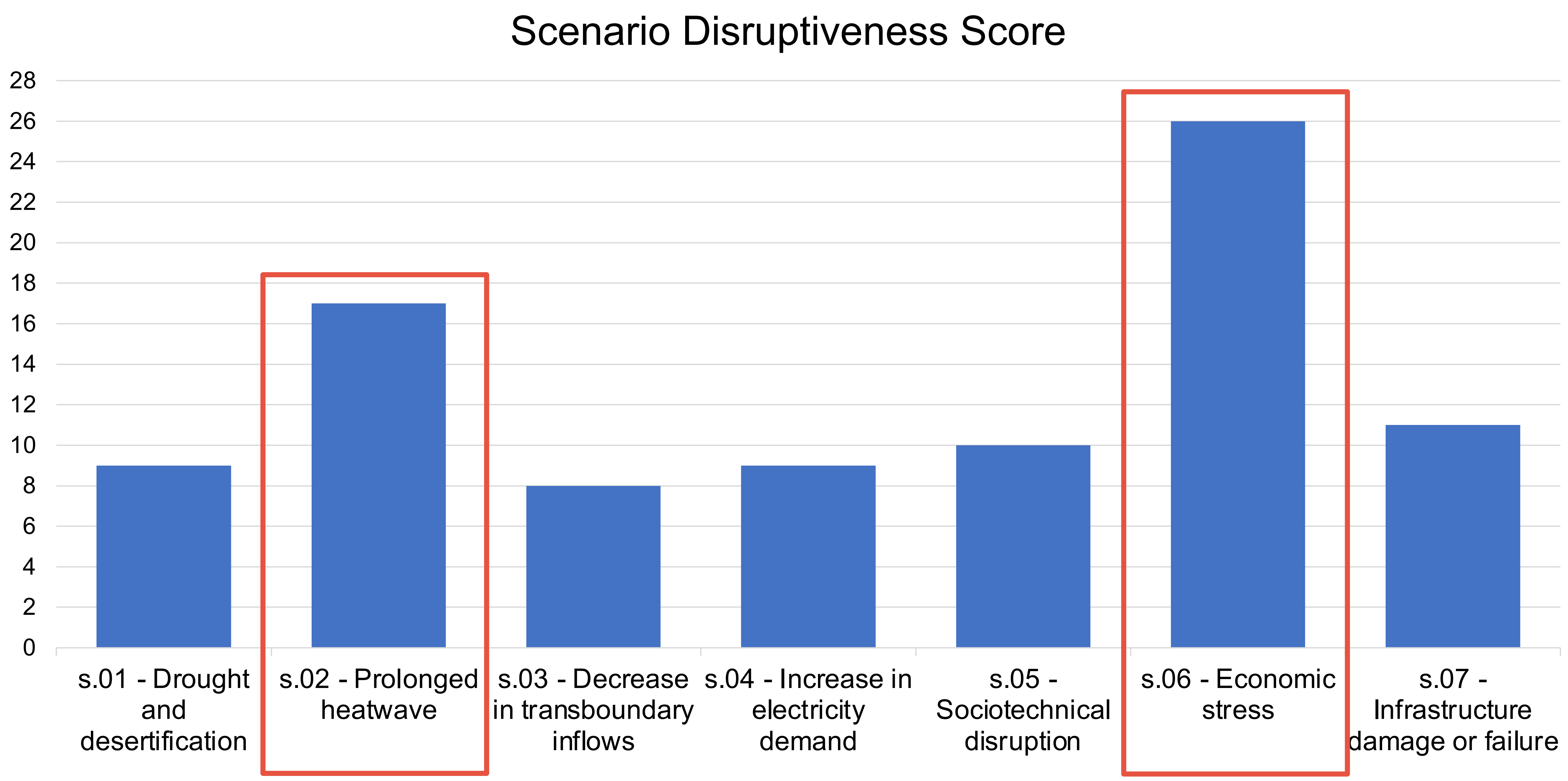
Risk quantification

- The disruptiveness score of a scenario represents the magnitude of system order disruption from baseline:

$$D(s_k) = \sum_{i=1}^{n} (R(x_i)_b - R(x_i)_k)^2$$

- Risk to the system is defined as the level of disruption to system order

- High disruptiveness score → higher level of risk to the system

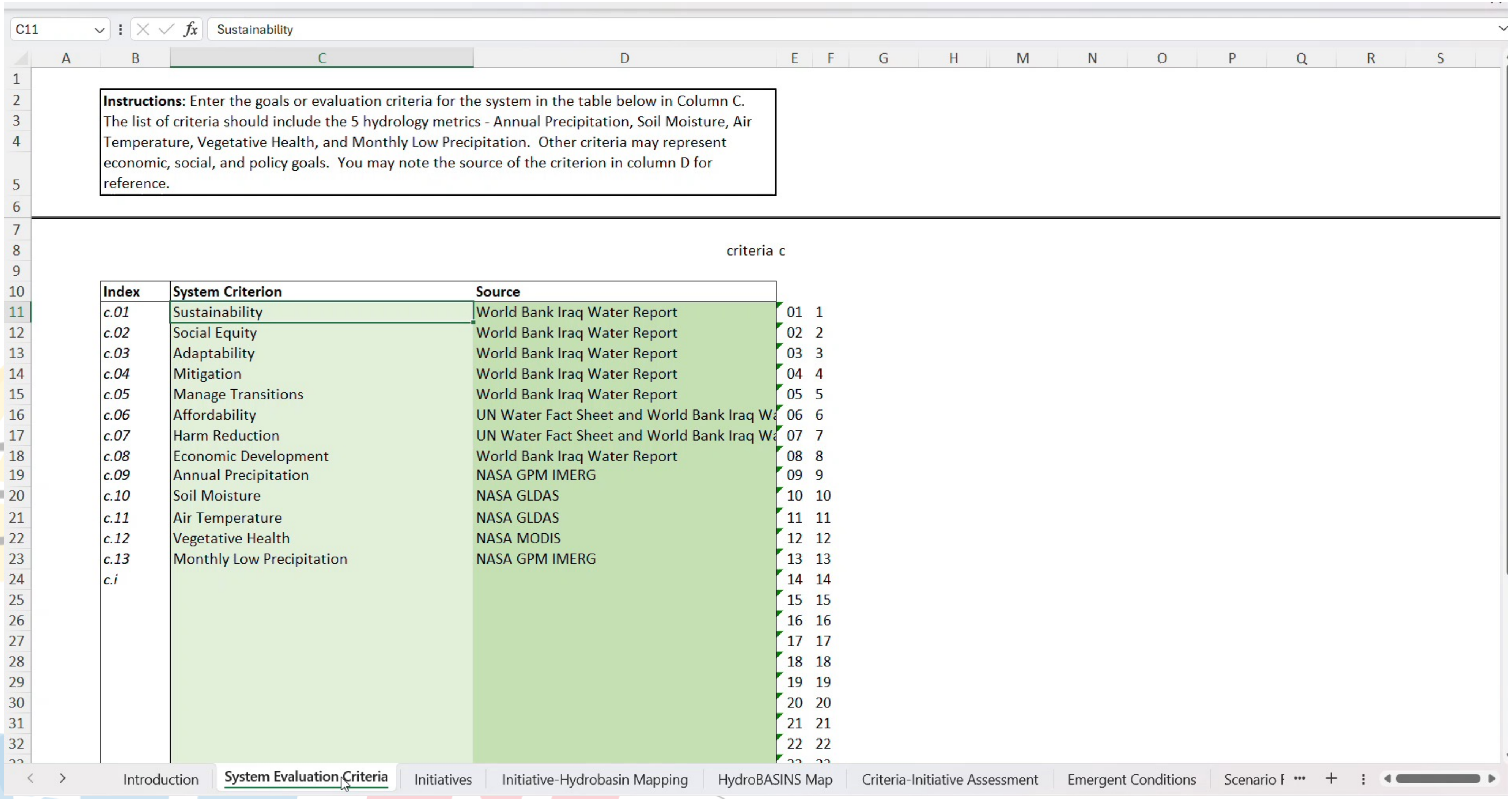

Scenario Disruptiveness Score
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
s.01 - Drought and desertification
s.02 - Prolonged heatwave
s.03 - Decrease in transboundary inflows
s.04 - Increase in electricity demand
s.05 - Sociotechnical disruption
s.06 - Economic stress
s.07 - Infrastructure damage or failure

Conclusions and Future Work

Conclusions

- Satellite-based hydrology data enhance traditional infrastructure system climate risk analysis
- Risk = level of scenario disruption to system priorities
- Stakeholder engagement (scenario development, criteria importance) and training are critical

Software Tool and User Training



C11 Sustainability

Instructions: Enter the goals or evaluation criteria for the system in the table below in Column C. The list of criteria should include the 5 hydrology metrics - Annual Precipitation, Soil Moisture, Air Temperature, Vegetative Health, and Monthly Low Precipitation. Other criteria may represent economic, social, and policy goals. You may note the source of the criterion in column D for reference.

criteria c

Index	System Criterion	Source		
c.01	Sustainability	World Bank Iraq Water Report	01	1
c.02	Social Equity	World Bank Iraq Water Report	02	2
c.03	Adaptability	World Bank Iraq Water Report	03	3
c.04	Mitigation	World Bank Iraq Water Report	04	4
c.05	Manage Transitions	World Bank Iraq Water Report	05	5
c.06	Affordability	UN Water Fact Sheet and World Bank Iraq Wa	06	6
c.07	Harm Reduction	UN Water Fact Sheet and World Bank Iraq Wa	07	7
c.08	Economic Development	World Bank Iraq Water Report	08	8
c.09	Annual Precipitation	NASA GPM IMERG	09	9
c.10	Soil Moisture	NASA GLDAS	10	10
c.11	Air Temperature	NASA GLDAS	11	11
c.12	Vegetative Health	NASA MODIS	12	12
c.13	Monthly Low Precipitation	NASA GPM IMERG	13	13
c.i			14	14
			15	15
			16	16
			17	17
			18	18
			19	19
			20	20
			21	21
			22	22

Introduction | System Evaluation Criteria | Initiatives | Initiative-Hydrobasin Mapping | HydroBASINS Map | Criteria-Initiative Assessment | Emergent Conditions | Scenario F

Future Work

- Electricity transmission and distribution networks
- Water treatment systems
- Policy-focus for environmental sustainability and low-carbon transitions
- Other countries in MENA/Central Asia

Thank you!

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34th Annual INCOSE
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