Balancing security, resilience, and sustainability of urban water supply services from local to global scales

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EGU, May 7, 2020

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Motivation

- Cities are
  - home to the majority of the global population
  - the largest consumers of natural resources
  - the largest producers of CO_2 emissions and environmental pollution
  - drivers of socioeconomic innovation
  - faced with the impacts of climate change and other global change impacts
- Achieving global sustainability goals therefore requires governance strategies that provide urban livelihoods in a locally and globally sustainable way

Governance of urban water supply systems (UWSS) in three dimensions

1. **Security: *Provision of water supply services to all citizens***
→ *state of the system (present condition)*

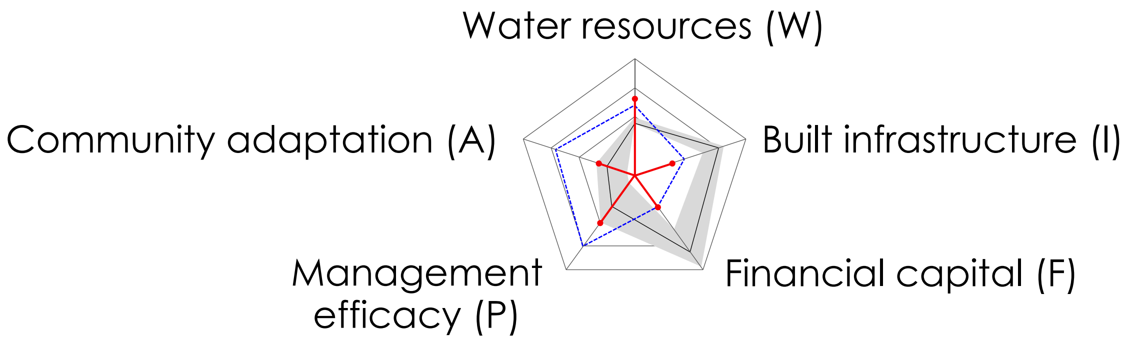
2. Resilience: *Response to and recovery from shocks*
→ *short-medium term system behavior*

3. Sustainability: *Long-term viability of system functioning* *for economy, society, ecology →ecosystem functioning is foundation for UWSS*

Governance of urban water supply systems (UWSS)
Security: More than water availability

1. Security: *Provision of water supply services to all citizens*

→ ***Integration of 5 capital availabilities***



Krueger et al., (2019) Global Environ Change

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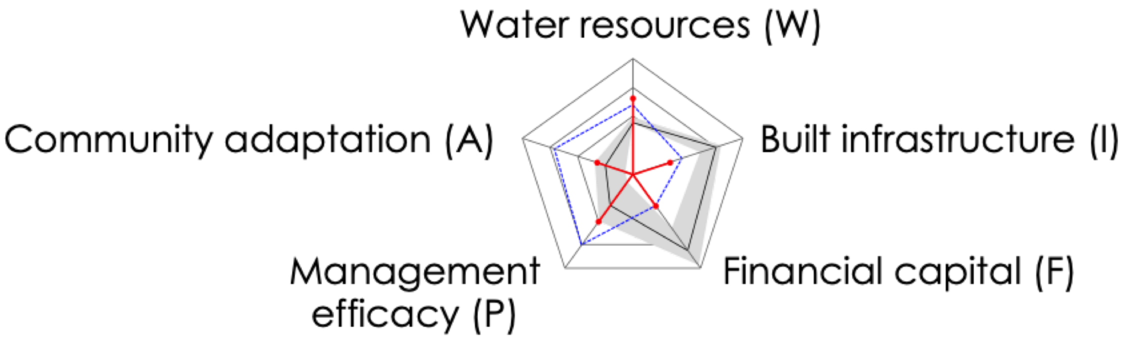
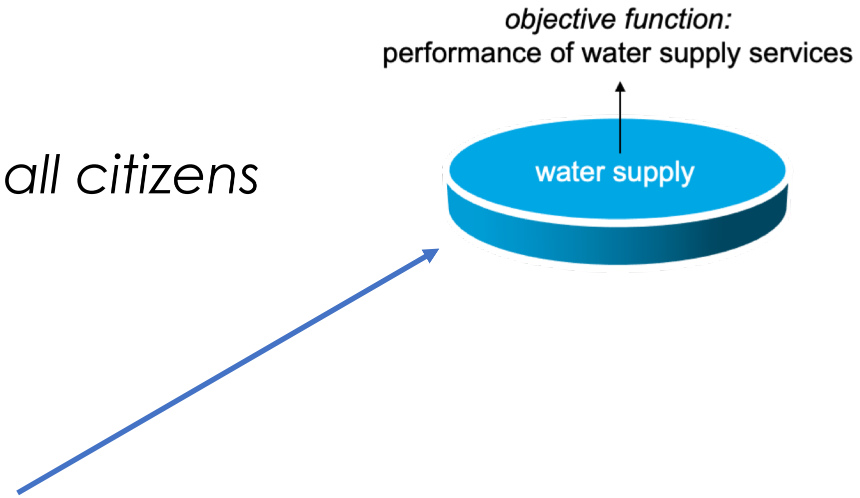
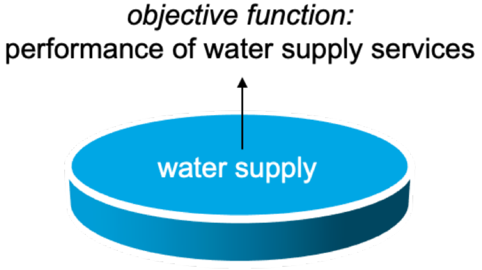




Krueger et al., (2019) Global Environ Change

Governance of urban water supply systems (UWSS)
Resilience: Response to disturbances

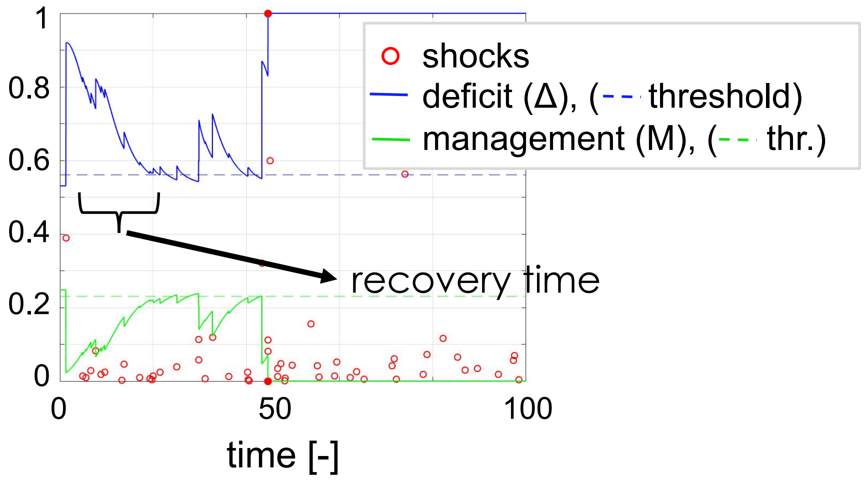


1. Security: *Provision of water supply services to all citizens*

→ ***Integration of 5 capital availabilities***

2. Resilience: *Response to and recovery from shocks*

→ ***dynamic system behavior***

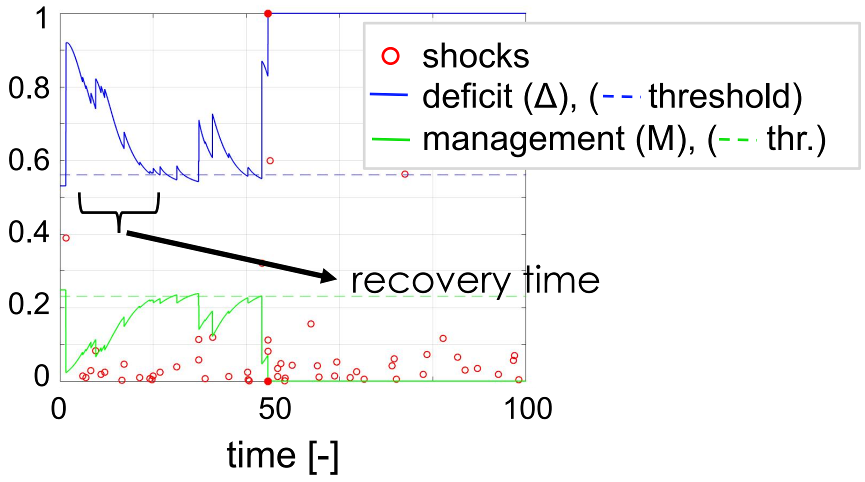


Krueger et al., Earth's Future (2019)

Governance of urban water supply systems (UWSS)
Resilience: Response to disturbances

1. Security: *Provision of water supply services to all citizens*
→ ***Integration of 5 capital availabilities***

2. Resilience: *Response to and recovery from shocks*
→ ***dynamic system behavior: requires response across sectors***



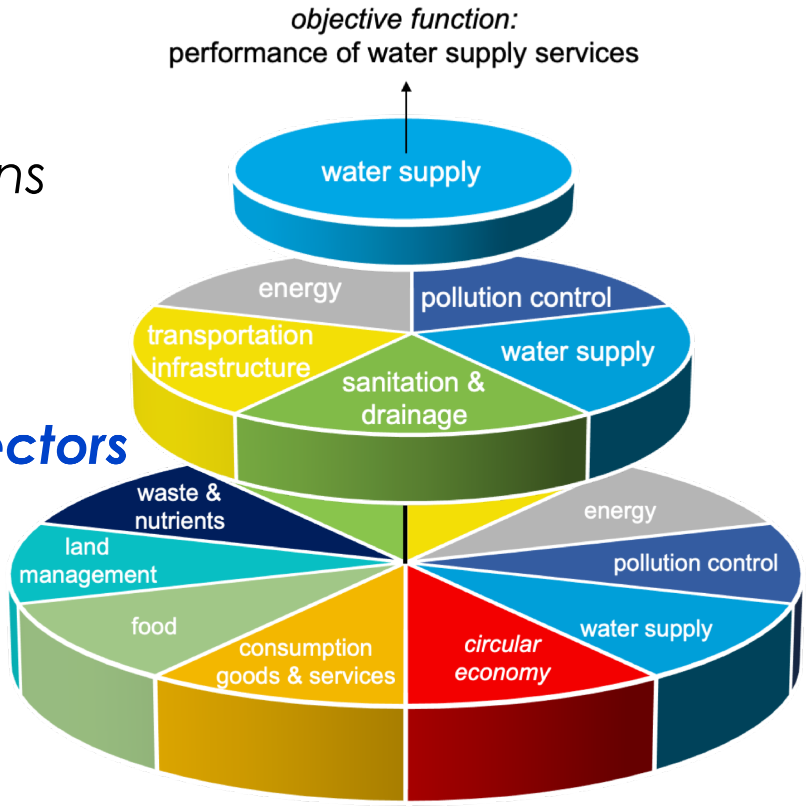
Krueger et al., Earth's Future (2019)

Governance of urban water supply systems (UWSS)
Sustainability: Long-term viability

1. Security: *Provision of water supply services to all citizens*
→ ***Integration of 5 capital availabilities***

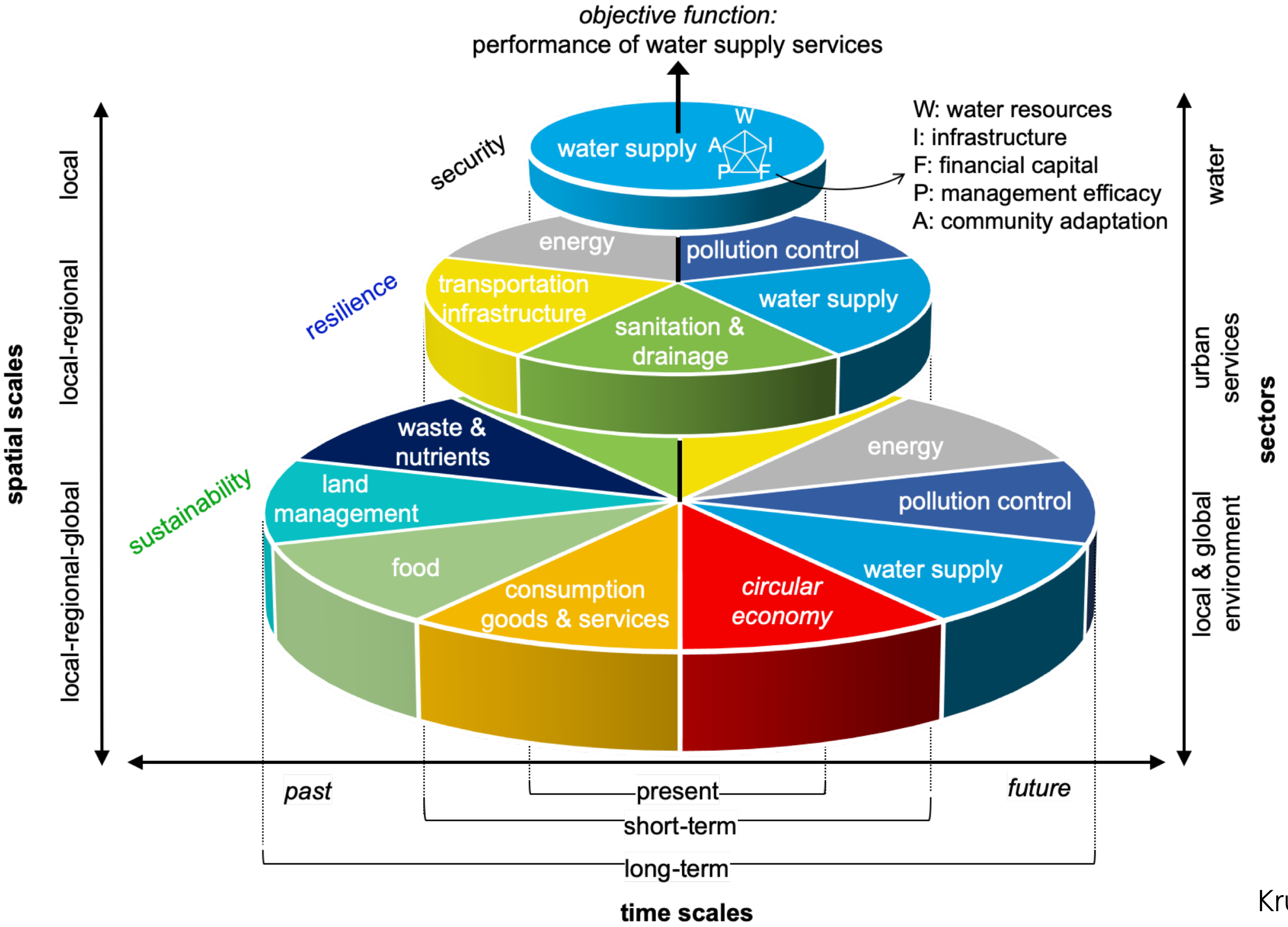
2. Resilience: *Response to and recovery from shocks*
→ ***dynamic system behavior: requires response across sectors***

3. Sustainability: *Long-term viability of system functioning for economy, society, ecology*
→ ***integration across sectors, space, and temporal scales***



Krueger et al., (2020) ERL

Framing security, resilience, and sustainability



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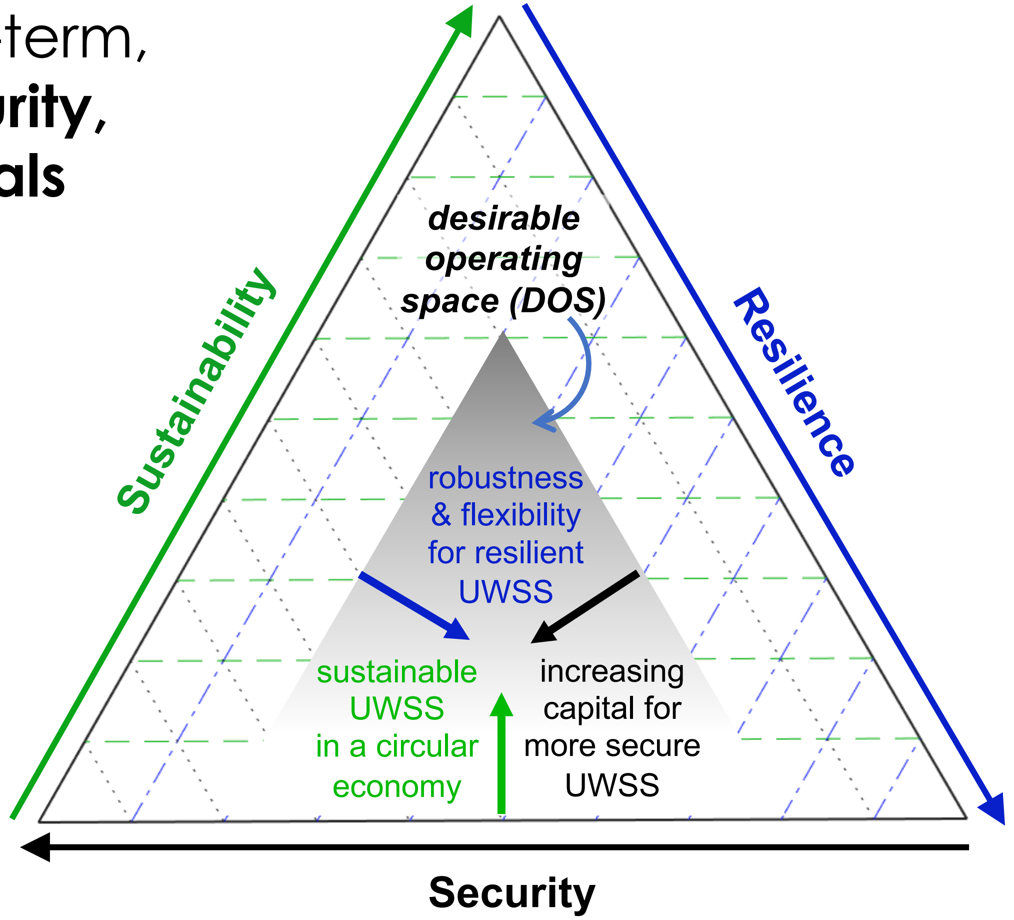
Balance

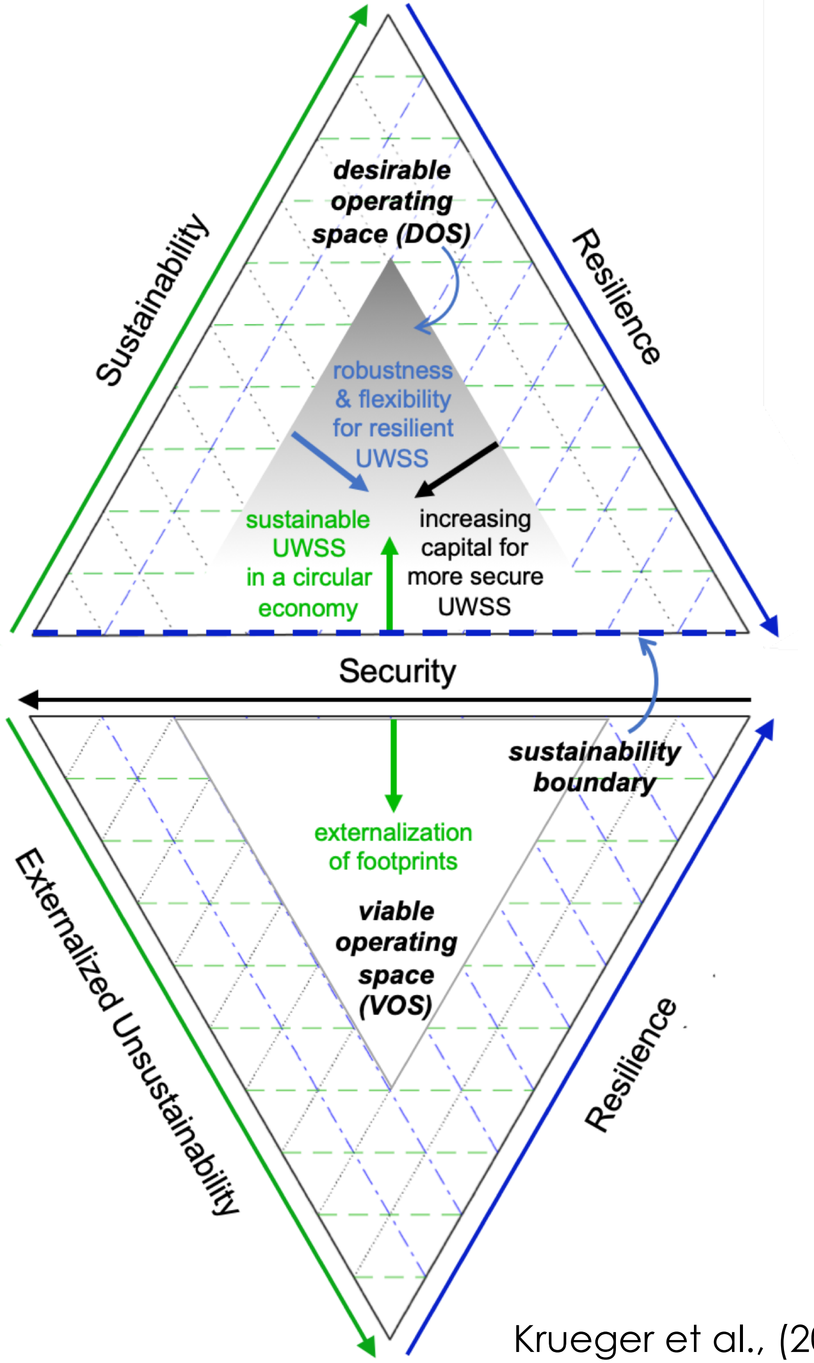
For UWSS to perform in the long-term, **governance must balance security, resilience, and sustainability goals**



Krueger et al., (2020) ERL

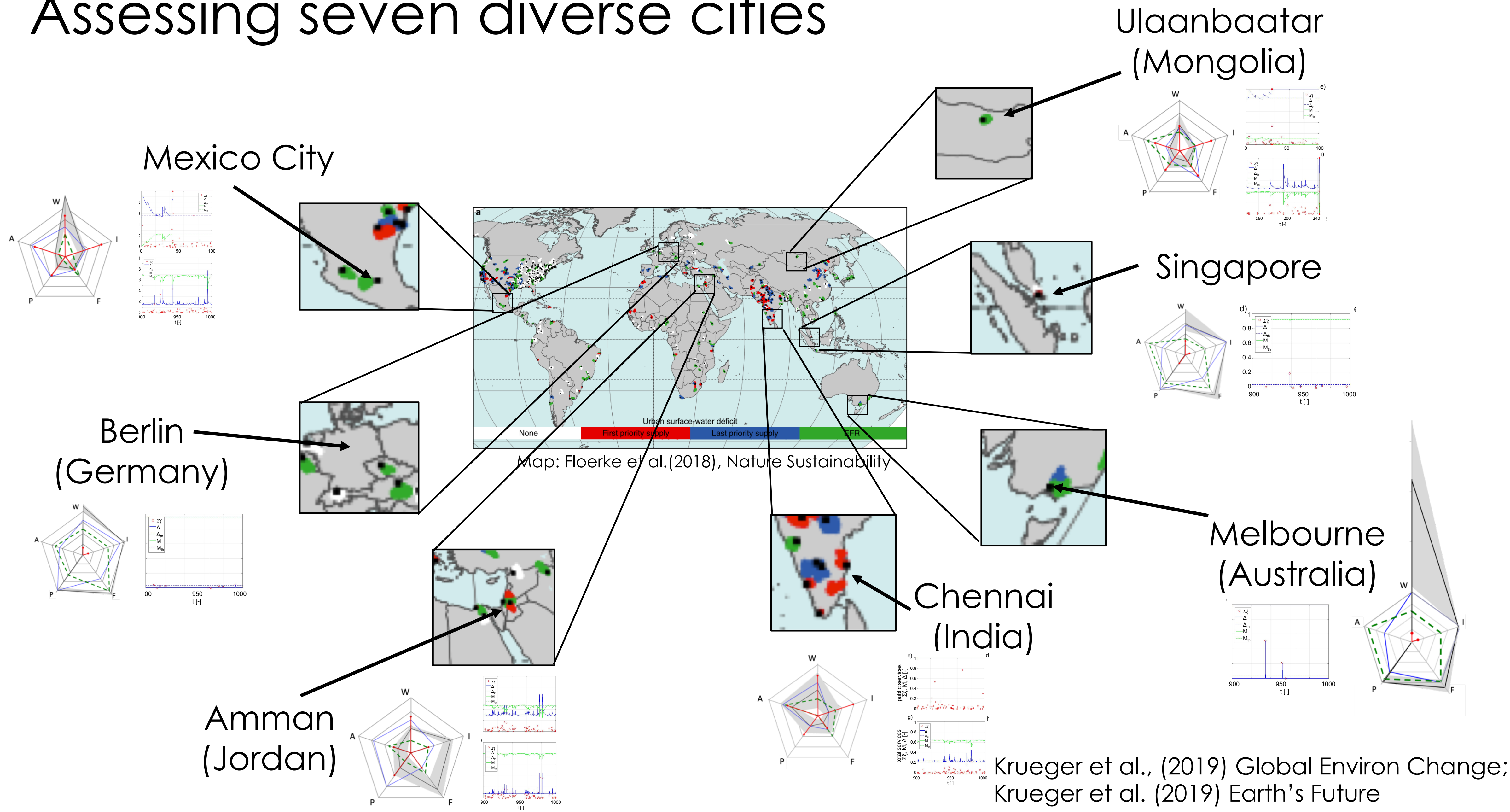
Externalization of costs

Instead, the environmental **costs of sustainable water supply are externalized.** E.g., protection of local catchment areas at the cost of overexploitation of global ecosystems, i.e., global water and ecological footprints exceed global carrying capacity (“Externalized Unusustainability”).



Krueger et al., (2020) ERL

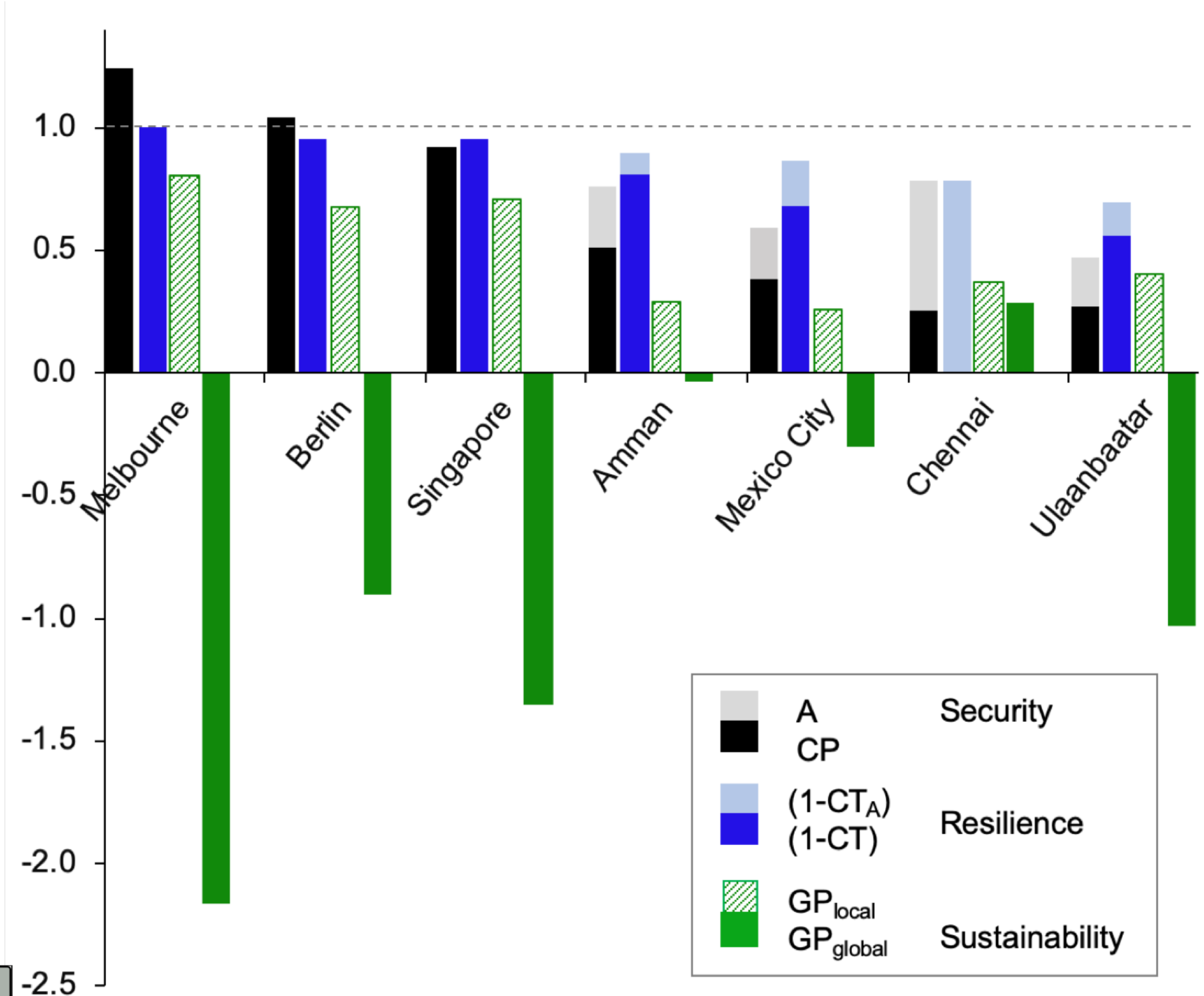
Assessing seven diverse cities



Map: Floerke et al.(2018), Nature Sustainability

Krueger et al., (2019) Global Environ Change;
Krueger et al. (2019) Earth's Future

Aggregated results



Notes:
A = Community Adaptation
CP = Capital Availability ("Capital Portfolio"); see *Krueger et al., 2019 (GEC)*
CT = Mean crossing time below expected service deficit (fraction of total time). Subscript A indicates modeled time series including community adaptation; see *Krueger et al. 2019 (Earth's Future)*
GP = Sustainable governance score ("Governance Portfolio"). Subscripts evaluate local sustainable management and global impacts

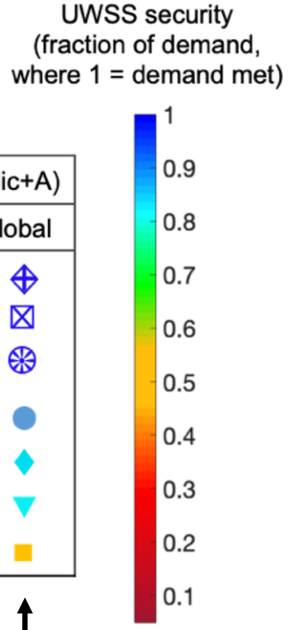
Krueger et al., (2020) ERL

Balance for seven case studies

services	public	total (public+A)	
sustainability	local		global
Melbourne	+		⊕
Berlin	×		⊠
Singapore	✳		⊛
Amman	○	● (hatched)	●
Mexico City	◇	◆ (hatched)	◆
Chennai	▽	▼ (hatched)	▼
Ulaanbaatar	□	■ (hatched)	■

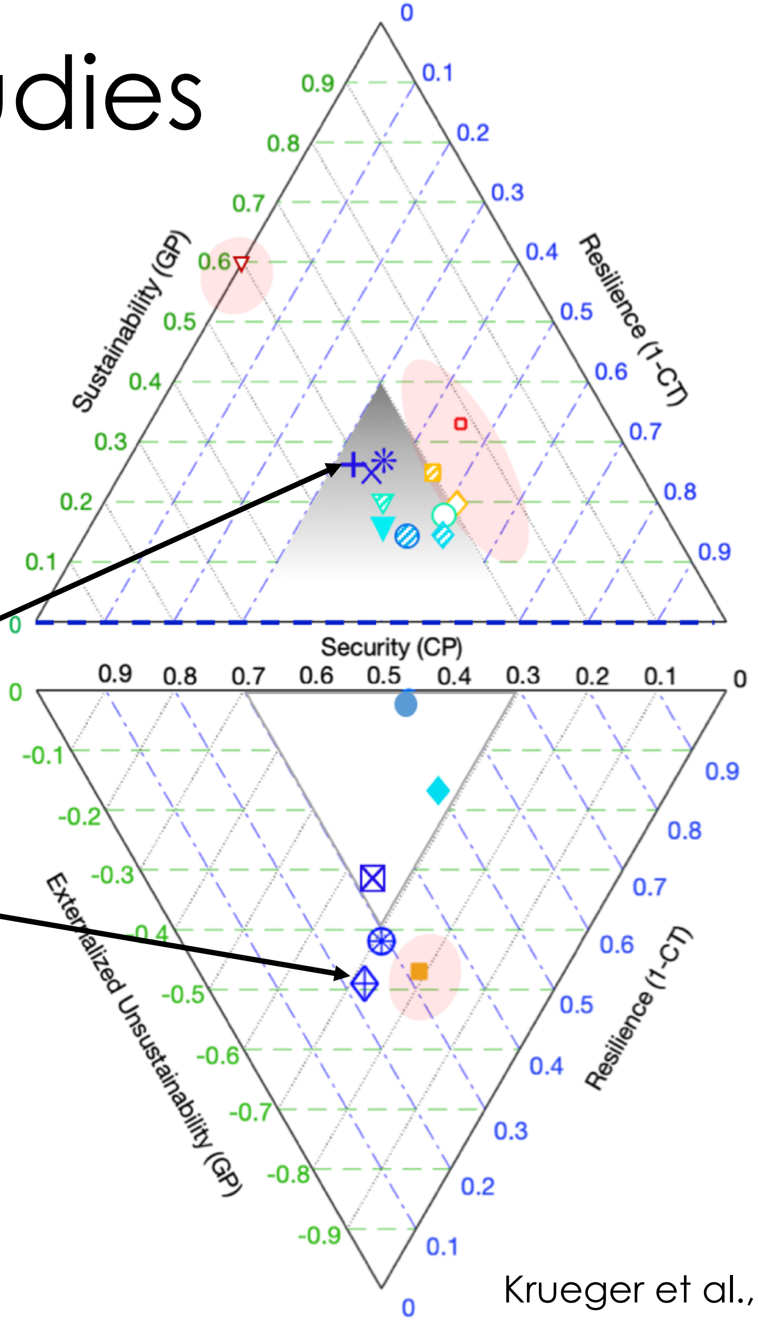
local sustainable governance

including global governance impacts



E.g., **Melbourne**: locally balanced

large global impact = globally highly unbalanced

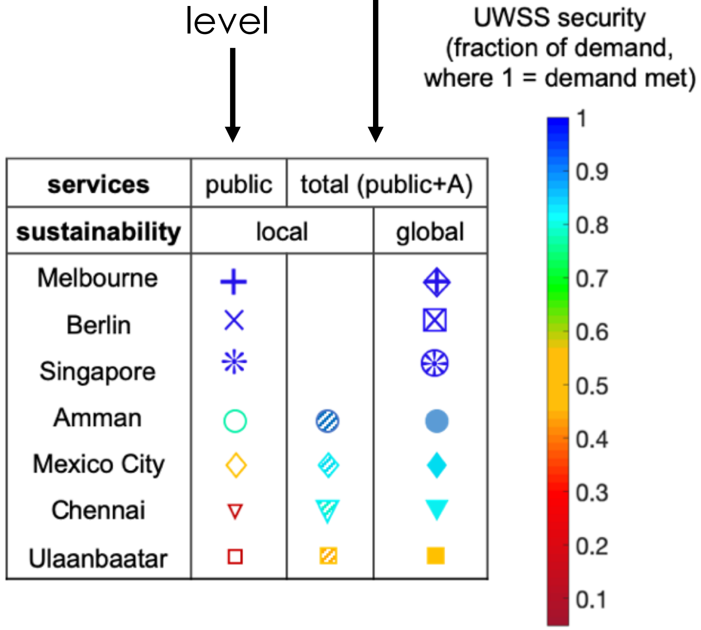


Krueger et al., (2020) ERL

Balance for seven case studies

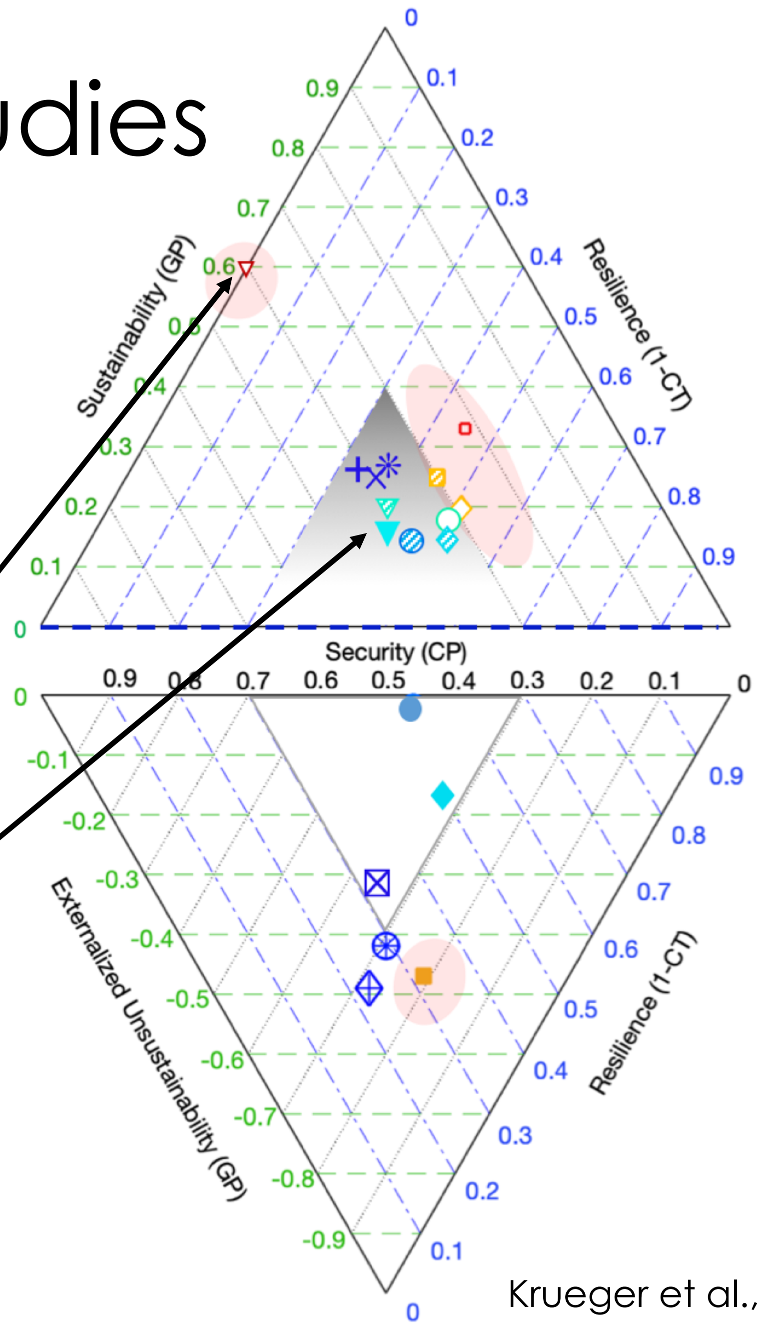
public services, e.g., provided at municipal level

total services include community adaptation (e.g., additional water bought by households on the private market/ collected from wells/ rivers)



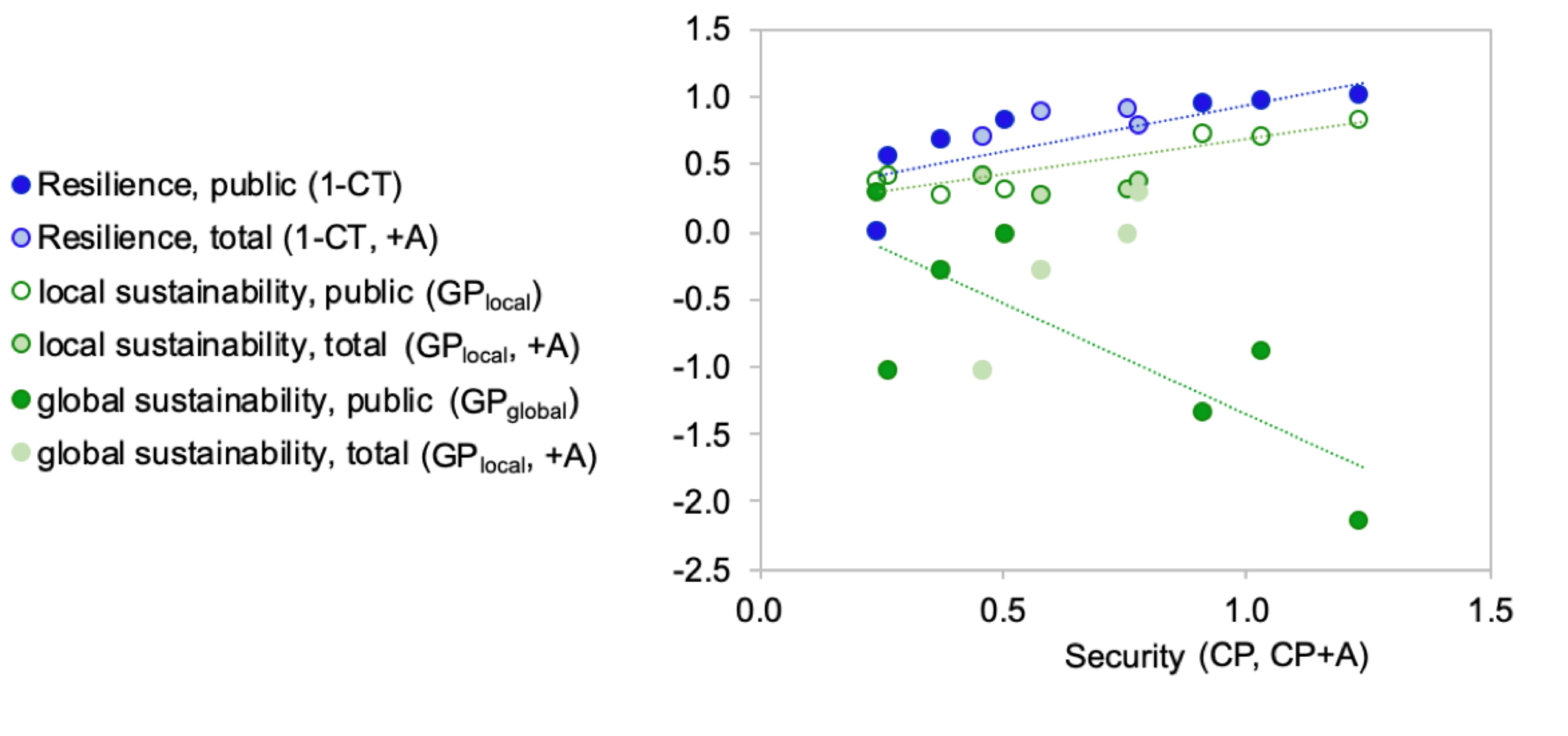
E.g., **Chennai**:
<u>locally non-resilient</u> (day zero occurred twice within two decades)

<u>Community Adaptation</u> (A) has allowed system to cope – until now



Krueger et al., (2020) ERL

Current urban water trajectories make water-secure and resilient cities globally unsustainable

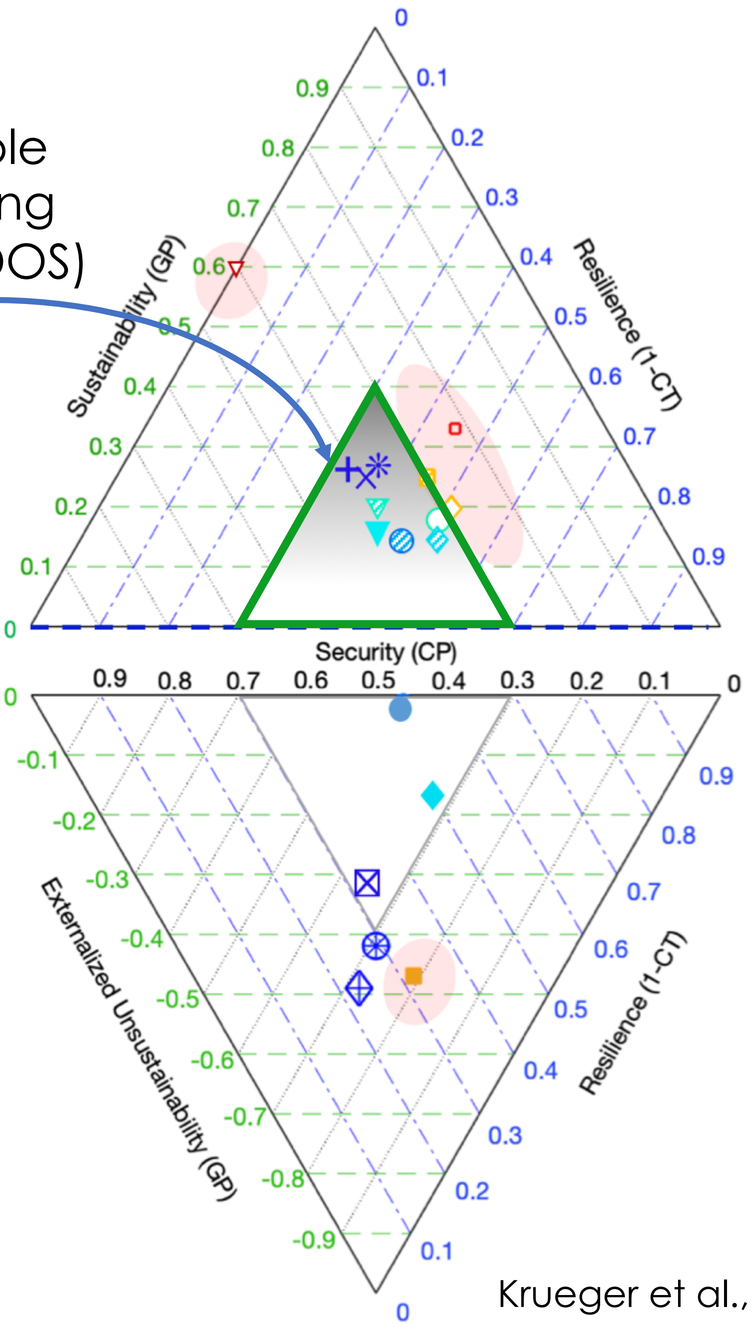


Krueger et al., 2020 (ERL)

Conclusion

The well-being of citizens requires that **urban governance**, in general, and governance of urban water supply systems, specifically, **must balance between security, resilience, and sustainability within a desirable operating space (DOS).** "Well-being" implies adequate services for all, ability to respond to and recover from shocks, and limiting impacts across space and avoiding intra- and inter-generational tradeoffs.

Desirable operating space (DOS)



Krueger et al., (2020) ERL

References:

Krueger E, Borchardt D, Jawitz JW, Rao PSC (2020): **Balancing Security, Resilience, and Sustainability of Urban Water Supply Services in a Desirable Operating Space**. *Environmental Research Letters*, 15 (3). Online

Krueger E, Jawitz JW, Borchardt D, Klammler H, Yang S, Zischg J, Rao PSC, 2019: **Resilience Dynamics of Urban Water Supply Security and Potential of Tipping Points**. *Earth's Future*, 7 (10), 1167-1191. Online

Krueger E, Borchardt D, Rao, PSC, 2019: **Quantifying Urban Water Supply Security Under Global Change**. *Global Environmental Change*, 56, 66-74. Online

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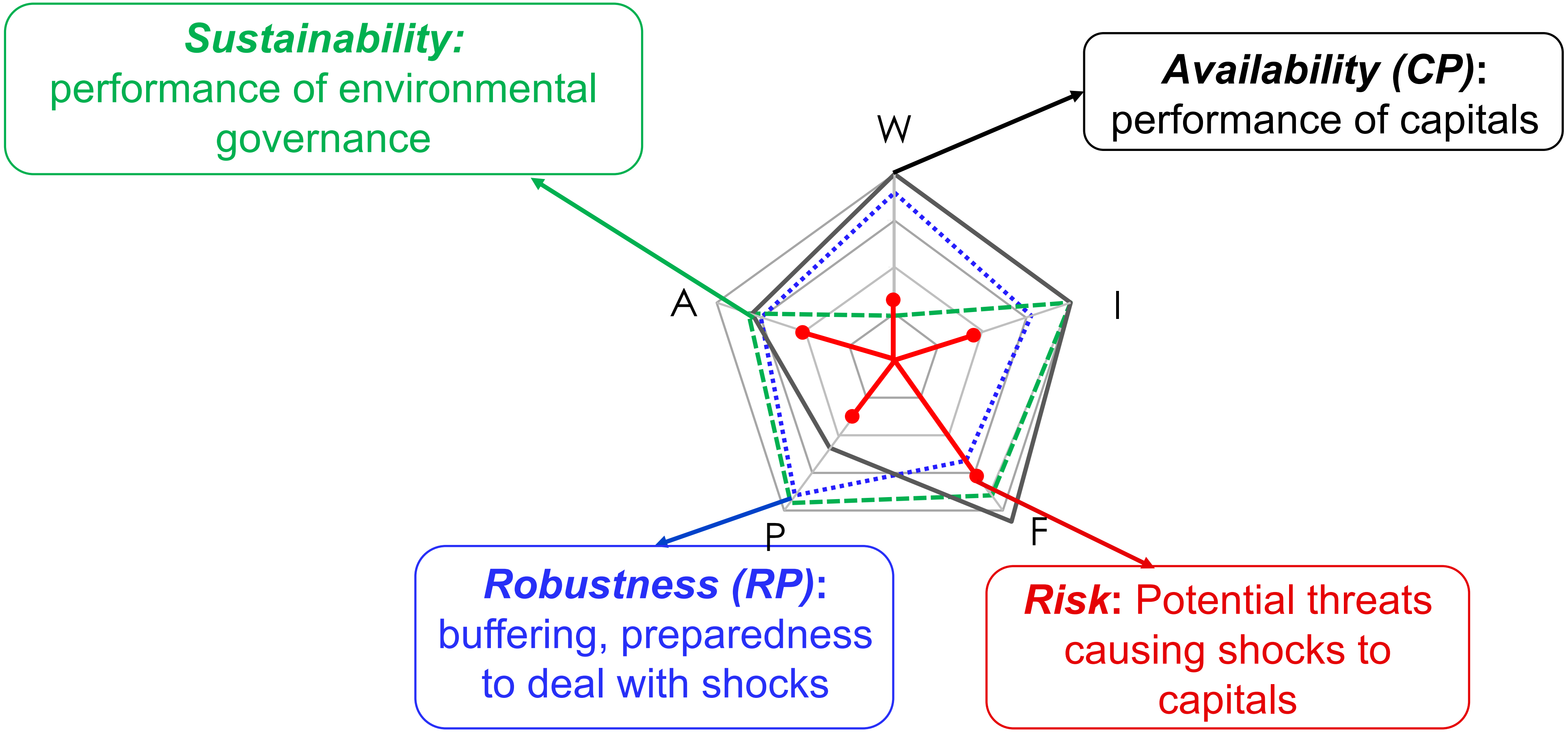
Additional slides: Methodology

Overview: Capital Portfolio Approach (CPA)



Krueger et al., (2019) GEC

Overview: System Dynamics of Services

Model Input

- risk (Shock) Portfolio (SP)
- Capital Availability (CP)
- Robustness Portfolio (RP)

Stochastic shocks (ξ):

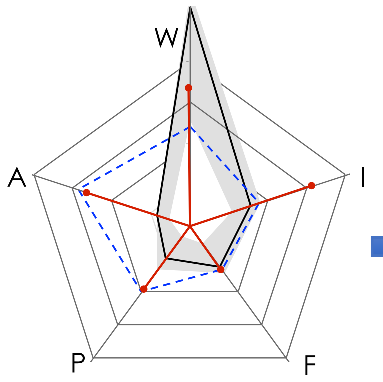
$$\sum_{i=1}^{\infty}(\xi_i - \pi_i)\delta(t - t_i)\ [1/T]$$

Service Deficit (Δ):

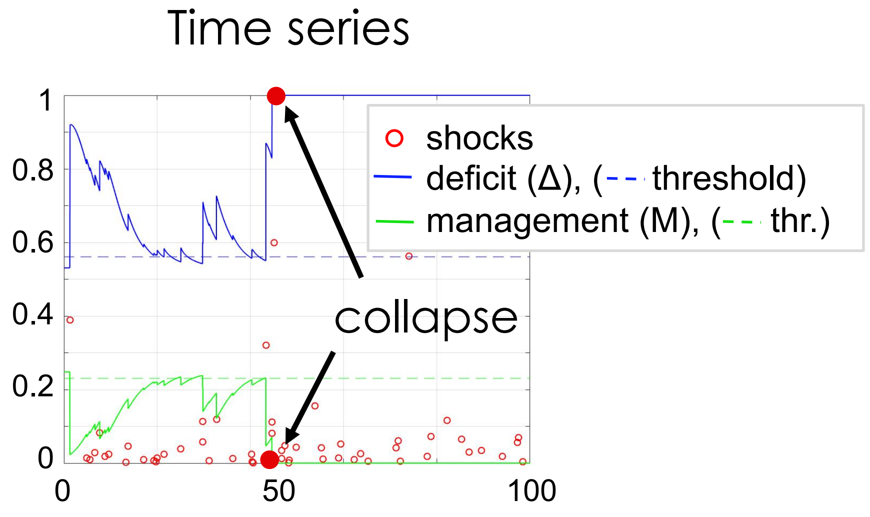
$$\frac{d\Delta}{dt} = (1 - \Delta)b - aM\Delta + \xi$$

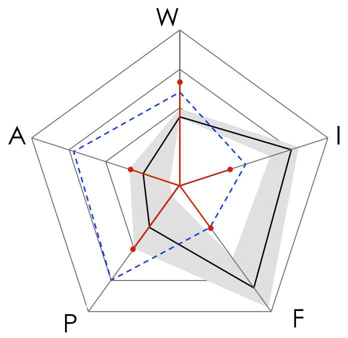
Service management (M):

$$\frac{dM}{dt} = (1 - c_1\Delta)M(1 - M) - r\frac{M^n}{\beta^n + M^n} - c_2\xi$$

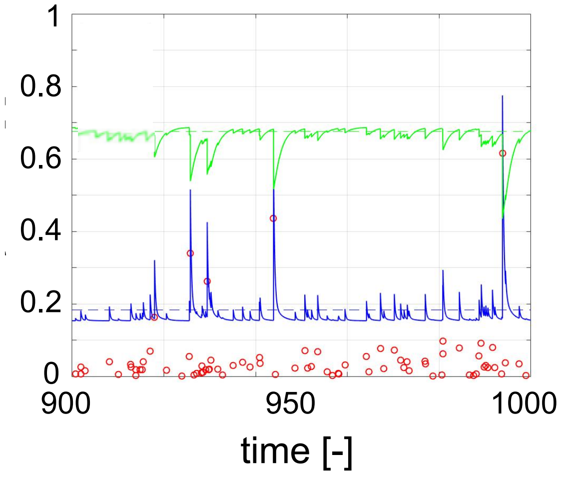


Mexico $City_{public}$





$Amman_{total}$



Krueger et al., (2019) Earth's Future

Model based on: Klammler et al., (2018) Env. Sys. Decis.

System Dynamics of Urban Water Supply Services

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- Capital Availability (CP)
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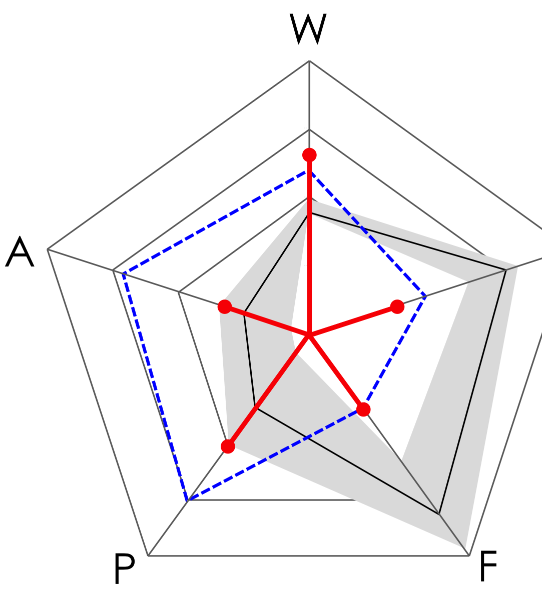

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Stochastic shocks

Service Deficit (Δ):
0 ≤Δ(t) ≤ 1; 1 = no services.

$$\frac{d\Delta}{dt} = (1 - \Delta)b - aM\Delta + \xi$$

Demand growth and service degradation

Efficiency coefficient

Service management (M):
0 ≤ M(t) ≤ 1;
1 = full capacity

$$\frac{dM}{dt} = (1 - c_1\Delta)M(1 - M) - r\frac{M^n}{\beta^n + M^n} - c_2\xi$$

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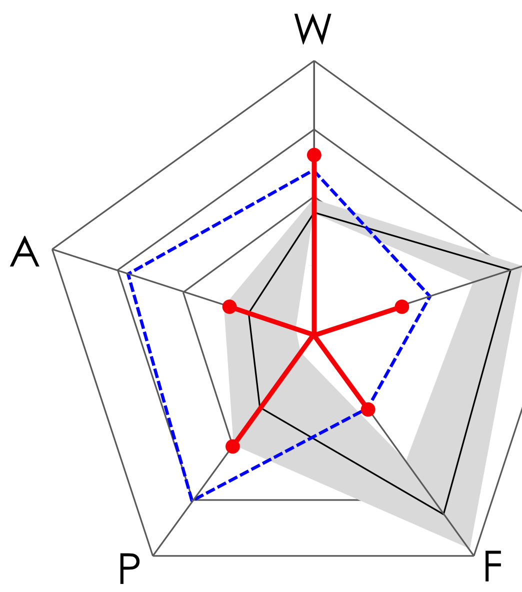

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Limits replenishment of M when Δ

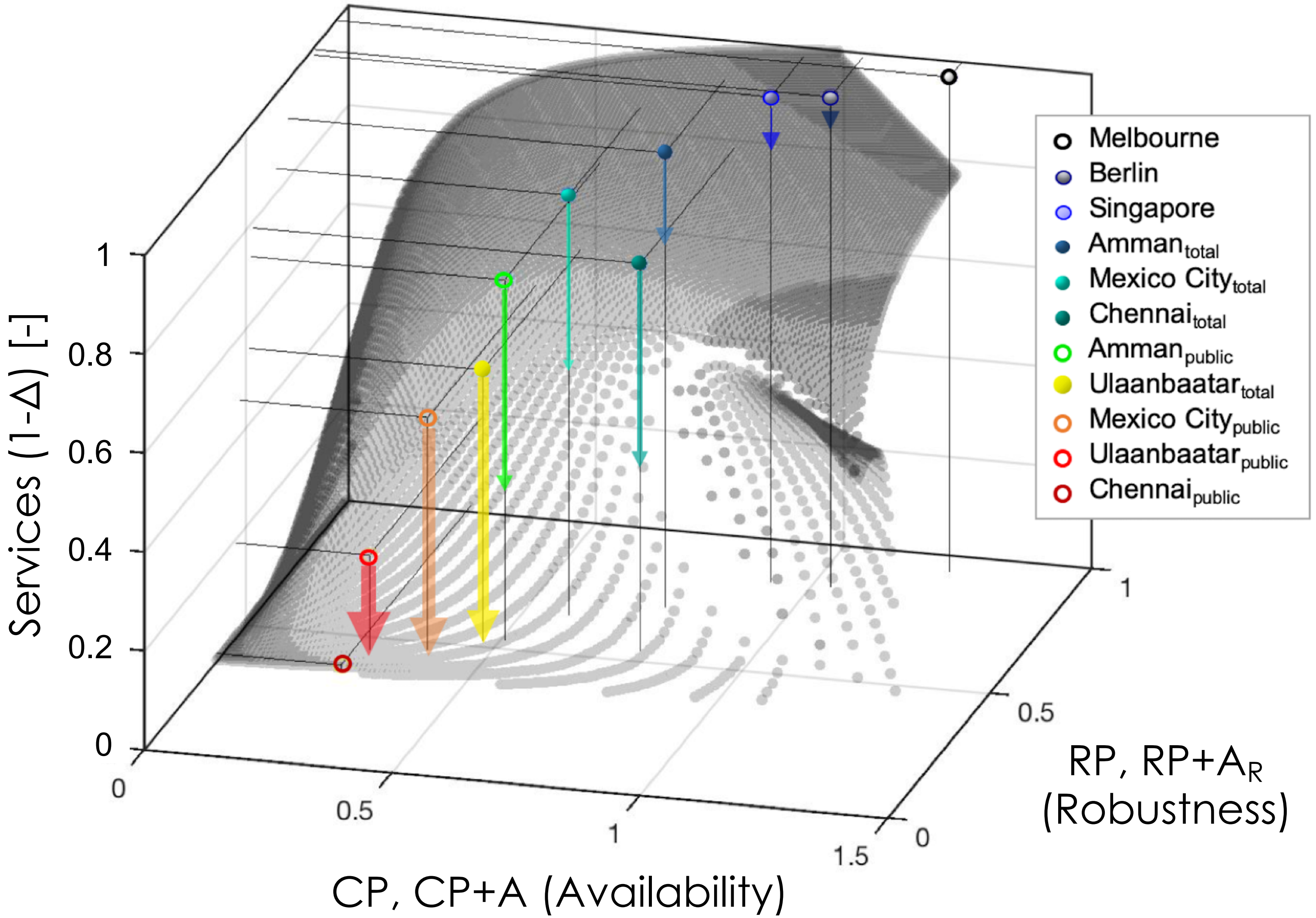
Max. depletion rate

shape and scale of degradation curve

Direct impact of shocks on M

Krueger et al., 2019 (Earth's Future)
Model based on: Klammler et al., (2018) Env. Sys. Decis.

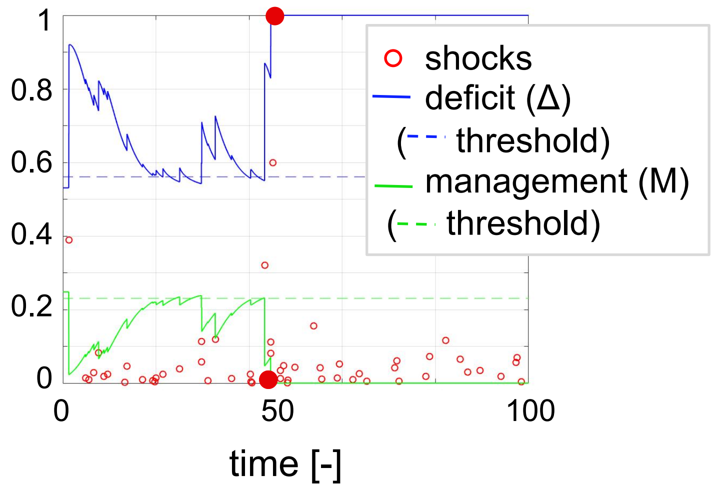
Resilience Landscape



Dynamics:

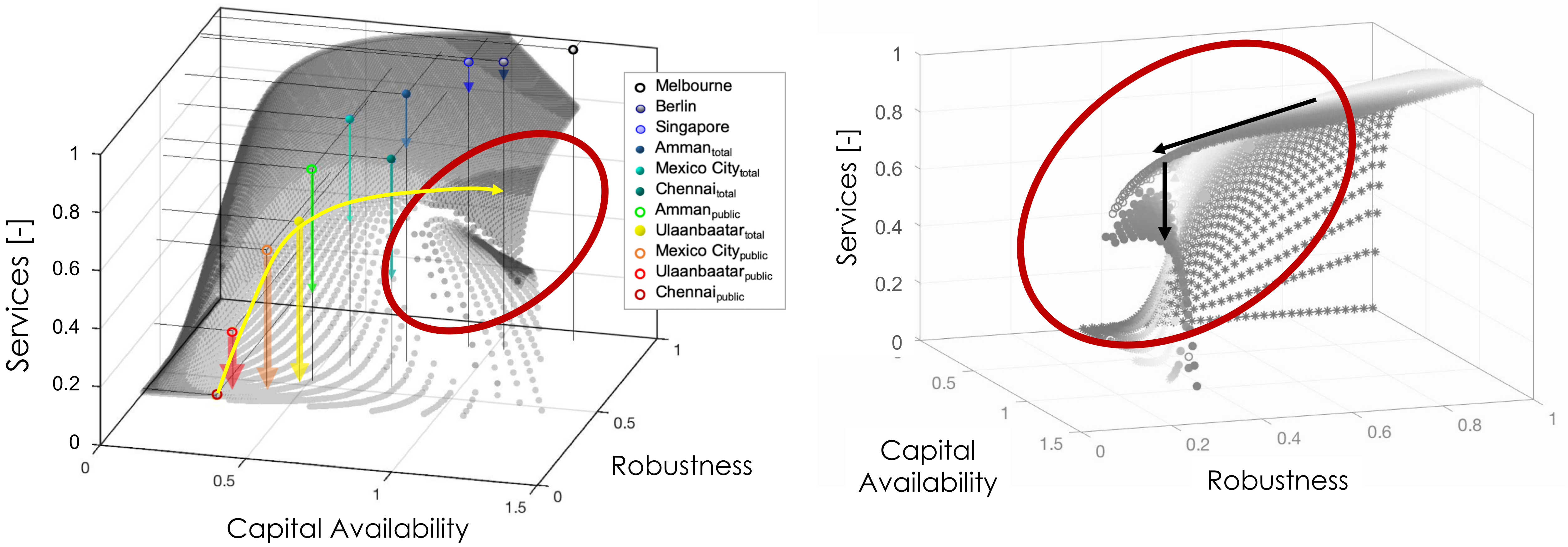
length: max. shock impact on M

width: crossing time avg. Δ



Krueger et al., (2019) Earth's Future

Tipping points ?

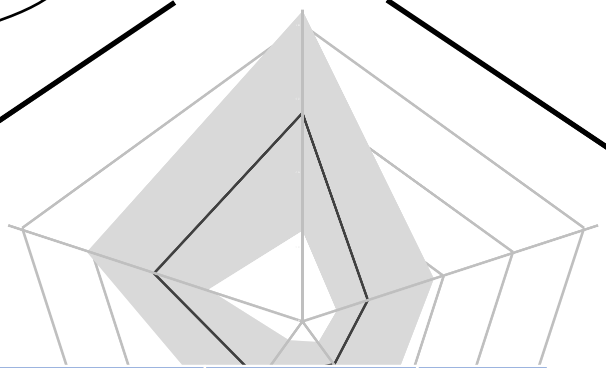


Krueger et al., (2019) Earth's Future

Quantification of Capital Portfolio

→ *W=1:*
No water stress. Available water resources >= 100$m^3cap^{-1}y^{-1}$.

Water resources (W) →



Water Availability (W)

category	Threshold ($m^3cap^{-1}y^{-1}$)	W
no stress	>100	>1
scarcity	100-50	1-0.5
water stress	50-25	0.5-0.25
high water stress	<25	<0.25

Water resources robustness (W_R)

attribute	no stress (4)	low stress (3)	stress (2)	high stress (1)	score
storage-to-flow	>0.6	0.6-0.3	0.3-0.2	<0.2	1-4
import dependence	<0.15	0.15-0.25	0.25-0.5	>0.5	1-4
use-to-resource	<0.1	0.1-0.2	0.2-0.4	>0.4	1-4
water quality	precautionary principle	source control & polluter pays	emissions regulations	monitoring	0-4
source diversity	multiple types	two sources & types	one type	one source	1-4
					W_R: Σ(scores)/20

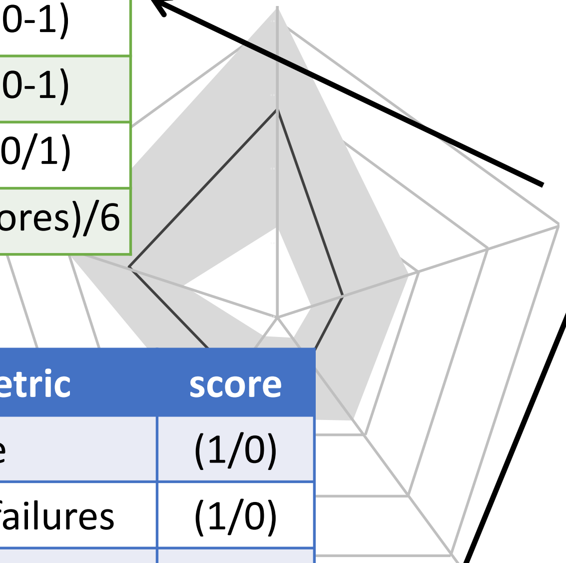
Sustainable water governance (G_W)

attribute	score
Ecological Footprint (EFP)	
Water Footprint (WFP_{global})	
$G_{wglobal}$=1-(EFP+WFP)/2	
Water Reach (WD)	
Recycled/Reused Water (Fraction)	
Renewable energy use in WS	
G_{Wlocal}: Σ(scores)/3	

Krueger et al., (2019) GEC
Krueger et al., (2020) ERL

Sustainable Infrastructure Governance (G_I)

Attribute	score
Fraction of waste water treated	(0-1)
Degree of modularity	(0-1)
Fraction of pop. covered by sanitation	(0-1)
Reuse of storm- and wastewater	(0-1)
Energy production from waste/wastewater	(0-1)
Nutrient reuse from sewage sludge	(0/1)
	$G_I = \Sigma(\text{scores})/6$



Infrastructure robustness (I_R)

category	infrastructure robustness metric	score
operation and maintenance	anticipatory maintenance	(1/0)
	emergency solution for power failures	(1/0)
	inter-sector coordination	(1/0)
	continuous water supply	(1/0)
	monitoring system for leakage detection	(1/0)
physical constraints	average materials age < 50 yrs	(1/0)
	redundancy of critical nodes	(1/0)
	decentralized sources	(1/0)
	possibility of emergency zone isolation	(1/0)
		$I_R = \Sigma(\text{scores})/9$

→ *I=1:*
Capacity to deliver all available water resources at drinking water quality to all households at demanded volumes.

Infrastructure (I)

Infrastructure Availability (I)

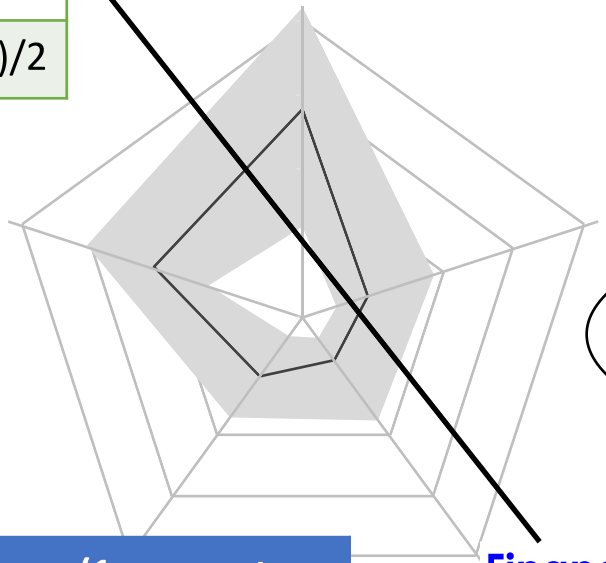
→ *I = connection rate*(1-leakage) – q * W_{drink}*

- leakage: fraction of water lost
- W_{Drink}: fraction of drinking water demand
- q: coefficient (1=treatment required, 0=water delivered at drinking water quality

Krueger et al., (2019) GEC
Krueger et al., (2020) ERL

Sustainable Financial Governance (G_F)

Attribute	score
Cost recovery > 90%	(1/0)
Financial Dependence ((FDI+ODA/GNI)	(0-1)
	G_F=(1-FDM+CR)/2



→ *F=1:*
Water sector budget (income over spending) is sufficient to operate and maintain fully functional infrastructure system.

Financial capital (F)

Financial Availability (F)

$$F = \frac{annual\ water\ sector\ income}{annual\ water\ sector\ expenditure} * I$$

Financial robustness (F_R)

Attribute	score (1=present, 0=absent)
Dependence on int. donors for infrastructure investment < 50%	(1/0)
Is medium – high income city (available income for unexpected expenditures)	(1/0)
energy autonomy is > 50%	(1/0)
	F_R=Σ(scores)/3

Krueger et al., (2019) GEC
Krueger et al., (2020) ERL

Sustainable Governance (G_P)

Attribute	score
Centralization of information	(0-1)
Participatory management	(1/0)
Cross-sector management: sanitation, drainage, energy & industry, mobility, recreation, agriculture, amenities planning, education	Avg. (1/0)
	$G_M = \Sigma(\text{scores})/3$

→ *P=1:*
Efficient, flexible, and accountable water governance institutions with adequate complexity.

Management Efficacy (P)

→ *Robustness of Management Power (P_R)*

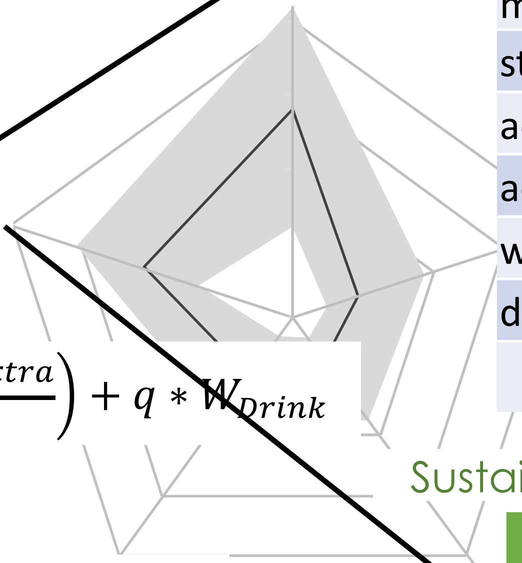
1) emergency operations planning
2) capacity to improvise, innovate, expand operations
3) national support programs for disaster recovery
4) City ranking

Management Efficacy (P)

Category	Attribute	score (1=present, 0=absent)
institutional efficiency	clear structure with communication protocols for information sharing	1 / 0
	feedback-loops	1 / 0
	mechanisms for inter-sector coordination	1 / 0
	training & innovations for resilience and sustainability	1 / 0
accountability	mechanisms for participatory decision-making/management	1 / 0
	mechanisms for follow-up of customer complaints	1 / 0
	integrity: Corruption Perception Index > 50	1 / 0
	administrative losses < 10%	1 / 0
regulatory complexity	urban-urban / urban-rural strategies	1 / 0
	transboundary agreements	1 / 0
	mechanisms for groundwater management	1 / 0
	mechanisms for surface water management	1 / 0
		$P_R = \Sigma(\text{scores})/12$

→ A = 1:
Services are fully covered by community adaptation; public services = 0.

Community Adaptation (A)



Capital Availability (A)

$$A = \frac{W_{extra}}{D} + supply\ gap * \left(1 - \frac{W_{public} + W_{extra}}{D}\right) + q * W_{Drink}$$

W_{extra}: additional water accessed by the community through private measures [m^3y^{-1}]
D: demand [m^3y^{-1}]
supply gap: intermittence [days/days]
W_{public}: water delivered at household level (W-leakage)
W_{Drink}: fraction of drinking water demand/total demand
q: coefficient (1=treatment required, 0=water delivered at drinking water quality

Community Robustness (A_R)

attribute	score
is medium - high income city (*median* household income)	(1/0)
access to alternative water services (e.g. private market)	(1/0)
storage capacity > 7days	(1/0)
access to information for emergency response	(1/0)
active community structures	(1/0)
water treatment before drinking	(1/0)
direct access to water sources (e.g., wells, rivers, etc.)	(1/0)
	$\mathbf{A_R}=\Sigma$(scores)/7

Sustainable Governance of Community Adaptation (G_A)

Attribute	score
Environmental awareness	(1/0)
Demand management	(1/0)
Community engagement	(1/0)
Inequality	(0-1)
	$G_A=\Sigma$(scores)/4

Risk profile

Risk category	Risk type description	Susceptible capital	experience/ potential threat
Geological and geographic hazards	earthquakes, tsunamis, volcanic eruptions, landslides	I A	0/1
	land subsidence caused by local groundwater over-exploitation impacting infrastructure degradation	I	0/1
Socio-economic and geo-political threats	socio-economic/political changes/ unforeseen high immigration rates	W I F P A	0/1
	immediate threat of war/terrorism	W I F P A	0/1
	experiences competition for resources	W P	0/1
	immediate threat exists/has been subject to economic crises	F P A	0/1
	illegal tapping into water pipes occurs	I	0/1
Contamination hazard	risk from industrial spills exists (upstream industry)	W I A	0/1
	has risk of epidemic incidents through degraded infrastructure (can occur in combination with floods)/ potential of groundwater degradation from intensive farming and lack of sanitary infrastructure	W I A	0/1
Climate and weather-related hazards	Flood/drought risk	W	0/1
	extreme temperatures (freezing and bursting of pipes)	I	0/1
	risk of storms and wildfires with potential of damaging infrastructure	I	0/1

Krueger et al., (2019) GEC