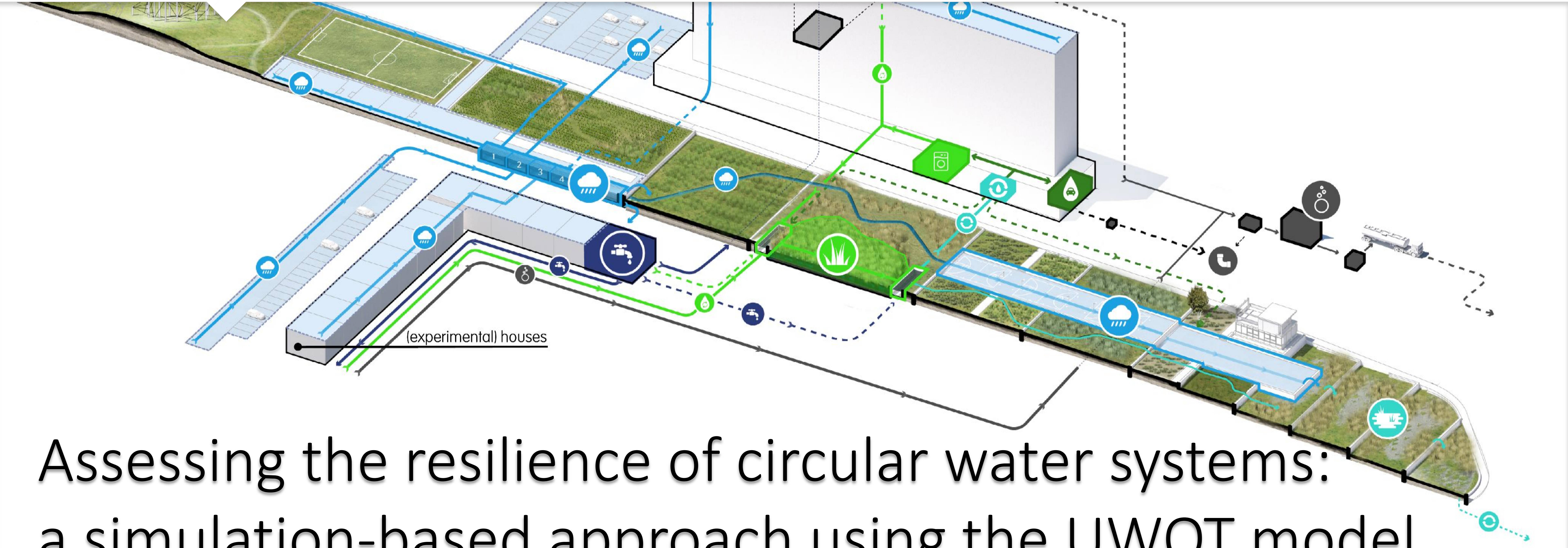
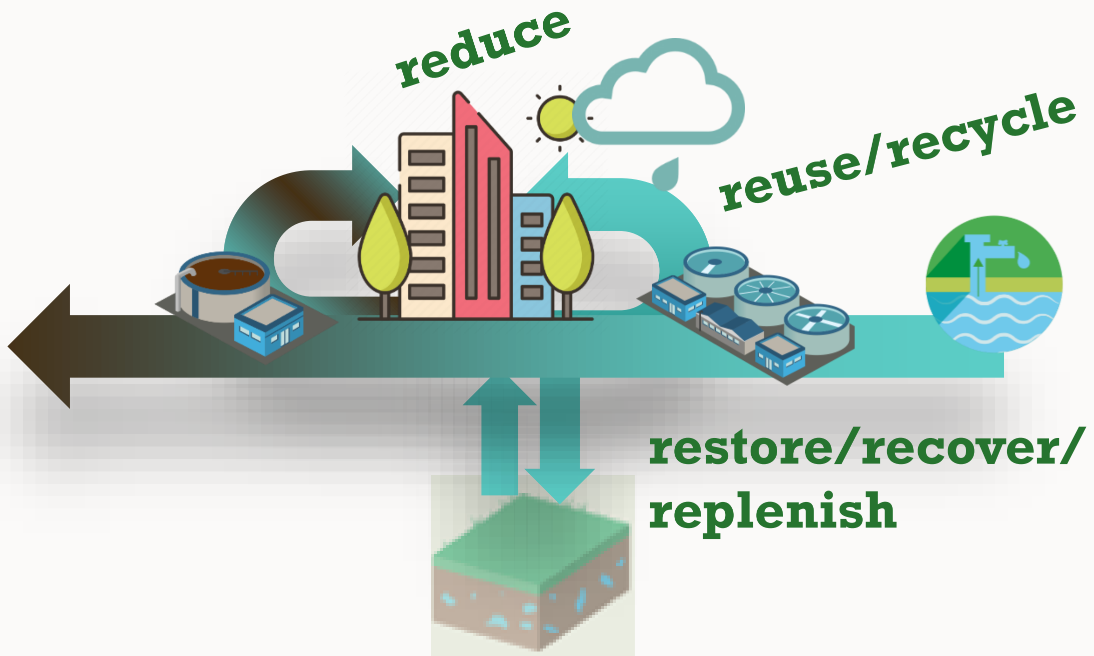


Assessing the resilience of circular water systems: a simulation-based approach using the UWOT model

Dimitrios Bouziotas, MEng, MSc

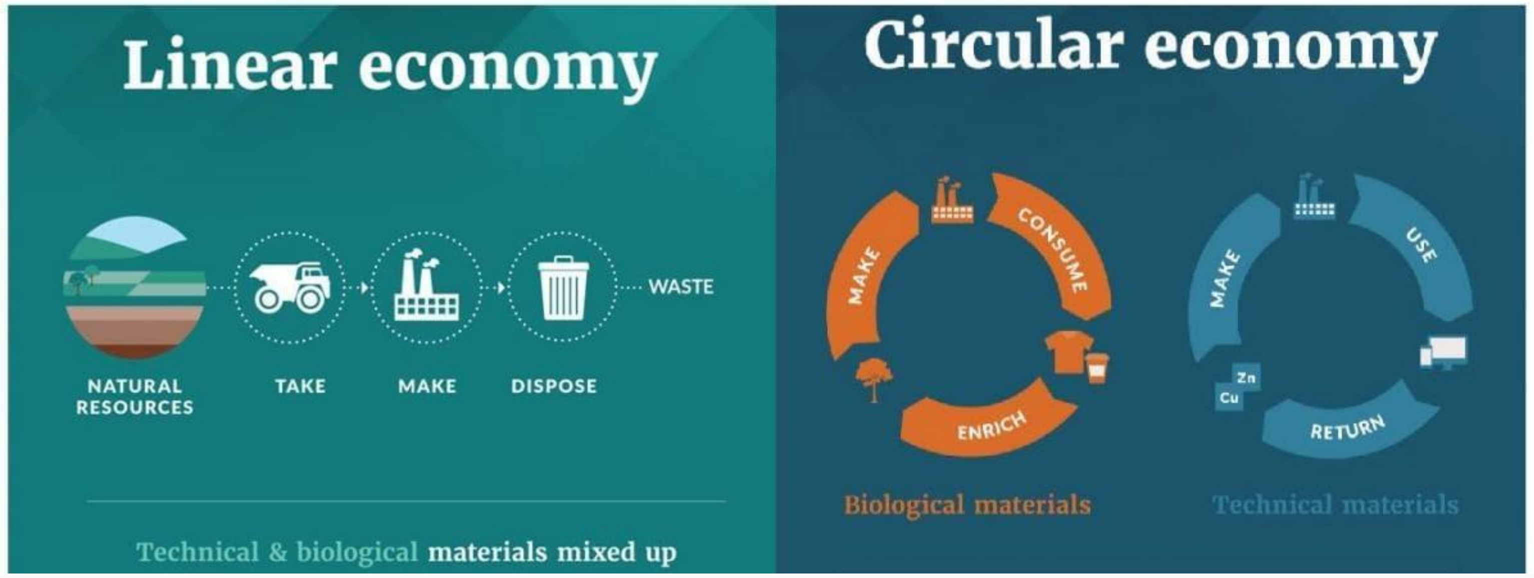
Context: circularity in water management

Conventional terrestrial water systems are linear:
produce (potable) water – **use** – **dispose** (as quickly as possible)
limitations of make-use-dispose model: Intensive source exploitation, high cost of eco degradation, large infrastructure, capital intensity



Circular water management is proposed as alternative:

- Emphasis on **enabling loops** (6R principle: Reduce, Reuse, Recycle, Restore-Replenish-Recover)
- Water reuse/recycling: Greywater recycling at residential and commercial buildings
- Water reduction: More proactive **reduction of demands** (water-smarter devices at households)
- Stormwater management: Addition of **local sources** (rainwater harvesting), retention of stormwater (Sustainable Urban Drainage Systems)
- Recovery and reclamation of natural sources (Aquifer Storage Recovery)



circular water
An analogue of circular economy (using water as a resource)

Context (II): circularity and links with resilience

As a cyclic management practice similar to natural system behaviour, circularity has intuitive, conceptual links to both **sustainability** and **resilience**.

- **Less waste** means more a **sustainable** practice.
- Loops and parallel flows increase system **redundancy** (redundant -> resilient)
- A **looped system** is (arguably) more tolerant against **stresses**.

However, the literature shows few **explicit links** between circularity, sustainability and resilience (Kirchherr et al. 2017)

- More (quantitative) examples linking the concepts are needed.
- Demonstrators using natural (real) systems are needed.

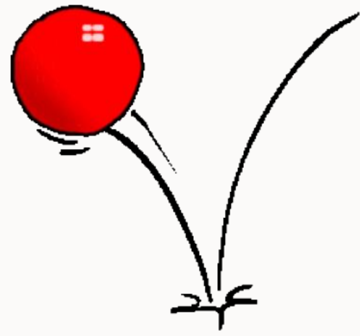
This work presents **quantitative links** between circularity and resilience, with an application in a real, regional water system.

Methods: Quantifying resilience in water systems

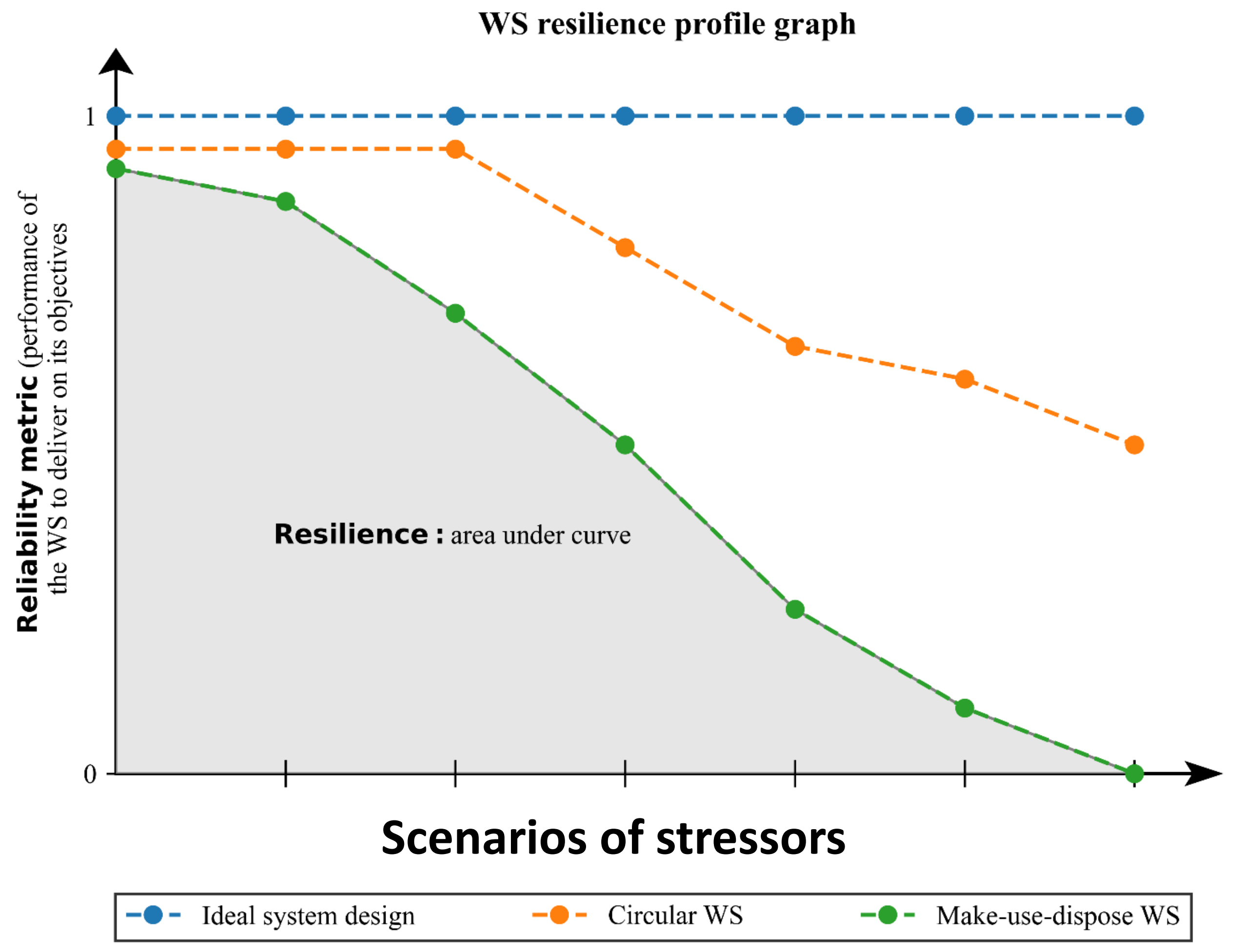
Resilience (Makropoulos et al., 2018):
The degree to which a Water System (WS) continues to perform well under increasing stress and disturbance.

re·sil·ience
rəˈzilyəns/
noun

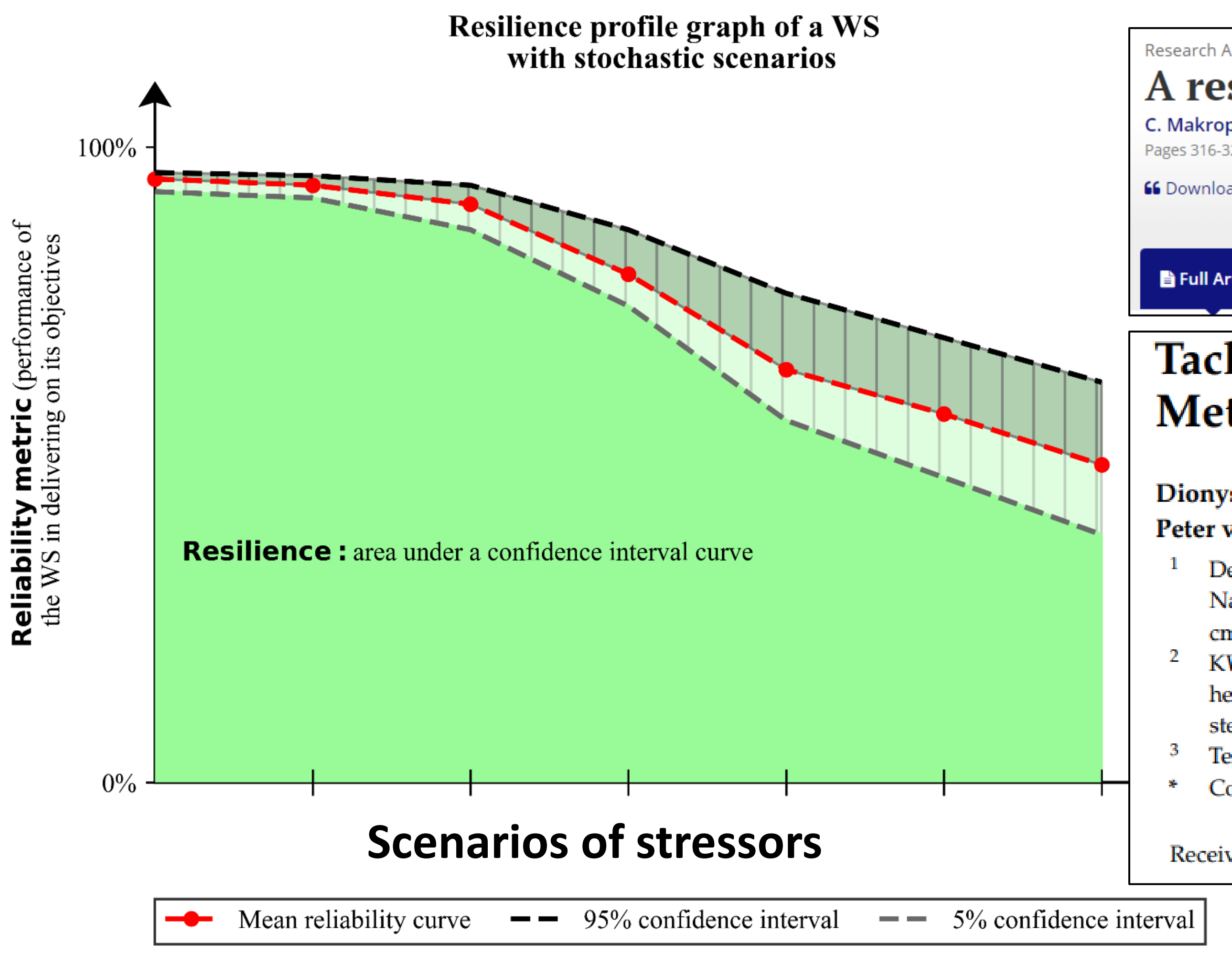
1. the ability of a substance or object to spring back into shape; elasticity.
"nylon is excellent in wearability and resilience"
2. the capacity to recover quickly from difficulties; toughness.
"the often remarkable resilience of so many British institutions"

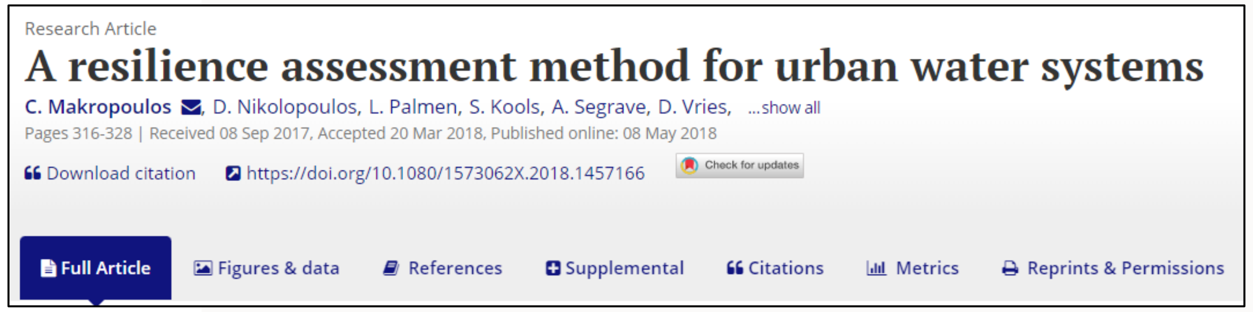


(a) Deterministic approach



(b) Probabilistic-stochastic approach





Research Article

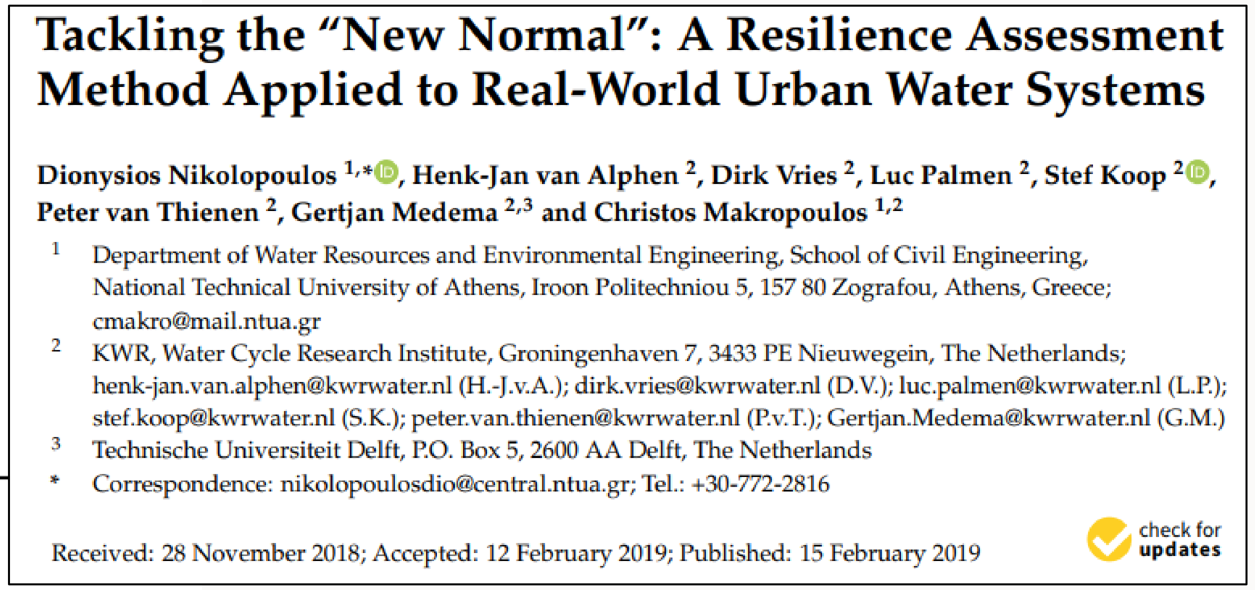
A resilience assessment method for urban water systems

C. Makropoulos, D. Nikolopoulos, L. Palmen, S. Kools, A. Segrave, D. Vries, ...show all

Pages 316-328 | Received 08 Sep 2017, Accepted 20 Mar 2018, Published online: 08 May 2018

Download citation https://doi.org/10.1080/1573062X.2018.1457166 Check for updates

Full Article | Figures & data | References | Supplemental | Citations | Metrics | Reprints & Permissions



Tackling the "New Normal": A Resilience Assessment Method Applied to Real-World Urban Water Systems

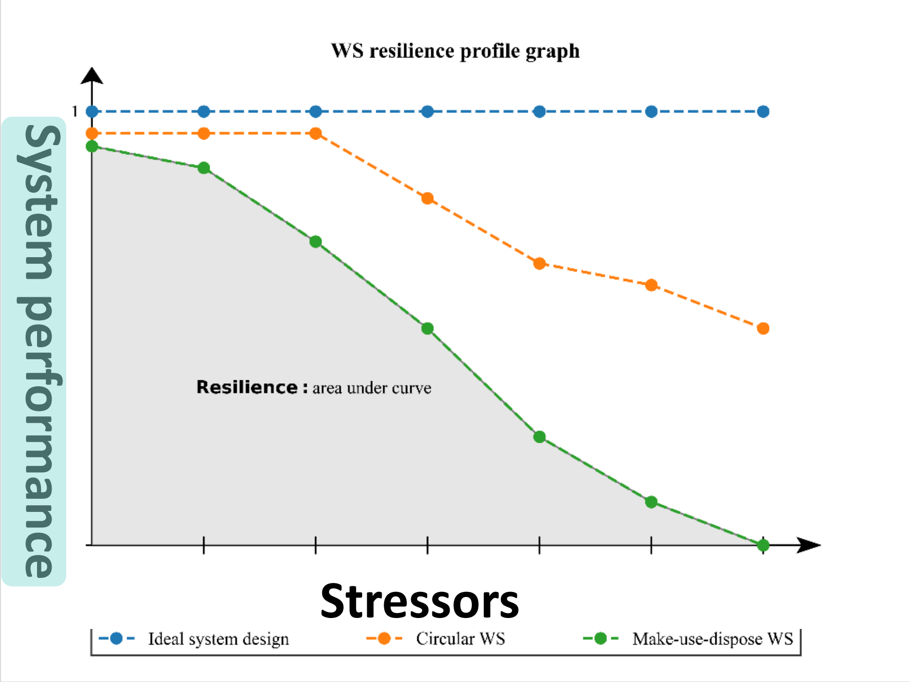
Dionysios Nikolopoulos [1,*], Henk-Jan van Alphen [2], Dirk Vries [2], Luc Palmen [2], Stef Koop [2], Peter van Thienen [2], Gertjan Medema [2,3] and Christos Makropoulos [1,2]

1 Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Politechniou 5, 157 80 Zografou, Athens, Greece; cmakro@mail.ntua.gr
2 KWR, Water Cycle Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands; henk-jan.van.alphen@kwrwater.nl (H.-J.v.A.); dirk.vries@kwrwater.nl (D.V.); luc.palmen@kwrwater.nl (L.P.); stef.koop@kwrwater.nl (S.K.); peter.van.thienen@kwrwater.nl (P.v.T.); Gertjan.Medema@kwrwater.nl (G.M.)
3 Technische Universiteit Delft, P.O. Box 5, 2600 AA Delft, The Netherlands
* Correspondence: nikolopoulosdio@central.ntua.gr; Tel.: +30-772-2816

Received: 28 November 2018; Accepted: 12 February 2019; Published: 15 February 2019 check for updates

Methods (II): simulation-based tools for circular systems

Resilience is **system performance vs. stress**



A **method** is needed to quantitatively evaluate system performance under a variety of different scenarios (with different stressors).

Evaluation through a stress-testing testbed called UWOT:

- UWOT is a simulation environment for arbitrary circular water systems.
- Able to quantify the performance of a system given daily scale forcing (demands, inputs, local rainwater etc.).
- To calculate resilience, UWOT is run recursively over an array of stressors and the system performance is assessed every time.

UWOT:
A modular simulation engine for (arbitrary) circular water systems

modular
Bottom-up, component based urban water cycle model

simulation engine
Built in C/Python, expandable, able to simulate daily/hourly flows
Typical scenarios run for 5-50 years (~10^4 values)

circular water system
able to model a range of circular interventions:
RWH, GWR, ASR, blue-green areas, water reducing appliances

arbitrary systems
from appliance level and up, house/neighborhood/city
Can model water quantity, as well as a single conservative pollutant in water quality (mg/L)

The way UWOT works

Signal-based, from demand nodes to sources.

Add household appliances, mix them together under different households.

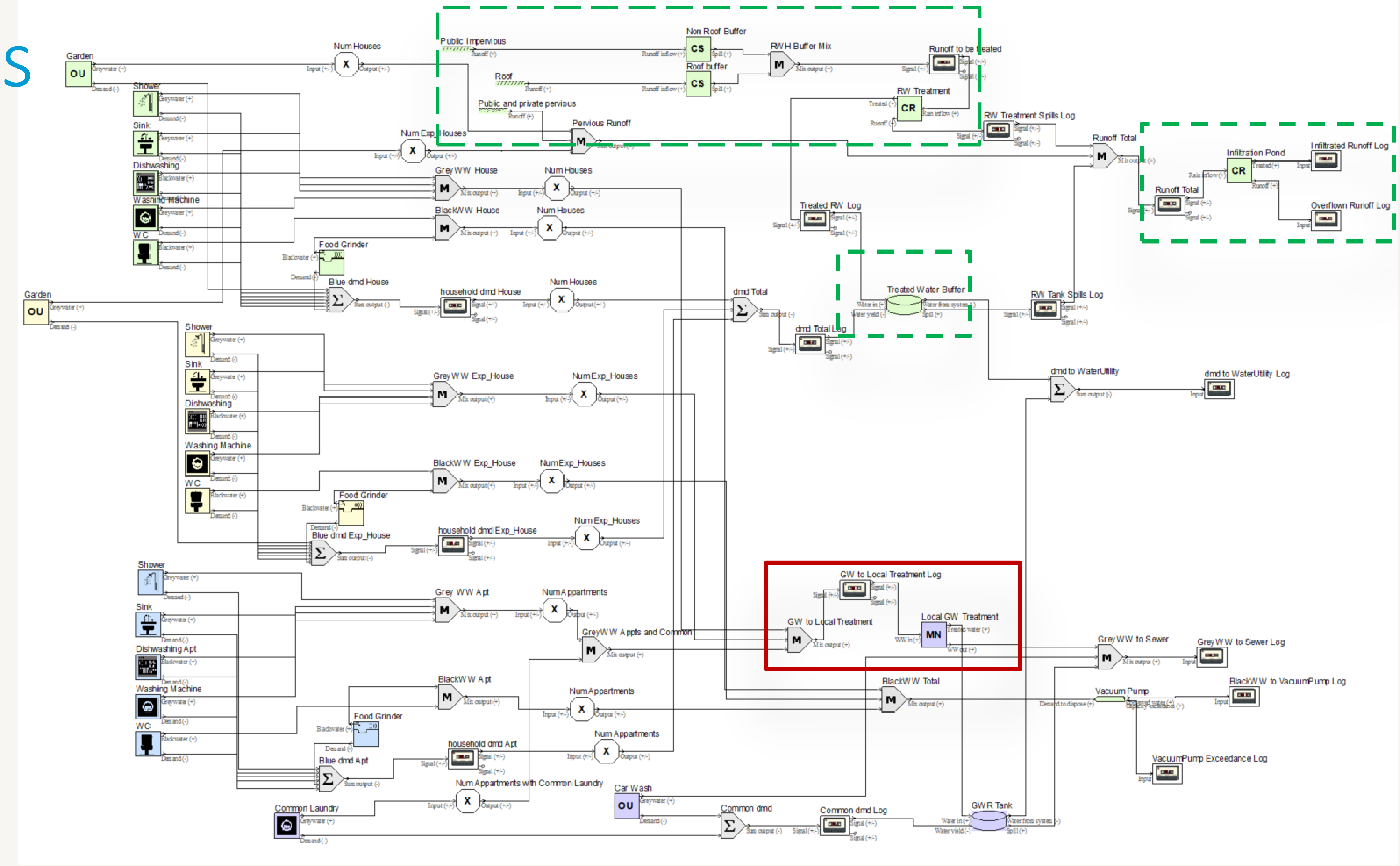
Include rainwater management, greywater recycling components, or regional measures (ASR).

Log stored water, covered demands, required energy at each time step.

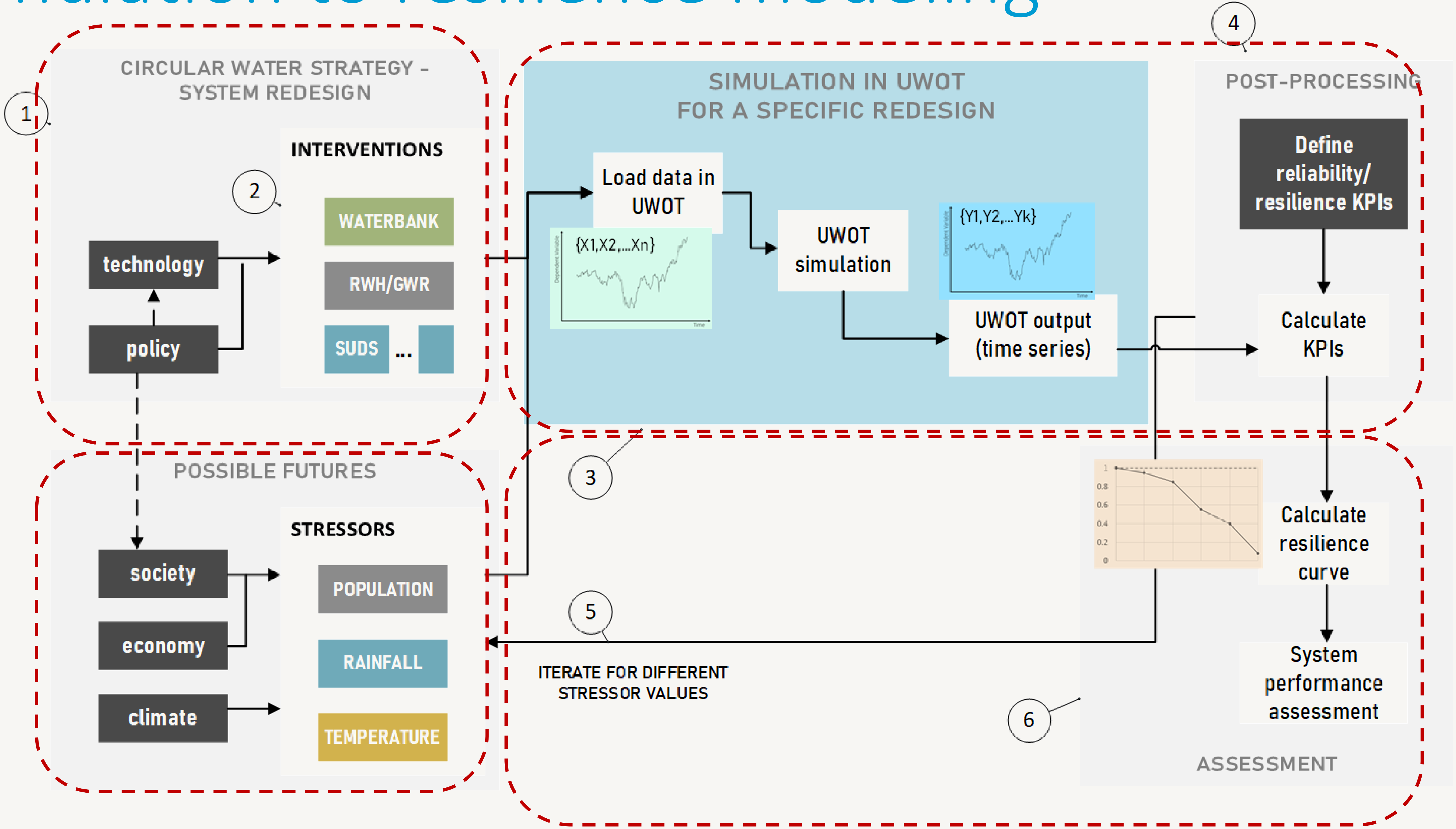
View results for a specified topology (set of techs).

Design and simulation of circular water systems: the UWOT model

Dimitrios Bouziotas [1], Dionysios Nikolopoulos [2], Klio Monokrousou [2], Jos Frijns [1] and Christos Makropoulos [1,2]

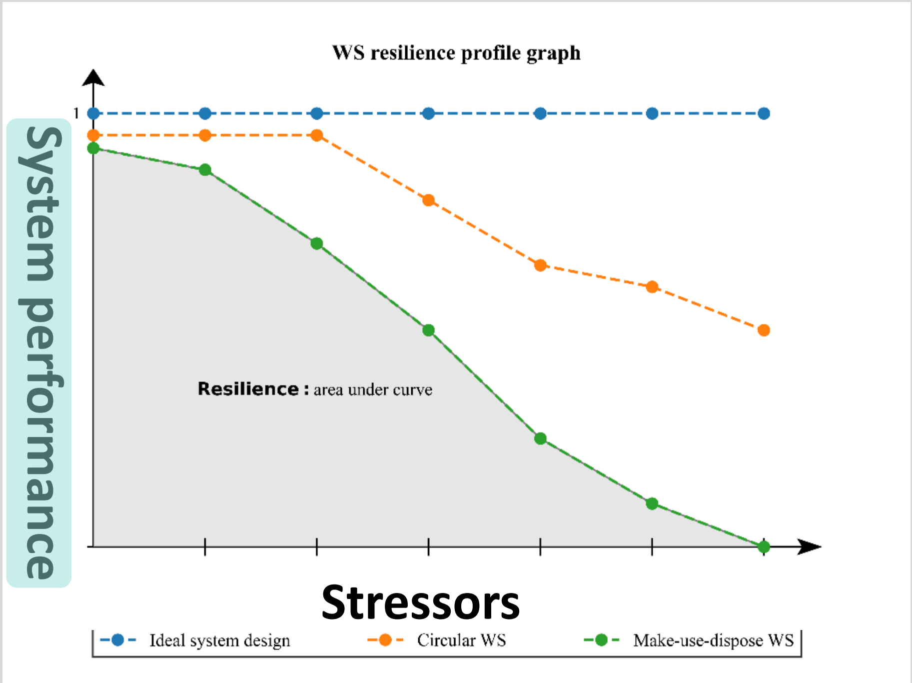


From simulation to resilience modeling



Performance metrics for resilience

Resilience is **system performance** vs. stress



A **metric** for the system performance is needed, able to be quantified through simulation.

The classic performance metrics for water systems are based on **reliability**, R (Hashimoto et al., 1982).

1. event- (or time-)based reliability $\mathbf{R_t}$: *the percentage of time (%) that a system operates well.*

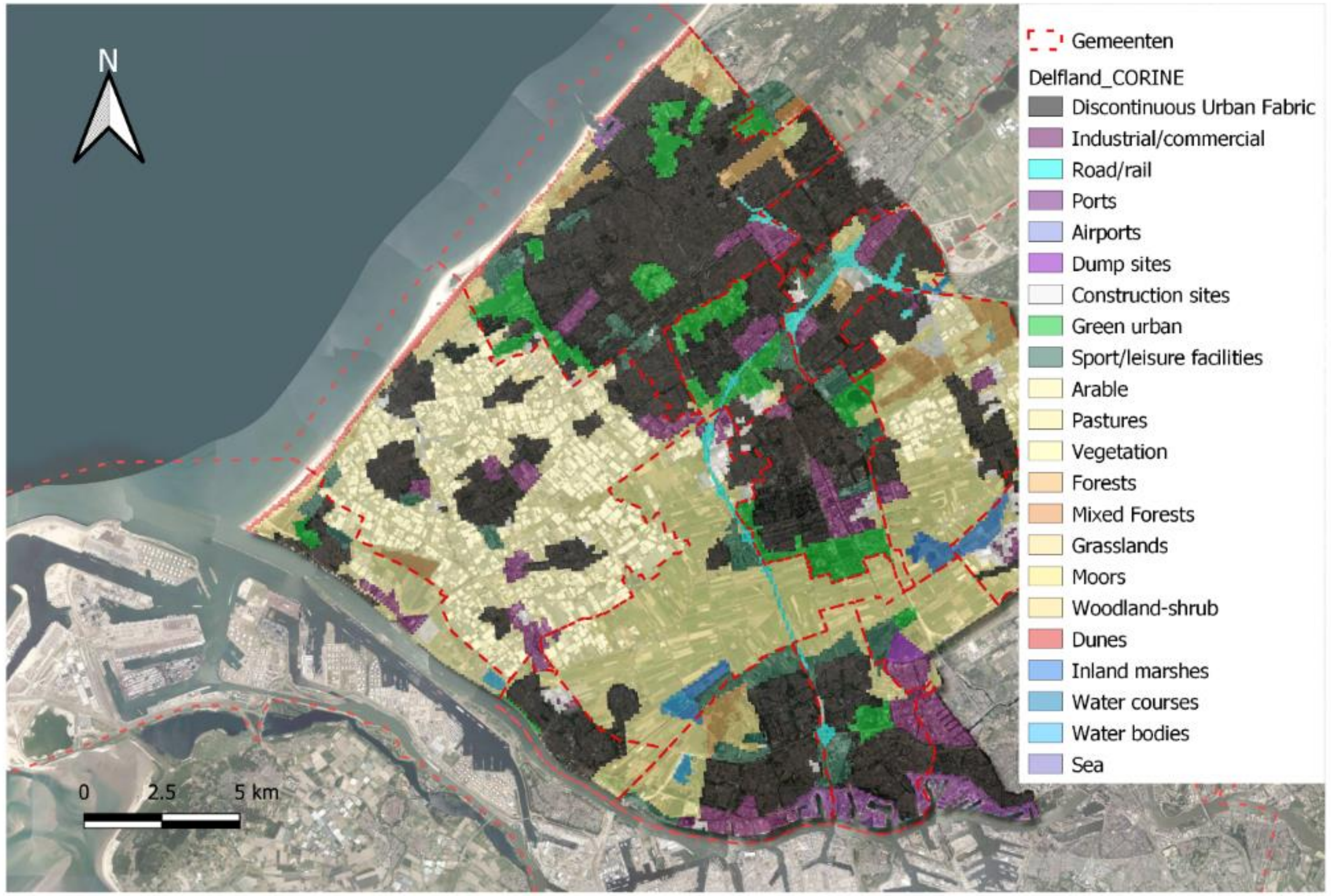
$$R_t = 1 - P_f = 1 - \frac{n_f}{n_{total}}$$

2. volumetric reliability $\mathbf{R_V}$: *the ratio of delivered (serviced) water volume to the demanded (requested) volume by the end users, over a specific simulation period (seasonal, annual, decadal)*

$$R_V = \frac{\sum_t V_{supply}}{\sum_t V_{demand}} = 1 - \frac{\sum_t V_{deficit}}{\sum_t V_{demand}}$$

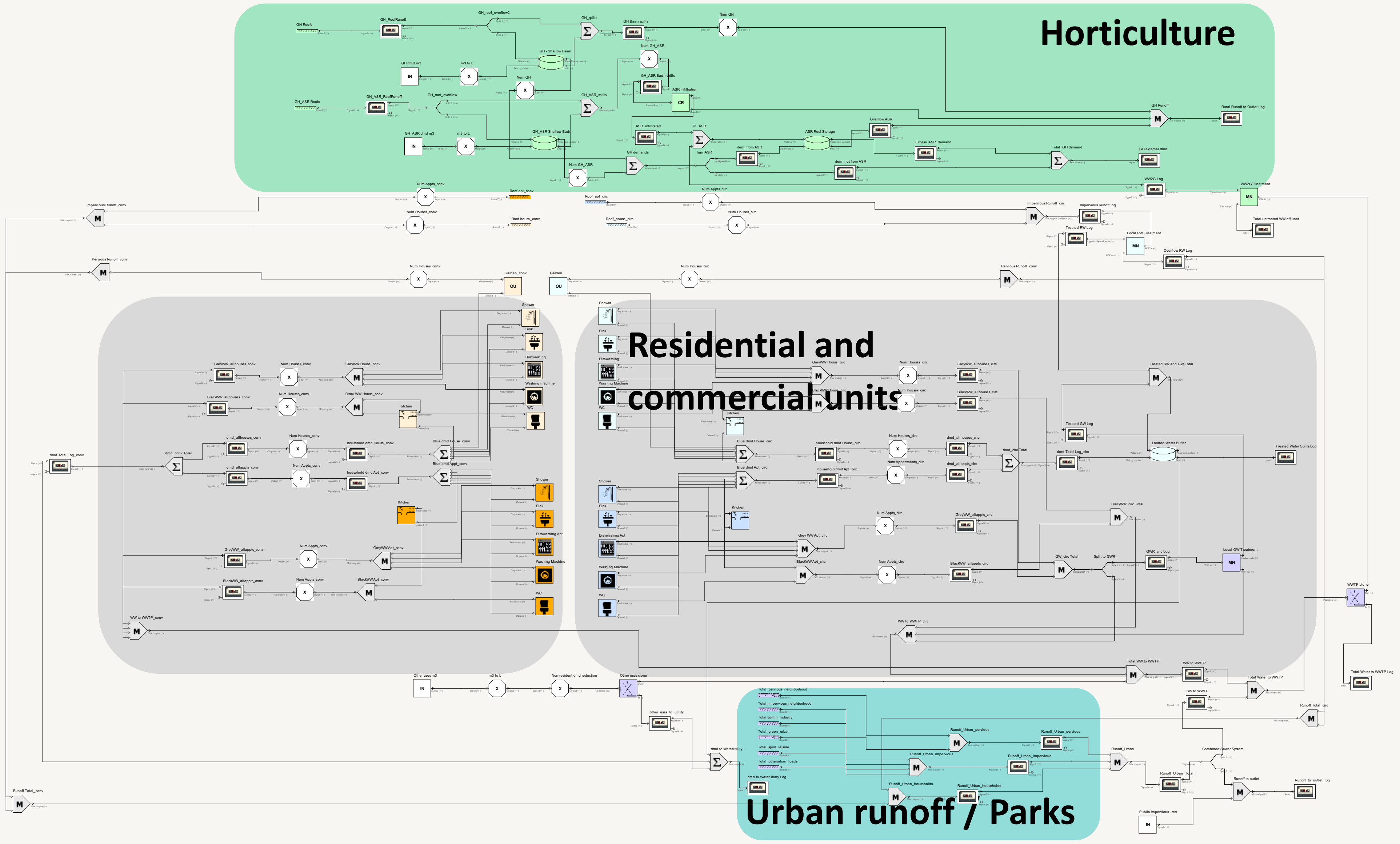
Both metrics *R* lie in [0,1], with 1 denoting perfect service (100% coverage) and 0 denoting fully failed service (0% coverage).

Regional case study: Delfland

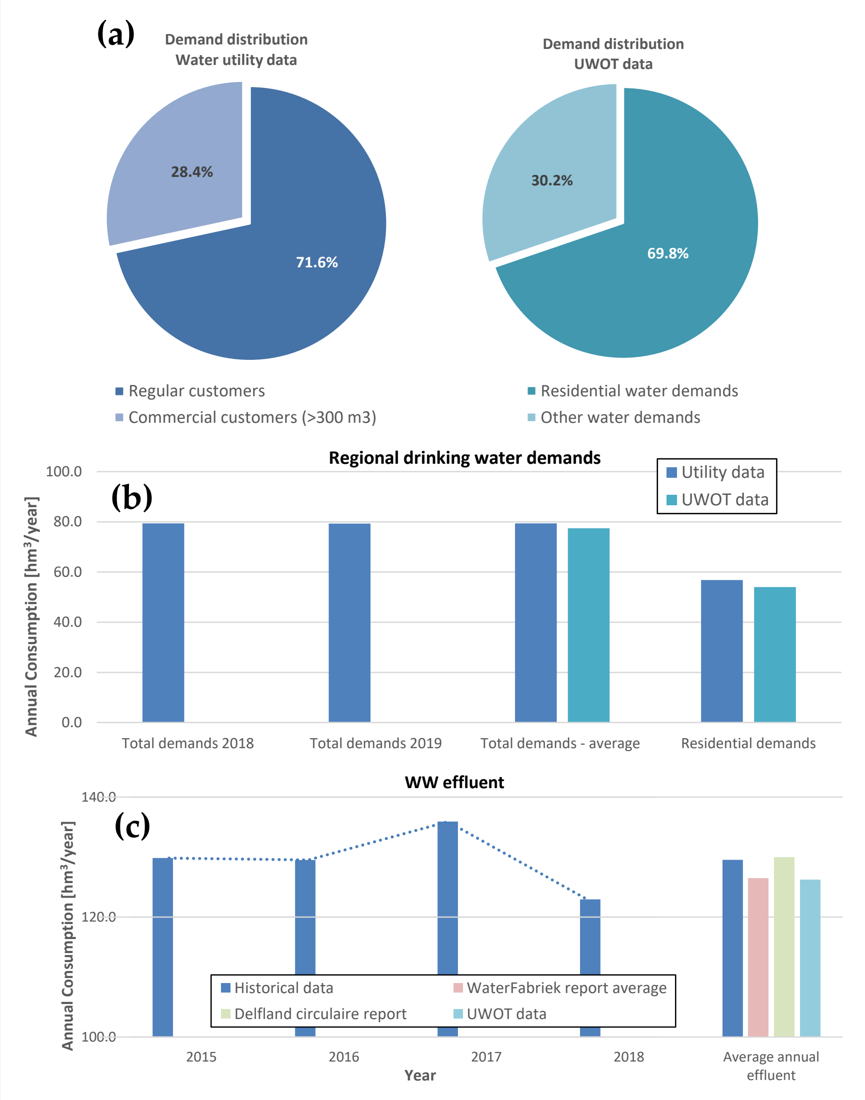


- Region with a total area of c. 410 km^2
- Features urban and industrial areas of high densities (Rotterdam, the Hague), as well as extensive greenhouse complexes in the Westland region.
- Renowned for its intensive greenhouse horticulture industry, with high irrigation demands (3000–10000 m^3/ha/year). Present system covers part of the demands using Rainwater Harvesting.
- One of the most densely populated spaces in the Netherlands and Europe, with approximately 1.2M inhabitants, 520,000 households.

Regional case study: Delfland (II)



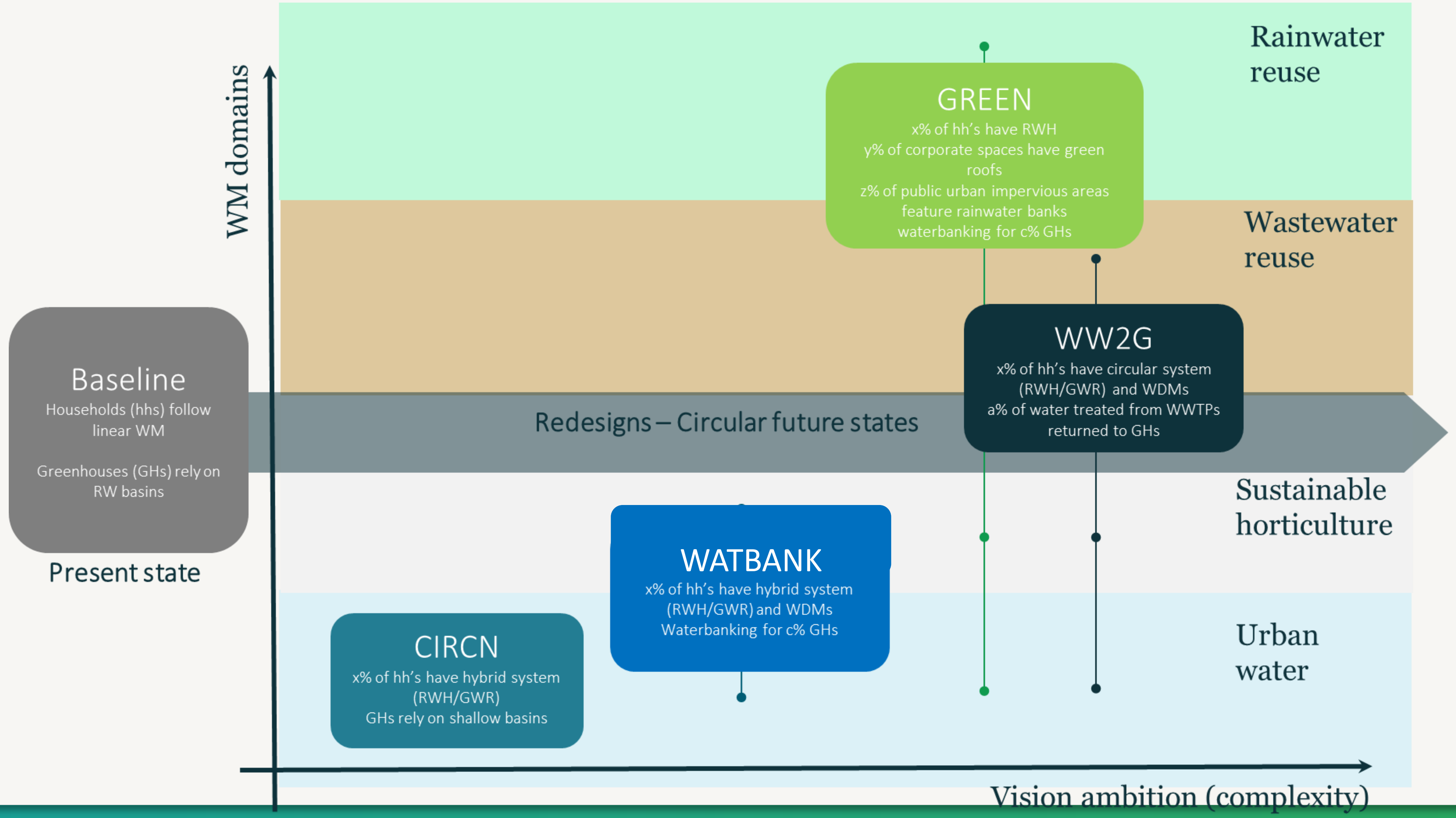
- A UWOT component model has been modeled for the region.
- Calibrated against real data and against other, sectoral studies against water demands, horticulture, regional WW effluent.



Description	Values/results in COASTAR	Values/results in UWOT model
Number of greenhouse units (HUs)	1291	1291
Rainfall on GH roofs [hm^3/year]	21.6	21.3
GH demand deficit, covered by RO [hm^3/year]	3.70	3.84
Overflow to surface water [hm^3/year]	4.70	4.72

Regional case study: Delfland (III)

- Towards a circular water system: regional redesign scenarios
- Four circular water strategies have been proposed and have their resilience calculated (along with the baseline)



Redesign	Parameter description	Unit	Parameter	CE dimension of WM interventions (referring to the redesign as a whole)			
				Reduce	Reuse	Recycle	Rest./Rep./Rec.
CIRCN	x_1% of circular houses	%	20.0%		x		
	x_2% of circ. apartments[1]	%	25.0%				
WATBANK	x_1% of circular houses	%	20.0%	x	x		x
	x_2% of circ. apartments[1]	%	25.0%				
	x_3% of houses with DRMs[2]	%	20.0%				
	x_4% of apartments with DRMs	%	25.0%				
	x_5% demand reduction for offices	%	20.0%				
	number of waterbanking GHs c	-	600/1291				
GREEN	x_1% of circular houses	%	20.0%		x		x
	x_2% of circ. apartments[1,4]	%	25.0%				
	y% of the commercial/industrial surface converted to green roofs	%	20.0%				
	z% of public impervious spaces converted to green spaces	%	20.0%				
	number of waterbanking GHs c	-	600/1291				
WW2G	x_1% of circular houses	%	20.0%	x	x	x	x
	x_2% of circ. apartments[1]	%	25.0%				
	x_3% of houses with DRMs	%	20.0%				
	x_4% of apartments with DRMs	%	25.0%				
	x_5% demand reduction for offices	%	20.0%				
	a% of WW effluent gets reused[3]	%	5.0%				

Comments:

[1] It is technically easier to introduce household interventions in stacks of apartments, hence the increased uptake.

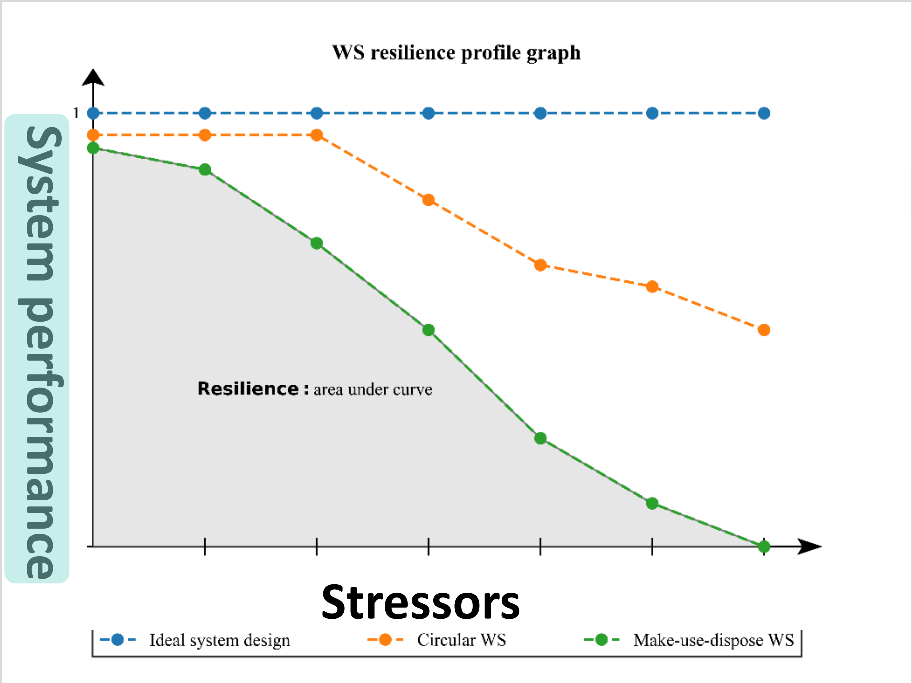
[2] As a limitation to the model, two house types are considered (conventional and circular), each with a household and apartment template, where DRMs are applicable only in circular types. As such there is the topological limitation that x_1=x_3 and x_2=x_4.

[3] This refers to the effluent capacity of one large WWTP closer to the horticulture area (Krajenbrink et al., 2021).

[4] Circular households and apartments in the GREEN scenario feature only a RWH system, instead of a hybrid RWH/GWR one.

Operationalisation of reliability metrics for Delfland

Resilience is **system performance** vs. stress



event- (or time-)based reliability $\mathbf{R_t}$:
the percentage of time (%) that a system operates well.

$$R_t = 1 - P_f = 1 - \frac{n_f}{n_{total}}$$

volumetric reliability $\mathbf{R_V}$:
the ratio of delivered (serviced) water volume to the demanded (requested) volume by the end users, over a specific simulation period (seasonal, annual, decadal)

$$R_V = \frac{\sum_t V_{supply}}{\sum_t V_{demand}} = 1 - \frac{\sum_t V_{deficit}}{\sum_t V_{demand}}$$

$$RCE = 1 - P_{f,cap} = 1 - P(Q > Q_c) = 1 - \frac{n_{Q>Qc}}{n_{total}}$$

RCE: Reliability against Capacity Exceedance
% of time that the capacity is not exceeded

$$RDD = 1 - P_f = 1 - P(Q_{DD} > 0) = 1 - \frac{n_{DD>0}}{n_{total}}$$

RDD: Reliability against Demand Deficit
% of time that deficits were not observed

DW, WW, SW

horticulture

$$PC = \frac{V_{supply,cap}}{V_{demand\ totals}}$$

PC: Present-day Coverage
% of demand volume able to be covered by the present-day supply capacity

$$SC = \frac{V_{supply,sust}}{V_{demand\ totals}}$$

SC: Sustainable Coverage
% of demands able to be sourced sustainably

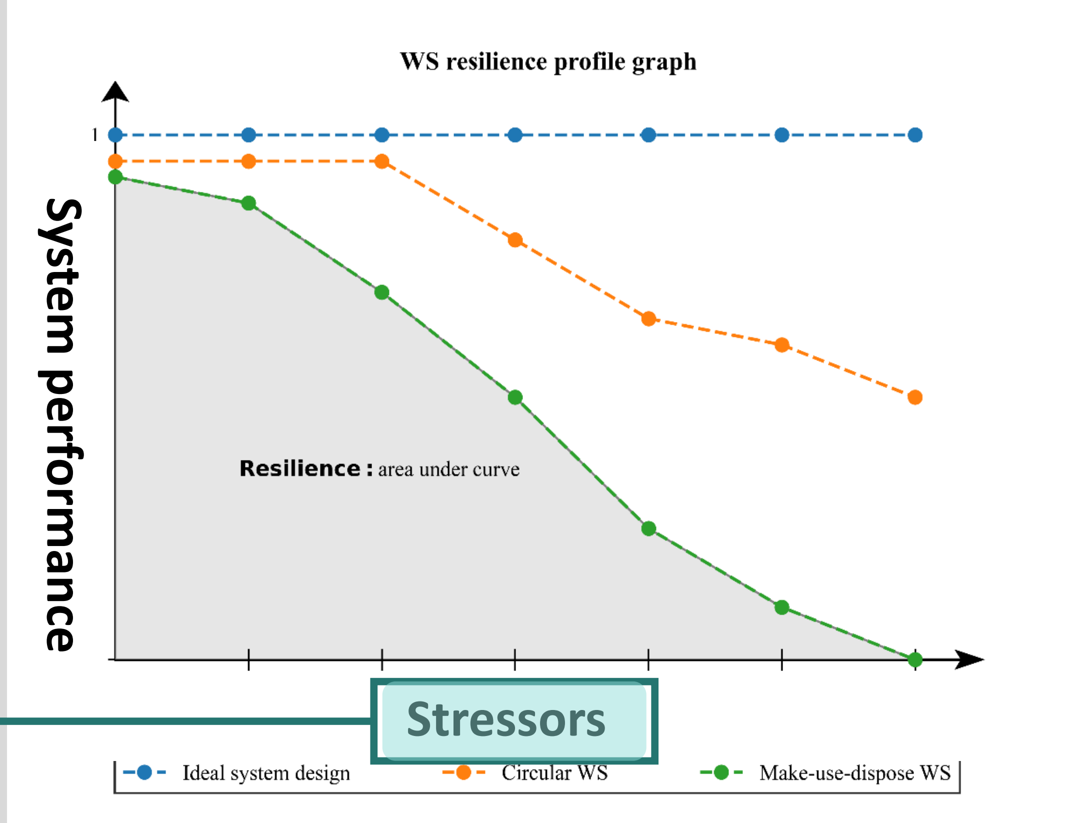
Stressors for Delfland

External factors that might change and affect system performance, leading to deterioration.

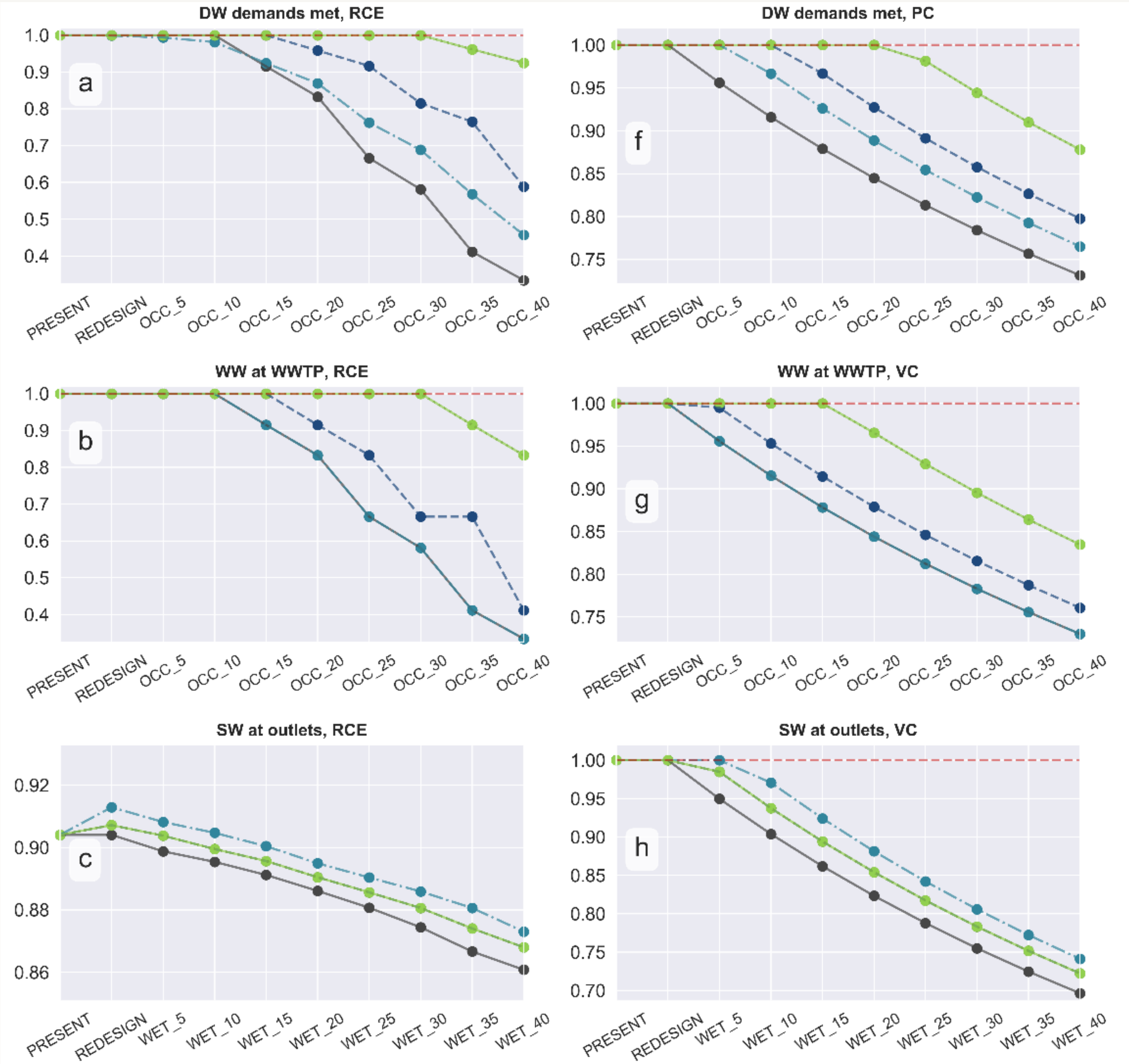
- **Rapid deterioration** of the system performance is reflected by a steep, declining resilience profile.
- A resilient system remains horizontal (performance unaffected by stressor).

Abbreviation	Stressor description	Defined as
OCC	Population and occupancy increase	% increase in present-day occupancy
HORTI	Horticulture demand increase	% increase in present-day horticulture demands
CLIMATE	Regional climate regime change	KNMI climate scenario and the corresponding interpolated regional station timeseries (precipitation, temperature).
WET	Wetness increase	% increase (shift) in the values of nonzero daily rainfall.
DRY	Dryness increase	% decrease (shift) in the values of nonzero daily rainfall.

Resilience is **system performance** vs. stress

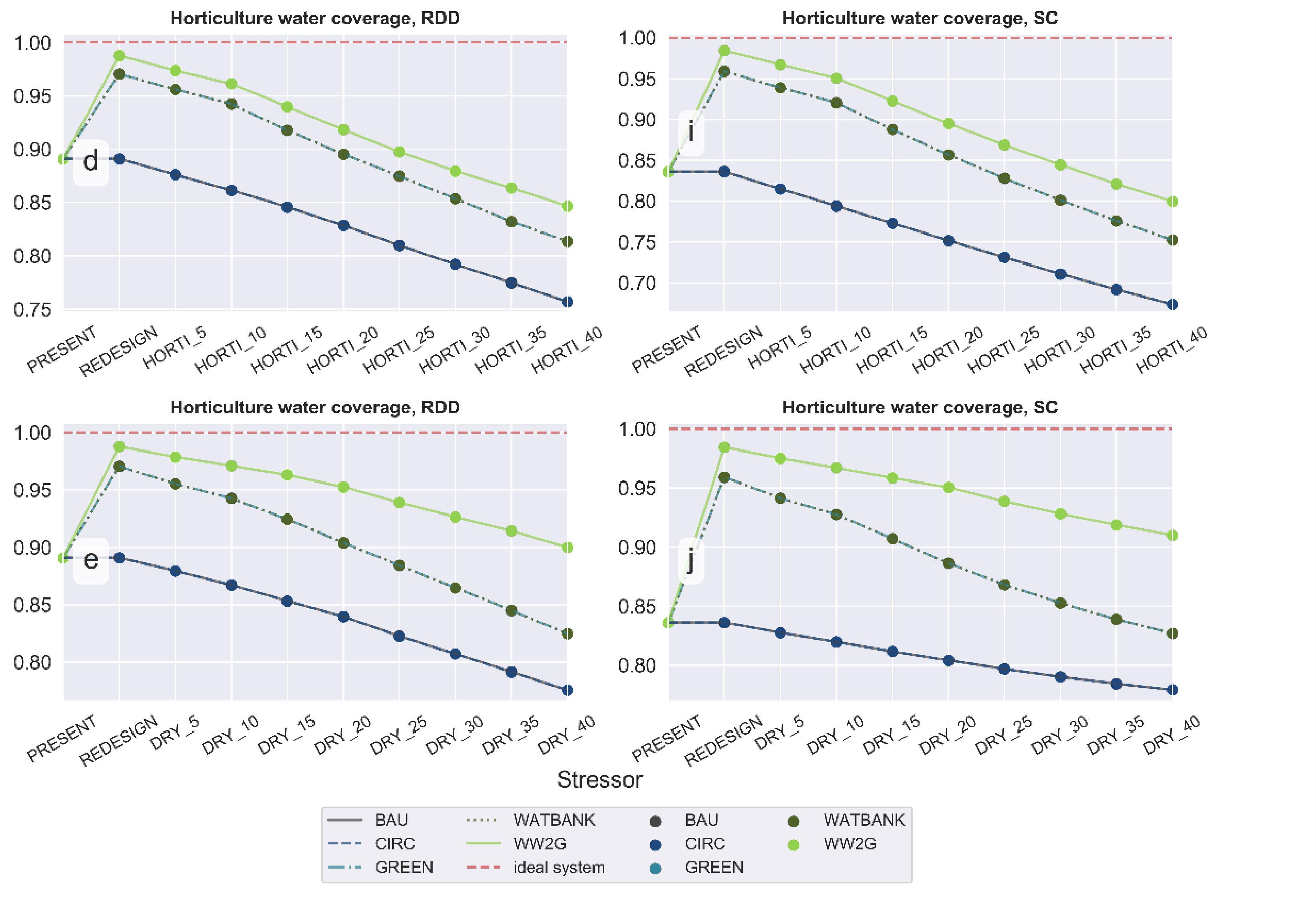


Results



- Individual stressor analysis.
- We test different domains (and reliability metrics) against individual stressors
- Different system redesigns

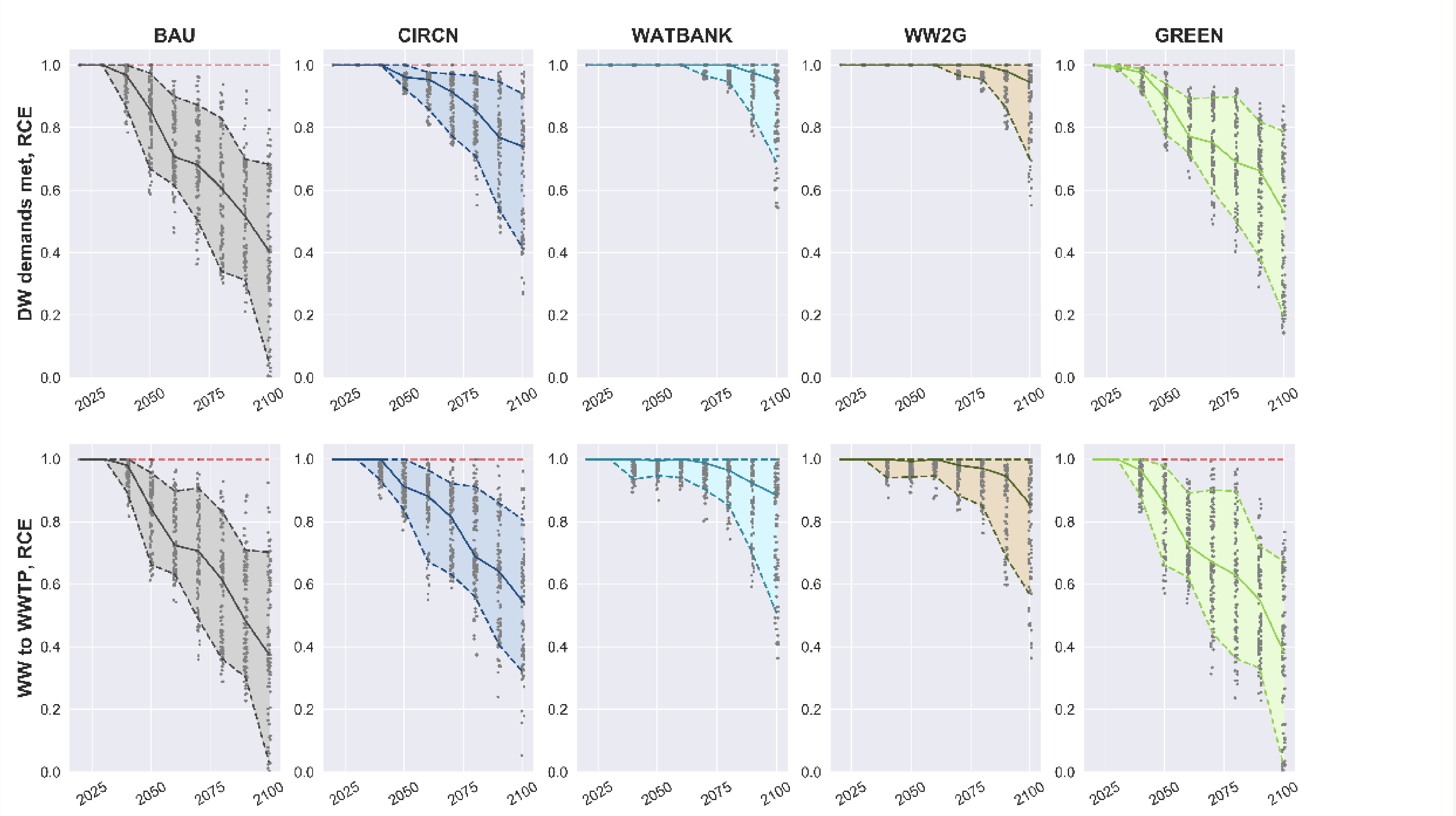
(HORTI demands, OCC, WET/DRY)

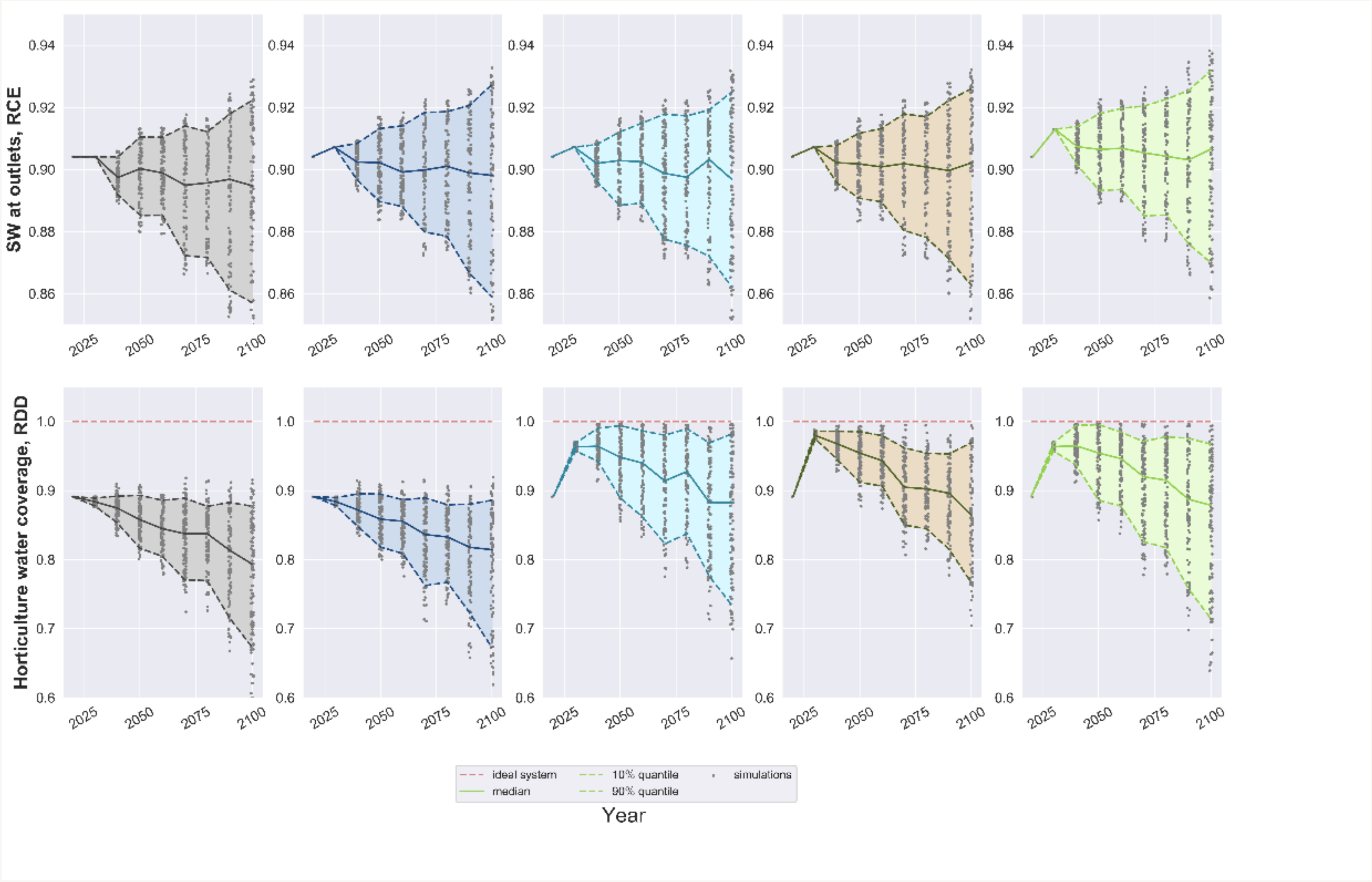


Results (II)

year of reference	2030	2040	2050	2060	2070	2080	2090	2100
stressor								
DRY/WET % change	-	[-10%,10%]	[-20%,20%]	[-20%,20%]	[-30%, 30%]	[-30%, 30%]	[-40%, 40%]	[-50%, 50%]
climate scenario	2030	2030	2050 (1 of 4)	2050 (1 of 4)	2085 (1 of 4)	2085 (1 of 4)	2085 (1 of 4)	2085 (1 of 4)
occupancy % increase	[0,5]	[0,10]	[5,15]	[5,20]	[10,30]	[10,30]	[15,40]	[15,50]
horticulture demands % increase	[0,5]	[0,10]	[5,15]	[5,20]	[10,30]	[10,30]	[15,40]	[15,50]

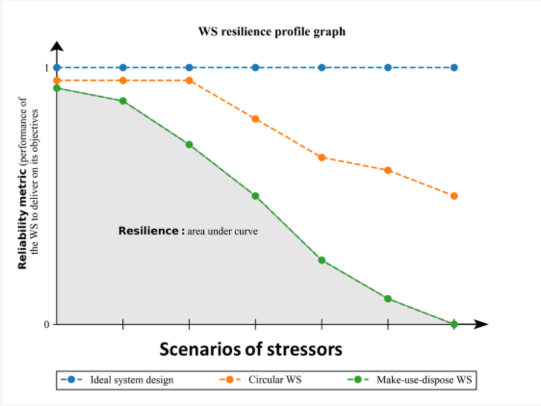
- A **probabilistic methodology** accounting for random change in multiple stressors.
- Exploring the effect of multiple stressors changing simultaneously.
- User assumes the **stressor bounds** per decade, as well as the **type of distribution**.

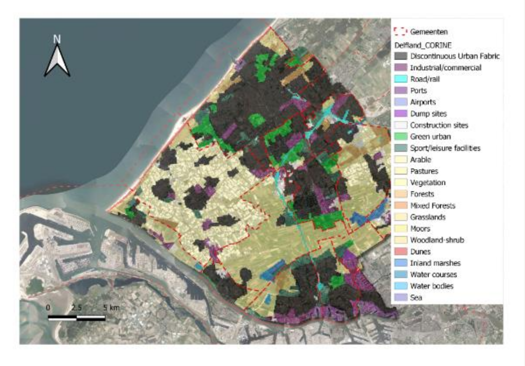


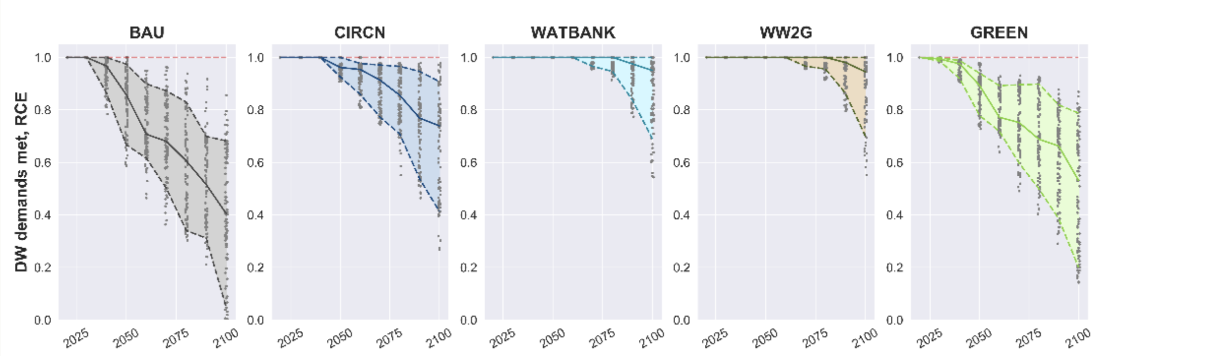


Conclusions

- We have presented a framework to **quantify the resilience** of both linear and **circular water** systems.
- Resilience is based on the so-called **resilience curves/profiles**: a projection of **system performance** over gradually worsening **stressors**.
- The framework is based on recursive **simulation using UWOT**, and able to quantify the resilience of arbitrary terrestrial systems (local – neighborhood, regional, whole-city). The application shown here is regional (Delfland, ~410 km^2).
- The case study of Delfland demonstrates, in a quantitative way, that **introducing circularity to a regional system affects its resilience positively**, in multiple water cycle domains (DW/WW/SW/horticulture).
- The positive influence (and domain specificity of it) depends on the circular measures, but in general: the more elaborate the circular strategy is, the more profound the influence towards resilience (multiple loops in multiple domains, multiple 'R' in a 6R circularity strategy covered).







Thank you for your attention!

Relevant (submitted) work

Article

Assessing the resilience of circularity in water management: a modeling framework to redesign and stress-test regional systems under uncertainty

Dimitrios Bouziotas[1,2,*], Sija Stofberg[1], Jos Frijns[1], Dionysios Nikolopoulos[2] and Christos Makropoulos[1,2]

1 KWR Water Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands; Dimitrios.Bouziotas@kwrwater.nl (D.B.); Sija.Stofberg@kwrwater.nl (S.F.S.); Jos.Frijns@kwrwater.nl (J.F.)
2 Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens (NTUA), Iroon Politechniou 5, 157 80 Zografou, Athens, Greece; cmakro@mail.ntua.gr (C.M.)
* Correspondence: Dimitrios.Bouziotas@kwrwater.nl; Tel.: +31 6 54294093

References:

Hashimoto, T., Stedinger, J.R. & Loucks, D.P. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. Water Resources Research

Kirchherr, J., Reike, D. & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling. [Online]. 127. p.pp. 221–232. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0921344917302835.

Klein Tank, A., Beersma, J., Bessembinder, J., van den Hurk, B. & Lenderink, G. (2014). Monograph. KNMI '14: climate scenarios for the Netherlands - a guide for professionals in climate adaption

Makropoulos, C., Nikolopoulos, D., Palmen, L., Kools, S., Segrave, A., Vries, D., Koop, S., van Alphen, H.J., Vonk, E., van Thienen, P., Rozos, E. & Medema, G. (2018). A resilience assessment method for urban water systems. Urban Water Journal.

Nikolopoulos, D., van Alphen, H.-J., Vries, D., Palmen, L., Koop, S., van Thienen, P., Medema, G. & Makropoulos, C. (2019). Tackling the "New Normal": A Resilience Assessment Method Applied to Real-World Urban Water Systems. Water. [Online]. 11 (2). p.p. 330. Available from: http://www.mdpi.com/2073-4441/11/2/330.

KWR

URBAN WATER MANAGEMENT AND HYDROINFORMATICS GROUP

National Technical University of Athens

Dimitrios Bouziotas
dimitrios.bouziotas@kwrwater.nl
Researcher, Resilient Management and Governance, KWR

Dionysios Nikolopoulos
Researcher, Hydroinformatics, NTUA

Sija Stofberg
Researcher, Geohydrology, KWR

Jos Frijns
Senior Researcher,
Team Leader Resilient Management and Governance, KWR

Christos Makropoulos
Professor in Urban Hydrology, Hydro-Informatics & Water Resources Management , NTUA
Principal Scientist, KWR