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Stochastic stress-testing approach for assessing resilience of urban water systems from source to tap

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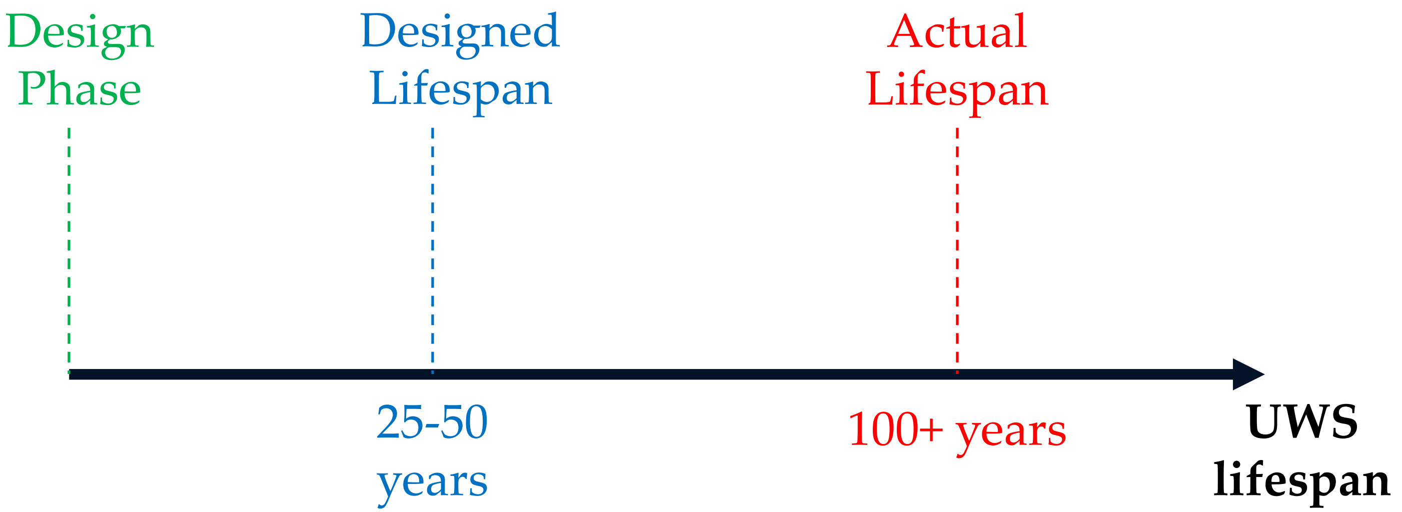
Urban water systems' (UWS) design & lifespan



Design Phase

Designed Lifespan

Actual Lifespan

25-50 years

100+ years

UWS lifespan

- Urban water systems are typically designed for a long lifespan, i.e., 25-50 years.
- However, in industrialized countries, designs are often outlived (e.g., in UK, France, USA, the entire systems (or parts of them) are over a century old) - most urban water systems were designed and built between 1930 and 1980.
- Budget for replacement is limited throughout the world
- Renewal rates are very low

Challenges for UWS

- Various aspects of the world are volatile and ever-changing, interacting with UWSs and affecting their operation and performance
  - Hydroclimatic factors (water availability and quality)
  - Socioeconomic factors (shifting demographics, urban growth, water demand patterns, economic crises, etc.)
  - Policy factors (e.g., water price, incentives for water conservation)

Urban water planners cannot foresee future

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Unknown and unknowable future pressures to UWS

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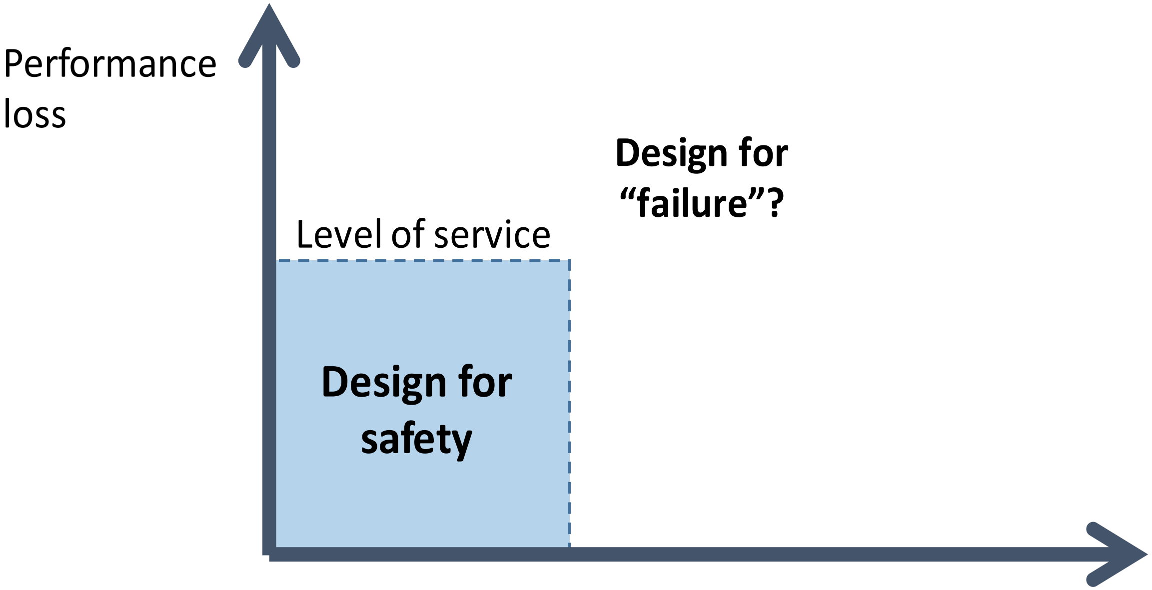
Long-term, large-scale uncertainty

UWS design paradigm shift

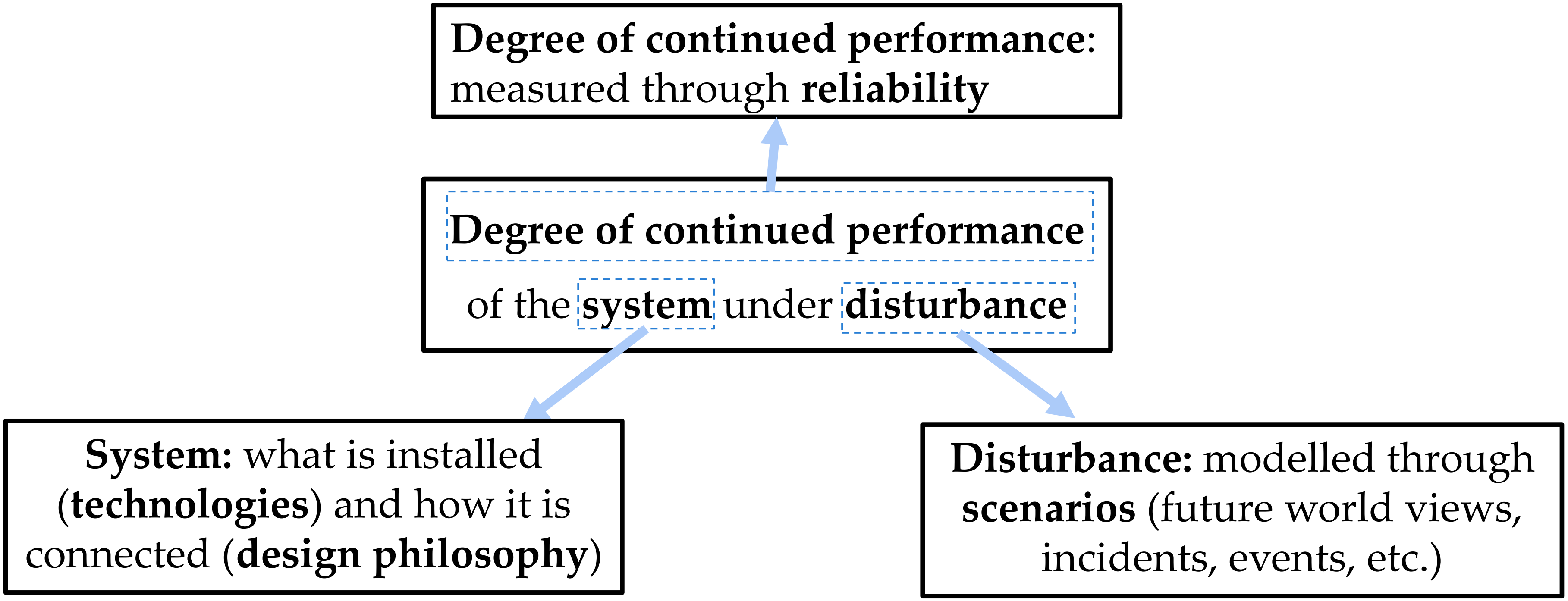
- Rethinking design objectives under large-scale uncertainty: 'fail-safe' system design vs 'safe to fail'



- Interest in **how our water systems 'behave'** when faced with accidents/incidents and/or extreme events and/or when faced with changing conditions.
- Interest in the capability of the system to **bounce back** quickly from a non-satisfactory state to delivering its goals again.
- Desired trait for UWS: **resilience**

Operationalizing resilience

- Holling (1973) on ecological systems' resilience: "the capacity of a system to absorb disturbance … so as to still retain essentially the same function, structure, identity, and feedbacks"
- Building on it, Makropoulos et al (2018) defined resilience for UWS as: "the degree to which a water system continues to perform under disturbance"



Degree of continued performance: measured through **reliability**

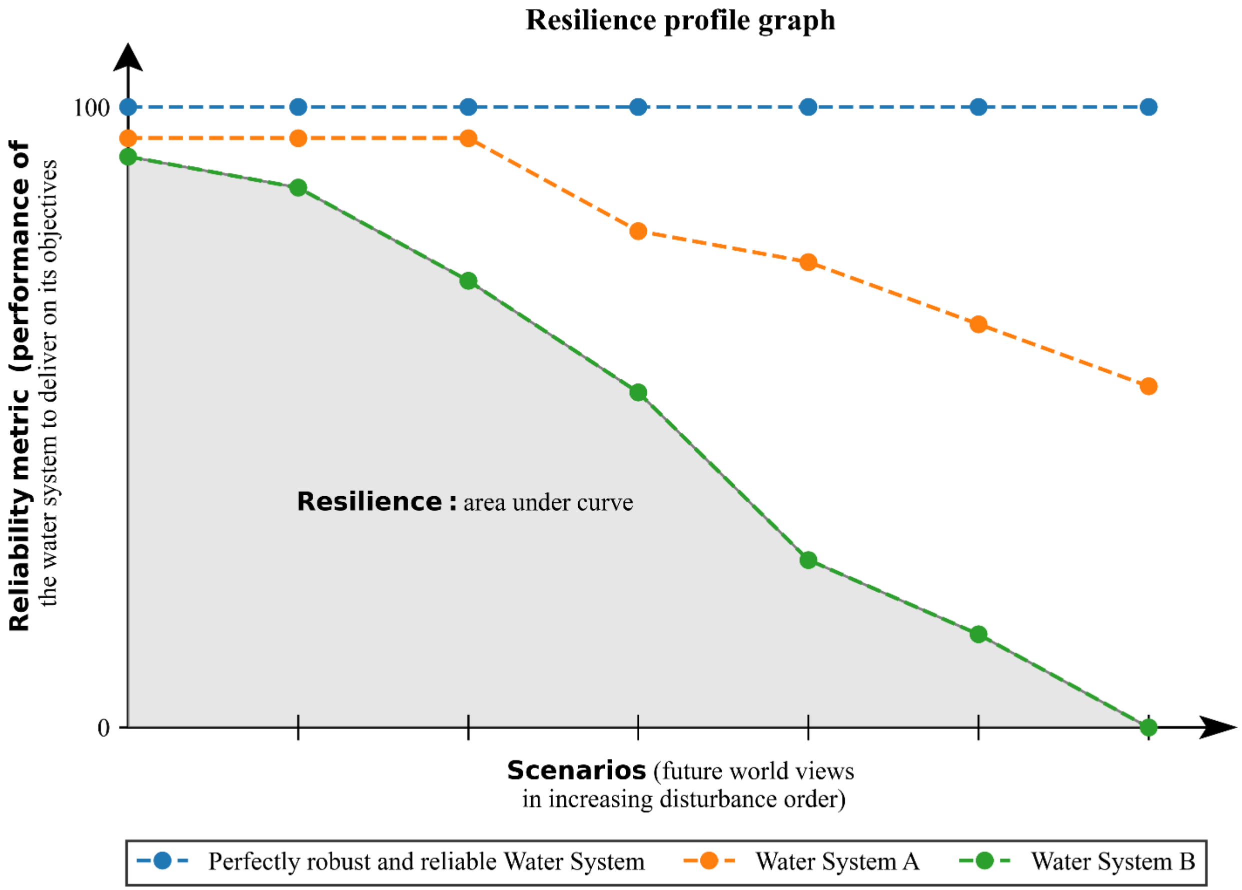
Degree of continued performance of the **system** under **disturbance**

System: what is installed (**technologies**) and how it is connected (**design philosophy**)

Disturbance: modelled through **scenarios** (future world views, incidents, events, etc.)

Communicating resilience with graphs

- Resilience is measured as the area under the reliability curve in a resilience profile graph, scaled between 0 and 1. This is achieved by comparing with the area of an ideal perfectly reliable system across all scenarios (ordered by in severity).
- The method has been applied to synthetic (Makropoulos et al 2018) and real-world UWS cases (Nikolopoulos et al 2019).



Need for an holistic simulation framework

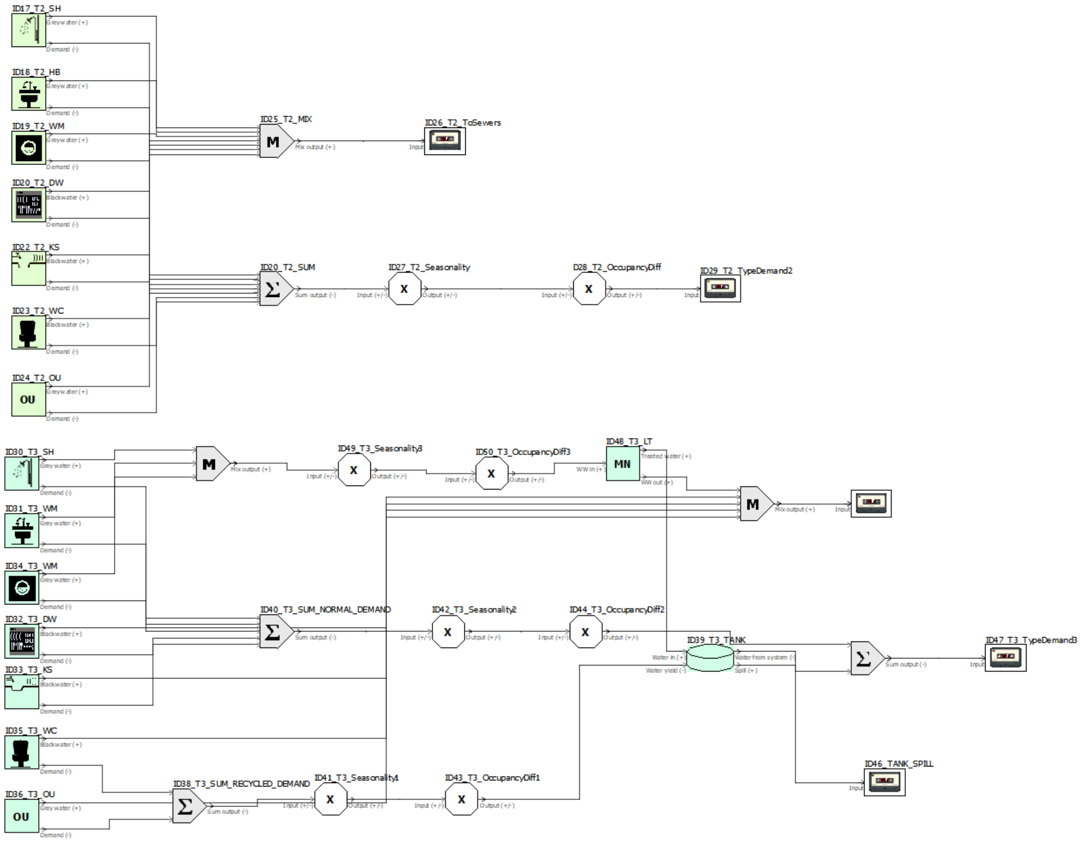
- The behaviour and properties of individual parts or sub-systems of a system is generally well modelled and understood.
- Modelling sub-systems under uncertainty: stochastic inputs and parameters or testing against a variety of future conditions
- Behaviour analysis of complex large systems with intertwining components: still a challenging task.
- A holistic analysis requires the usage of different simulation models for sub-systems with differences in:
  - inputs/outputs, data structures
  - computational complexity
  - temporal and spatial scales
  - metrics to measure performance
- Planners need to consider the assessment of different system topologies (deployment of technological assets) or different management decisions (operational decisions, target priorities, pricing strategies, etc.) across the whole system as a single unit under sets of significantly different, uncertain futures.

Coupling tools in a holistic simulation framework

- 4 tools: UWOT (Rozos and Makropoulos, 2013), EPANET 2.2 (Rossman et al, 2020), Hydronomeas2020 (Karavokiros et al, 2020) and AnySim (Tsoukalas et al, 2020)

UWOT

- Model water demand
- Utilized in the software coupling at household level to describe demographics, water use patterns appliance technology and temporal changes
- Different types of consumers can be modelled
- Coupled through Python API



Coupling tools in a holistic simulation framework

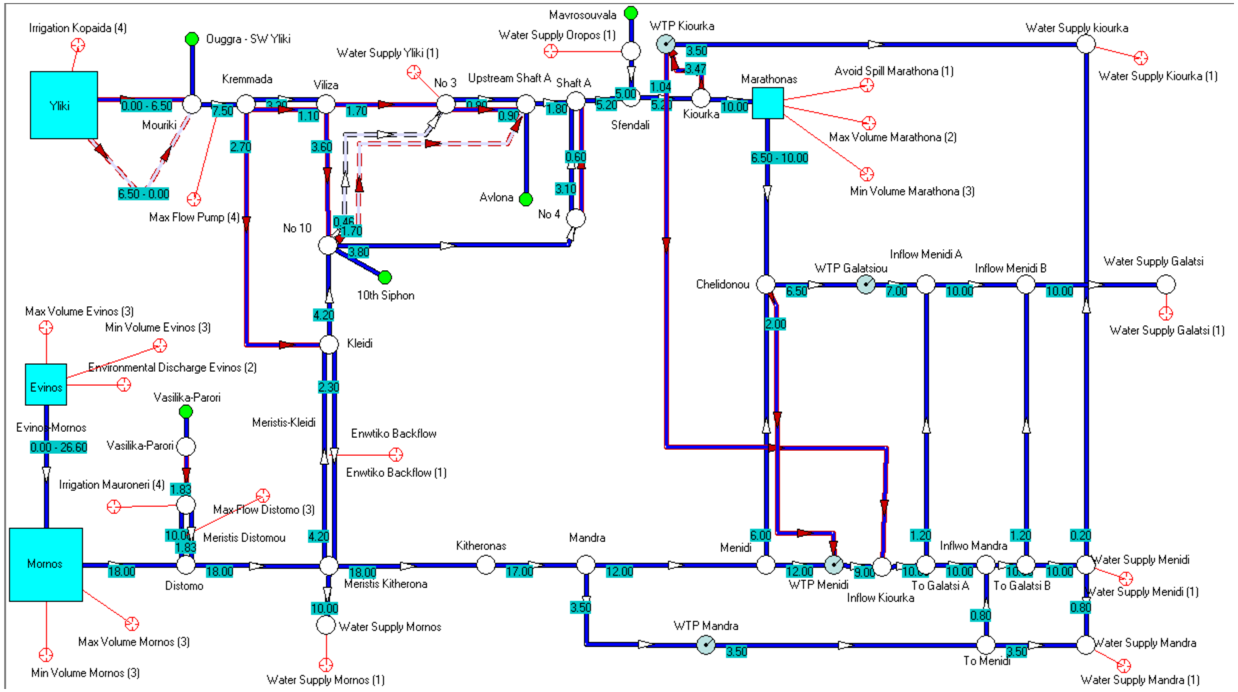
EPANET 2.2

- Hydraulic solver
- Utilized in the software coupling to model water hydraulics in the distribution subsystem of the UWS
- Employs a pressure driven demand analysis solver to accurately simulate failure circumstances
- Coupled through Python package WNTR (Klise et al, 2017)

Coupling tools in a holistic simulation framework

Hydronomeas2020

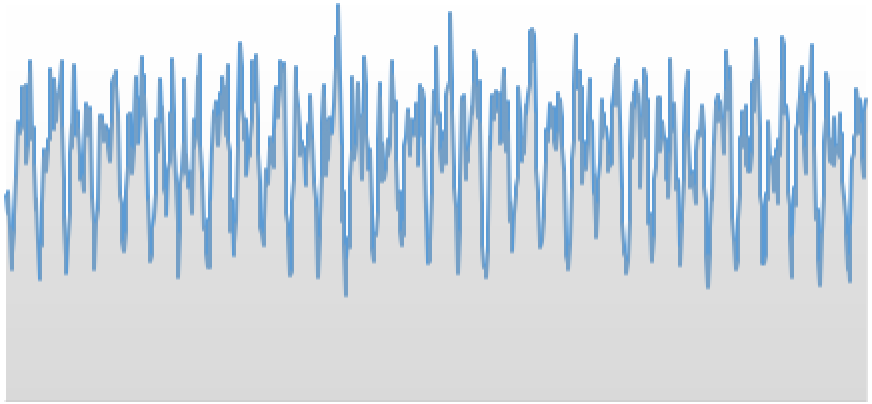
- Decision Support System for water supply works
- Utilized in the software coupling to model water availability, water supply, the water transportation system and decision making (target priorities, water policy, costs etc.)
- Coupled through the new Python version



Coupling tools in a holistic simulation framework

AnySim

- Stochastic model to provide synthetic inputs for the various tools
- Arbitrary time scales



Coupling the models

- AnySim generates stochastic inputs for all tools.
- UWOT generates the daily water demand of different household types for a design horizon, with changing appliances, population, behavioural demand etc.
- Nodes in EPANET are assigned a mix of household types (changing through time), and the nodal daily demand is aggregated. Disaggregation to hourly (or finer) timesteps is accomplished with stochastic patterns generated by AnySim.
- EPANET hydraulic simulation generates the daily water production needs, as well any failure to distribute water, water losses due to leaks etc.
- Hydronomeas2020 simulates the water supply and transportation component of the UWS with the daily water production needs as a target.
- Final reliability metric is aggregated from both hydraulic and hydrologic reliability sub-metrics from EPANET and Hydronomeas2020

Toy case study

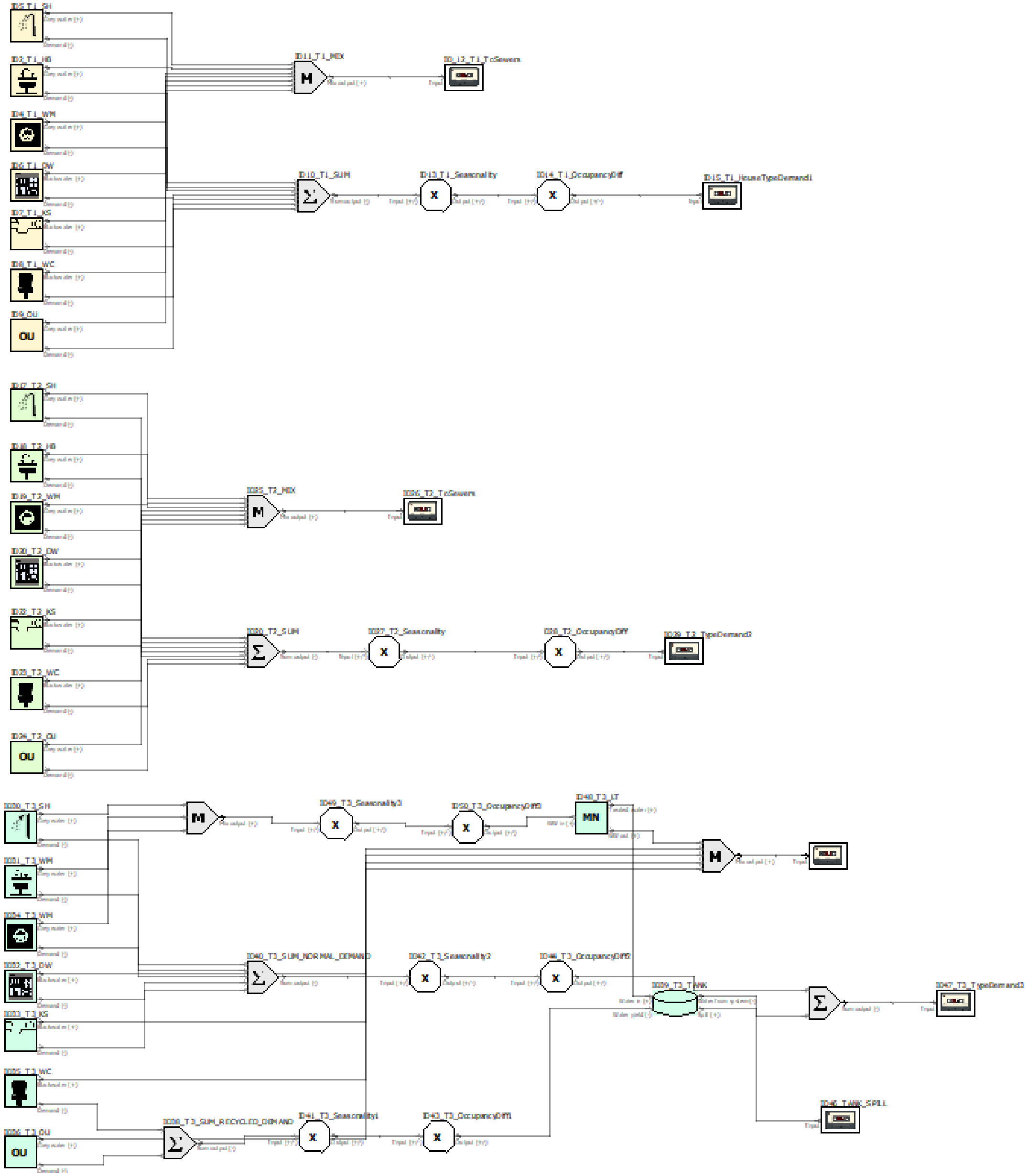
- C-Town water distribution network (Ostfeld et al. 2012)
- Controls are altered to allow full water flow form the source if needed.
- 5 synthetic hourly demand pattern multipliers generated by AnySim (one for each DMA), for a 25-year horizon.
- Pipe bursts are generated stochastically with a basic daily probability per km of pipe, affected also by the diameter of pipe.
- Every node represents a neighbourhood with a mix of three household types.
- The number of households in a node is changing through time to simulate urban growth.

Toy case study

- Household type 1: conventional appliances
- Household 2: water conserving appliances
- Household 3: water conserving appliances + local grey water recycling and a water tank for storage

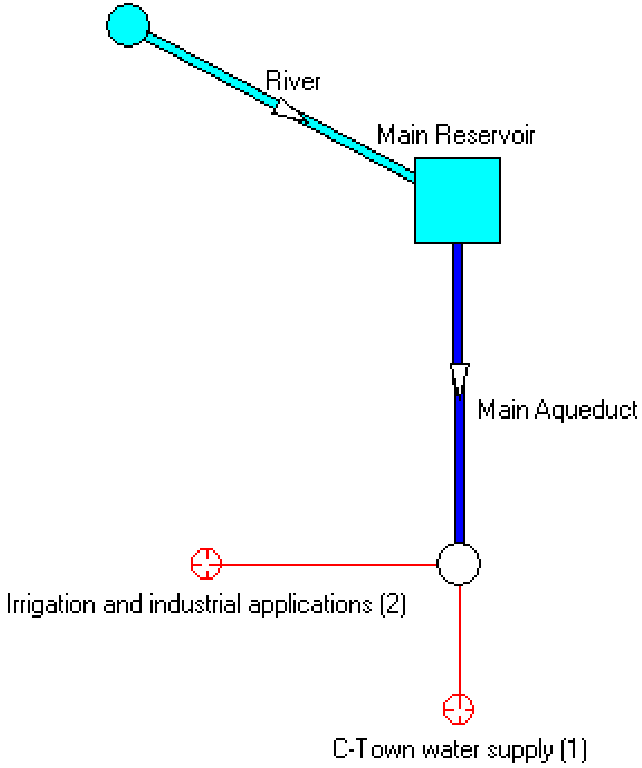
Changing parameters in a scenario:

- Average household occupancy
- Frequency of water appliances usage
- Seasonal demand fluctuation



Toy case study

- Simple water supply system consisting of a surface water reservoir, an aqueduct and two different water use targets (drinking water supply and non-potable irrigation and industrial applications).
- Rainfall, river inflows and evaporation are stochastically generated inputs from AnySim.
- Aqueduct leakage is a parameter that can be changed due to the decision-making process (allocating budget for repairs) in a future world view.
- Target priorities are parameters that can be changed due to the decision-making process in a future world view.



Systems and scenarios

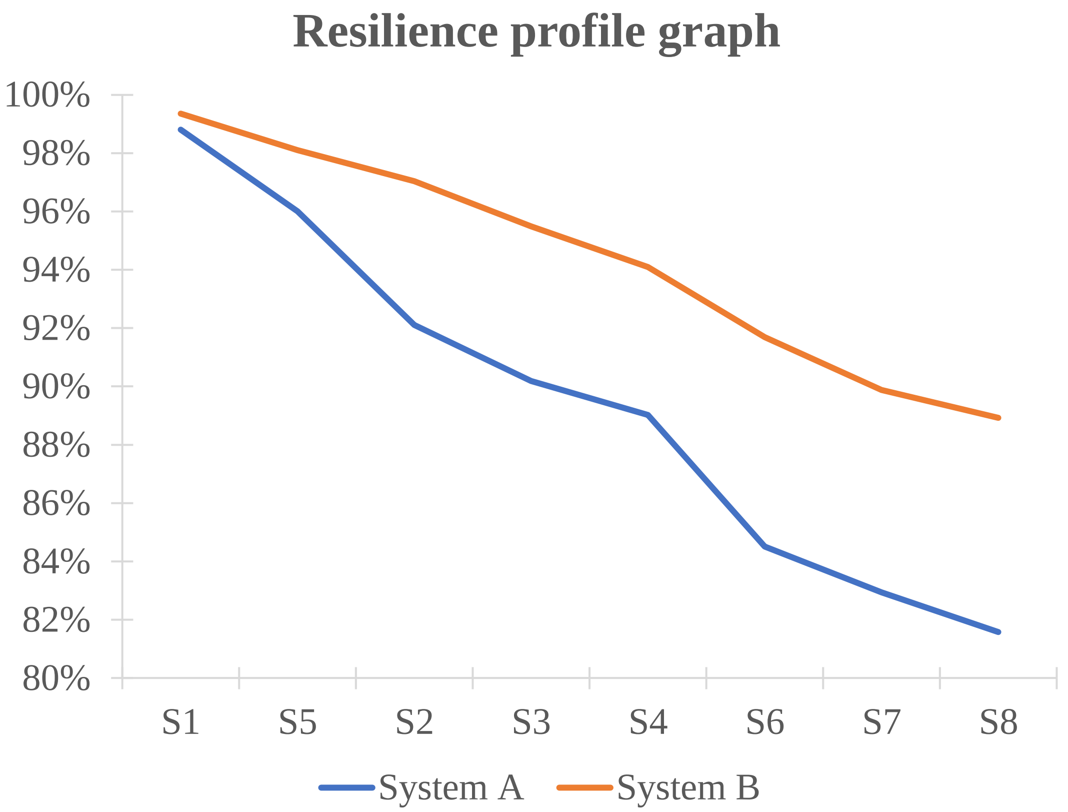
- System A: business as usual
- System B: incentives for consumers through subsidization to change household types to II and III, budget for repairs and replacement to aqueducts and pipes in the UWS

- 8 scenarios (future world views) for stress-testing the 2 systems:

Scenario	**Description**
S1	Baseline future world view
S2	Decreased water availability I
S3	Decreased water availability II
S4	Decreased water availability III
S5	Increased demand
S6	Increased demand and decreased water availability I
S7	Increased demand and decreased water availability II
S8	Increased demand and decreased water availability III

Resilience assessment results

- As demonstrated, System B is more resilient than System A when subjected to the same future world views.
- Resilience scores for the whole system as one unit (0-1):
  - System A: 0.894
  - System B: 0.943



Conclusions

- The resilience assessment methodology is extended to support holistic analysis on an UWS as a single unit.
- Both hydraulic and hydrological aspects of the system can be simulated through the coupling of EPANET 2.2 with Hydronomeas2020.
- UWOT can be utilized as a full-fledged demand generation model when coupled with the capabilities of AnySim to accept stochastic inputs and then disaggregate daily demand to finer time-scales for use in EPANET demand junctions, while Hydronomeas2020 simulates the water availability in EPANET reservoir nodes.
- The UWS resilience concept could be extended in the future to also include the stormwater and wastewater aspects of urban water systems in case studies.
- It is envisaged that the resilience assessment methodology and the coupled simulation framework presented here can aid water utilities in strategic planning, decision making, risk and asset management.

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