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A Stochastic Approach To Resilience Assessment Of Urban Water Systems From Source To Tap

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Abstract. The design of urban water systems faces long-term uncertainties in a multitude of parameters, from the hydroclimatic and socioeconomic realms, such as population growth, climate change and shifting demand patterns. To analyze such systems in a holistic way, many models for sub-systems are typically involved, while the performance of different designs is generally measured against a variety of metrics and in different times scales for each sub-system. In this work, we present a framework for stress-testing urban water systems based on the novel metric of a system's resilience, i.e., the degree to which a water system continues to perform under progressively increasing disturbance. The framework covers the entire water cycle, by coupling a water resources management model to a hydraulic water distribution model thus covering the water system from source to tap. The framework is underpinned by a stochastic simulation module supporting the representation and capturing of uncertainty throughout the water cycle. To assess the system's resilience under uncertainty, we "stress-test" it with an ensemble of scenarios whose parameters are stochastically changing within a design horizon. The approach is showcased through a synthesized case study.

Keywords: resilience assessment; water resources management; source-to-tap water systems; strategic planning; uncertainty

1. Introduction

Urban water systems are large and complex critical infrastructure systems, assembled by many sub-systems (e.g., water supply works, water distribution networks, cyber-physical control systems etc.) that must meet a multitude of often conflicting objectives (e.g., supply water of sufficient quality and quantity to consumers, irrigation, and industrial applications, minimization of costs, minimization of environmental impacts etc.). Typically, planners design urban water systems with a long lifespan in mind, spanning in the range of 25 to 50 years. However, in practice, this design horizon is often outlived, as evidence from the water systems of most metropolitan areas of the world suggests. There are parts of water systems still in use today that are over a century old in the more industrialized regions (e.g., in the UK, France, the US etc.). Numerous other systems throughout the world were typically built between 1930 and 1980 and have already surpassed or are reaching their planned lifetimes, with minimal replacement funding (Fletcher et al. 2017). Inevitably, this long service-time imposes unknown and possibly unknowable pressures in the water infrastructures, making the representation of the "true" behaviour of the urban water systems in the future a difficult task. These pressures concern a great variety of parameters (Makropoulos et al. 2018), that can be categorized in (a) hydro-climatic factors, affecting the availability of water of sufficient quantity and quality, (b) demographic and socioeconomic trends (e.g., urban growth, changing water demand patterns) influencing water demand, as well as (c) decision space parameters, within the influence of the planners, such as investment rates, incentives for consumers to conserve water etc.

Traditionally, safety factors are imposed in supply and demand during the design phase to account for uncertainty (Stakhiv 2011). Therefore, systems were often overdesigned to be 'fail-safe' (i.e., reliable) under all future circumstances, even though this proves to be expensive and futile. However, the volatile ever-changing landscape with anticipated changes in the water sector of unprecedented rate and magnitude, is becoming the «New Normal» (Nikolopoulos et al. 2019). Thus, the new concept of resilience is dominating the policy discourse for water systems management and planning, driving the transition to designing "safe-to-fail" (i.e., resilient) water systems.

Despite our good knowledge of the behavior and properties of individual parts or sub-systems of a system, even under uncertainty (e.g., by employing stochastic inputs and parameters and testing against a variety of future conditions), the behaviour analysis of complex large system with intertwining components is a challenging task. A holistic analysis requires the usage of various simulation models for sub-systems, with disparities in computational complexity as well as temporal and spatial scale. Likewise, different metrics are utilized to measure performance of the sub-systems. In addition to the challenge of aggregating this information from sub-systems for any given proposed system in the design stage, planners need to consider the assessment of different system topologies (i.e., deployment of technological assets) or different management decisions (e.g., strategic planning for assets, operational decisions, target priorities, pricing strategies, water conservation campaigns etc.) in retaining operational performance as a whole unit under sets of significantly different, uncertain futures. Hence, water companies need a standardized methodology to support performance assessment, such as the resilience assessment methodology presented in Makropoulos et al. (2018), which has already been applied on real-world systems for evaluating resilience of different system design paradigms (Nikolopoulos et al. 2019).

In this methodological approach, resilience is defined as "the degree to which an urban water system continues to perform under progressively increasing disturbance", whereas performance is measured by the reliability of the system to meet its objectives (i.e., with a metric such as coverage of water needs or frequency of non-failures). A special type of stress-strain graph is used, the resilience profile graph. The *y*-axis communicates the reliability in meeting the objectives of the water system against the combined stresses from scenarios of increasing disturbance order on the *x*-axis (ordinal scale). Resilience can be measured as the area under the reliability curve, scaled between 0 and 100 % by comparing with the area of an ideal perfectly reliable system across all scenarios. A visual example is shown in Figure 1. The scenarios (future world views) are created in increasing severity order by sets of temporally changing hydroclimatic and socioeconomic parameters compared to the baseline design scenario, e.g., increased population, decreased public expenditure for maintenance, decreased rainfall, combinations of these etc.

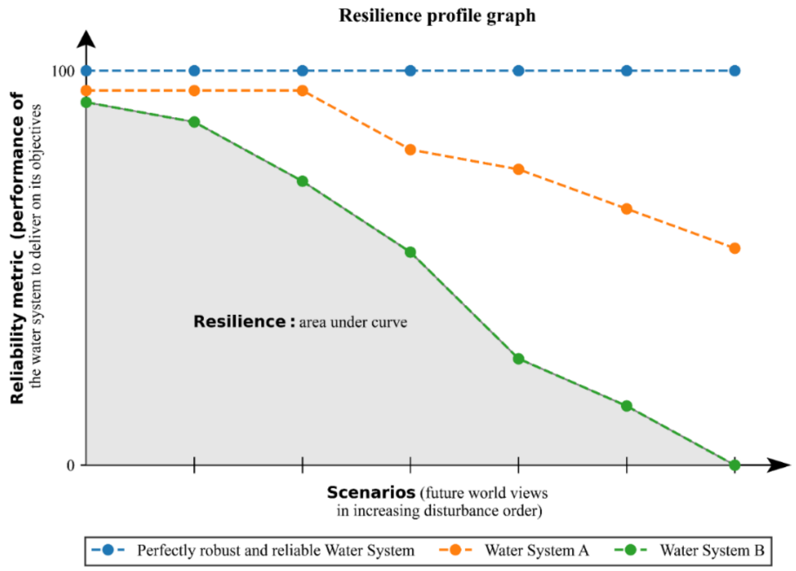

Figure 1. Example of a resilience profile graph

In the present work, we provide a significant expansion of the resilience assessment framework by incorporating new tools in addition to UWOT model (Rozos and Makropoulos 2013), which was used in earlier studies for the simulation of urban water systems. The new tools concern the development of the new Python version of Hydronomeas water resources management model (Koutsoyiannis, Efstratiadis, and Karavokiros 2002), named Hydronomeas2020 (Karavokiros et al. 2020), along with a new application programming interface (API) for automation and interconnection with the other tools, and the coupling of the open source EPANET 2.2 (Rossman et al. 2020) hydraulic solver with pressure driven equations, interfaced through the WNTR interface (Klise et al. 2017). The tools are coupled with feedback loops, to realistically simulate a complete urban water system "from source to tap". The coupled tools allow the automatic re-evaluation of alternative scenarios with stochastic parameters and stochastic input timeseries (e.g., demand patterns, inflows etc.). The parameters of scenarios and synthetic input timeseries are generated through a stochastic simulation engine, named as anySim (Tsoukalas, Kossieris, and Makropoulos 2020), able to model the probabilistic and stochastic behaviour of the processes of interest.

2. Coupling the individual computational tools into a holistic simulation framework

The UWOT model is used as a water demand generation model in this framework, in the micro-scale (household level). Any household appliance (e.g., sink, WC, shower etc.) and water technology (i.e., local grey water recycling, domestic rainwater harvesting etc.) can be simulated in UWOT, with the demand signals aggregated into groups representing different household types (e.g., flats, villas, houses in different regions of the system etc.). Each household type has dynamically customizable scenario parameters for a simulation, including frequency of use of each appliance, the occupancy (number of residents), seasonal water demand fluctuation and others. These parameters can be represented as stochastically changing timeseries to generate the daily demand per household type, for a long horizon simulation, e.g., 25 years.

EPANET 2.2 is used as the pressure driven analysis (PDA) solver for the long period water distribution network simulation, by evaluating each simulation day, with the end results (tank levels, pump states etc.) being the initial conditions for the following day. The PDA solver allows the capturing of daily failures due to hydraulic circumstances, such as total demand in a simulation step that exceeds the system's production and reserve redundancy in tanks, or due to water loss from leaks. The base daily demand of each EPANET node is defined for a scenario from two parameters, (a) the household-type composition timeseries, i.e., what percentage of households in each node relate to the types of households simulated with UWOT, (b) the nodal number of households timeseries, i.e., simulating urban growth and population chx`ange. The hourly pattern multipliers of the daily demand are generated via anySim R-package (Tsoukalas et al., 2020), using suitable AR-type Gaussian processes, as imposed by the stochastic structures observed, and non-Gaussian probabilistic distributions (Kossieris et al. 2019; Kossieris and Makropoulos 2018). Also, a customizable scenario module defines probabilities of leaks in each pipe of the network, based on pipe properties (length, diameter etc.) generating a stochastic daily timeseries of leak events in the system.

The daily water production timeseries of water distribution network (WDN) becomes the input demand target timeseries in the Hydronomeas2020 model that describes the water supply system topology (i.e., reservoirs, ground water wells, transport pipes, other water uses like industrial and agriculture etc.) and rules for water allocation to targets from the water supply works. The supply model supports the usage of stochastic hydrological timeseries, such as reservoir inflows, rainfall, evaporation etc., and captures failures in water supply for the water system.

After running the three coupled simulations in UWOT, EPANET 2.2 and Hydronomeas2020, two different reliability metrics are calculated and aggregated to a single whole system reliability metric. The hydraulic reliability metric is calculated by checking the daily frequency of non-failures of supply to the WDN's nodes the against a user-defined threshold, e.g., if more than 99% of nodes deliver the expected daily demand volume. The water supply reliability metric is calculated by non-failures in supplying the daily requested volume of water to the WDN from the water supply works of the system. For the whole system's reliability metric for a single scenario, a non-failure occurs at each step with satisfactory performance for both metrics. After generating a multitude of scenarios that stochastically explore various future world views, the resilience profile graph can be plotted for the estimation of the water system's resilience.

3. Demonstration of the resilience framework

The resilience assessment methodology is demonstrated in a medium-sized benchmark water system, consisting of C-Town water distribution network (Ostfeld et al. 2012), and a simple water supply system consisting of a small water reservoir, a main transportation channel, and an irrigation system (a secondary water use in addition to the drinking water supply). Three household types are modelled in UWOT: a) a household with conventional water appliances, with circa 263 l/d per capita demand b) a household with water conserving water appliances (e.g., dual flush, water conserving washing machines etc,), with circa 155 l/d per capita demand and c) a household with grey-water recycling technology, with circa 120 l/d per capita demand. Two water systems are formulated: System A with only conventional type households, and System B with a mix of 60%, 35% and 5% at the end of a period of 25 years, simulating gradual (linear in this case) change in household types. This could be the outcome of the long-term strategic planning of the water utility and state/municipal authorities to give consumers incentives (pricing strategy, a subsidy for water equipment etc.) to change their water consumption. Table 1 presents the eight synthetic scenarios that are created for the resilience assessment demonstration. The scenarios have different rates of change in the parameters and the magnitude of change in the end of the simulation period, compared with the baseline (design goal) scenario. Results in Figure 3 show that system B is more reliable (using the combined reliability metric for both hydraulic operation and water supply) in each scenario than system A by a significant margin, especially as the scenarios include more disturbance, thus being a more resilient system overall.

Table 1. Scenarios evaluated for water systems A and B

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

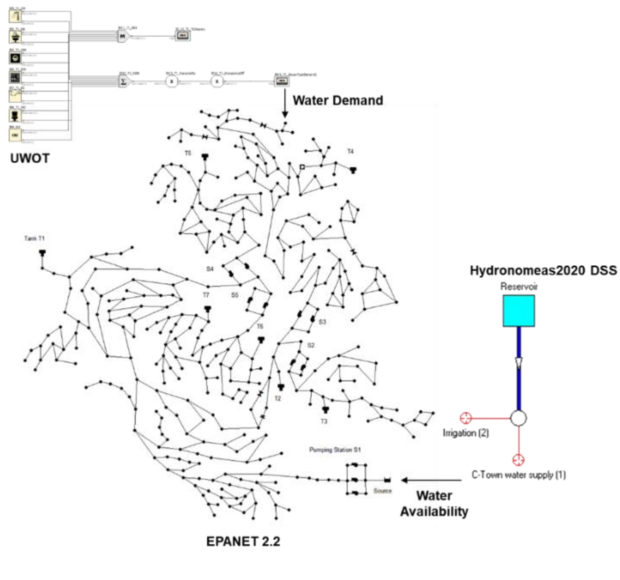

Figure 2. The coupling of simulation tools for C-Town benchmark

4. Conclusions

We presented a methodology of seamlessly coupling a variety of computational tools including a DSS, a water demand generation model, a hydraulic solver and a stochastic timeseries generation engine in a holistic simulation framework that captures uncertainty in water systems, thus allowing the estimation of resilience in long term design, strategic planning and risk assessment studies for water utilities.

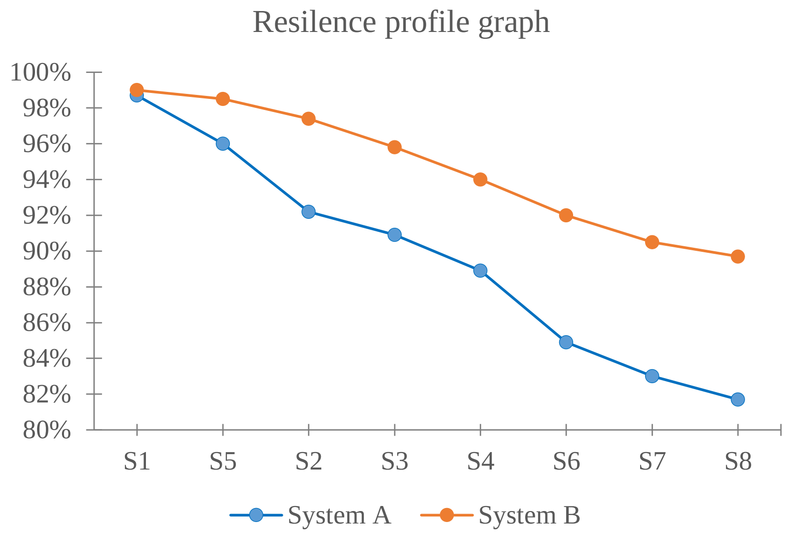

Figure 3. Resilience profiles for systems A and B.

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