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Cascading failure analysis in order to assess the resilience of a water supply system

Keywords

critical infrastructure, water supply, crisis situation, cascading failure

Abstract

Drinking Water Supply Service is considered vital in all societies, modern and old. As for all vital services, governance undertakes all possible measures to guarantee their supply continuity. However, severe service supply disruptions may occur under the action of threats, series of failures cascading or any combination of them.
Threats may be nature originated: climatic extreme conditions, earthquakes, floods. It may also be man originated: ill-informed managing actions, organisational misconduct or malevolence. As for failures, it can be humans or simply systemic: unproven technology, fatigue, ageing, overloading or operational hazards.
Whatever the origins of the disruptions, societies conceive legislations, standards and processes in order to enhance the resilience of the vital service supply systems and the correspondent critical infrastructures. They provide appropriate R&D frames and assets, amongst others, in order to conduct activities on critical infrastructures resilience modelling, simulation and analysis (MS&A).
The paper contributes into the development of a resilience concept and a methodology for integrating cascades of failures to help in crisis management decision making. The proposed methodology is applied on a case study belonging to the drinking Water Supply Services and its critical infrastructures.

1. Introduction

Water Supply service is considered vital in all societies, modern and old. As for all vital services, societies undertake all possible efforts to guarantee the continuity of the vital services and to protect the corresponding critical infrastructures. The efforts cover different levels: legislative, technical and surveillance & control. That can often be extended to: national, regional and international levels, in order to harmonise actions and identify best practices [2, 4].

International standards require that every potential consumer should have access to the proper quality and quantity of drinking water. Water supply operators should maintain the services at high operational level, with full respect of safety and availability standards [23, 24, 26, 30-33]. If water supply is accidentally disrupted, the operators should take every appropriate action to fully recover within the shortest possible delay. However, the operators' duty is also to counteract against water supply disruptions and loss of quality, through preventive actions, in compliance with the local law, standards and good practices [1, 10, 12, 13, 21].

This is always challenging because of the wide spectrum of hazards to be considered: random quality of intakes, human or systemic errors in processing plants or varying physical operational conditions. Climatic sever conditions can also initiate or amplify any of the previous hazards [3, 5].

Water supply system risk assessments are systematically and regularly carried on, in all modern societies. Risk assessments identify weaknesses in the water supply systems: conceptual, systemic, operational or organisational. They determine for each disruption scenario the potential consequences: health, sanitary, industrial, economic, etc. Preventive and even curative maintenance are often driven by these risk assessments. Risk assessments outputs support risk management and decision making activities, in case of service disruption crises, as well. These activities lead definitively to improving the societal awareness and enhancing the resilience of the water supply services [9, 11, 14, 27-29].

But, what does resilience mean? What are its metrics?

Literature is full of all kind of definition of resilience. An extensive survey of the resilience concept is out of the scope of this paper that is intended to propose a model and a methodology supported by an academic simple application. The proposed model integrates: the impact of a threat, the failure of components and processes and the recovery of the Water Supply Service (WSS) within a given interval of time. The model proposes equally some metrics that may in parallel be used to measure the resilience [16, 17].

The paper contributes into the development of a resilience model integrating cascade of events.

In the following section 2, we describe how standards identify major hazards in drinking water supply sector and define the water supply disruption events. One focuses on international, EU and Polish standards.

In section 3, one compares between some well-established operational concepts of resilience. Then, one underlines the major characteristics of the resilience concept that seems the most appropriate for critical infrastructures analysis and crisis management.

In section 4, an academic study case on assessing the WSS resilience is described, treated and discussed.

Section 5 will present a synthesis of the paper and some generic conclusions.

2. Standards and hazards identification for water supply system

The most significant efforts of developing high quality standards for water supply services are those undertaken by the International Water Association (IWA), the World Health Organisation (WHO) and the European Unions (EU). Efforts are oriented to ensure that citizens enjoy the right to water and sanitation

An international agreement IWA 6 was drafted during a workshop held in Tel Aviv, Israel, in October 2007, jointly organised by Israel's Water Authority and The Standards. The agreement covers issues relating to the various stages of management of the so-called water crisis.

Within the same scope, but independently, the WHO developed the Guidelines (3rd edition) [36], for Drinking-Water Quality and the so-called Water Framework Directive [35]. In the Guidelines (3rd edition), the WHO presented the assumptions to develop Water Safety Plans (WSP), integrating the approach of Water Cycle Safety Plans (WCSP). The approach takes into account the risk analyses and assessments and refer to the analysis of the water supply system safety [37].

One should equally signal the EU efforts to achieve the “universal access to water and sanitation”, through legislations such as the EU Directive 98/83/EC, which was amended in 2003, 2009 and 2015. In line with its continuous effort to better regulate [39], the EU Directive 98/83/EC has been revaluated in order to identify the Directive’s strengths and weaknesses. The results of the evaluation were published on December 1st, 2016 in the staff working document REFIT [25].

What does really emerge in these international efforts is the new “strong emphases on the use of the risk-based approach and the interest in the materials in contact with the drinking water” [40].

The topic of the paper is exactly on the same track.

2.1. Operational quality during crisis situation

Polish regulations, by the Minister of Spatial Economy and Construction, cover the CWSS functioning in crisis situations. Polish regulations integrate both aspects: sanitary mandatory conditions and supply technical specifications.

Accordingly in crisis situations, the water companies should: increase the dose of disinfectant, turn to work alternative technologies of water treatment or provide the water bypassing the Water Treatment Plant (e.g. water delivered by cisterns and water carts). Water provided from reserve intakes in the necessary amount, should be made in the technological systems designed to remove water contaminants in water treatment plants, mobile water treatment plants and special filters.

As for technical specifications, the minimum water pressure in the water supply network should be 0.1 MPa for the municipal water pipeline, 0.06 MPa for the rural water pipeline. If the CWSS does not work and in the areas are not covered by the water supply network, water is provided from emergency wells.

Two kinds of water requirements in crisis situation can be distinguished [15, 16, 22]:

- the necessary water quantity (for a few weeks’ time): people - 15 dm^3/(person.day), public utility - 50% of their normal demand, industrial plants – quantity necessary to guarantee

operation, water pipeline needs: 5-15% of daily production, fire protection - depending on needs and specific character of the area, as determined by the relevant fire brigade,
- the minimum water quantity (for a few days' time): people - 7.5 $dm^3/(person \cdot day)$.

Water pipeline should have the possibility to:
- isolate designated water intakes with the operational possibility to use the whole network or fragments of it.
- switch on to alternative water treatment technology (e.g. periodical dosage of active carbon in a powdery form),
- increase the dosage of disinfecting agent,
- supply water omitting Water Treatment Plant.

Water pipelines and emergency wells should be equipped to be empowered from emergency power generating units necessary for pumping water. Needed fuel reserves should be sufficient for 400h, but not less than 200 hours of the generating sets working.

These time figures of 200h and 400h will be guiding figures for the presented case study.

2.2. Crisis definition and criteria

According to the polish regulation, one can identify the severity of the WSD as a function of three operational parameter: the average pressure drop in the network, the maximum available quantity/habitat and the down time of the nominal water supply service.

On the basis of [Polish Regulation (30 December 2002) about serious failures (No 5/58)] the situation is critical if the disruption lasts longer than two hours and the number of people without drinking water is at least 500.

Different operating states in water distribution system functioning can be distinguished. Also the state of partial serviceability can occur which is characterized by short-term disruption and/or decrease in daily water production. These losses in serviceability can represent more than thirty percentage of maximum daily water demand and less than maximum daily water demand or interruptions in water supply up to 24 h. A Water Supply Disruption is considered as such when the nominal capacity of water supply is less than thirty percentage of the maximum daily water demand, for time-intervals exceeding one day for individual settlements, districts or parts of the city.

The figures of 30% loss in the nominal water supply capacity for time-intervals exceeding 24 hours will be guiding the case study, presented in the paper.

2.3. Risk management

In 2004 the WHO presented the directives for developing the so-called Water Safety Plan (WSP) [37], 3rd edition. The main element of the WSP is the developing system risk analysis for all the water supply subsystems, in order to ensure service continuity and consumers safety. The WSP is carried on based on expert's judgement, past available operational and legal requirements. Risk management is the processes of identification, assessment and managing identified risks in normal and accidental situations [19, 20].

Among the most important components of sustainable management strategies for water supply system is the ability to integrate risk analysis and asset management decision-support systems, as well as the ability to incorporate in the analysis financial parameters that are associated with the networks functioning.

An efficient risk management process should have the ability to perform an exhaustive screening and analysis of all plausible events or sequences of events that may endanger the water supply services continuity. That should incorporate threat identification, hazardous events occurrence, and their consequences [27].

The fundamental level of these covers: the threat identification, failure data, model development and consequences analysis. That includes risk quantification using dynamic models in order to describe dependencies, vulnerability and different processes, e.g. materials ageing.

The water suppliers should, also, develop a list of possible disruption scenarios in crisis situations facing possible threats [17, 18].

In the paper only one threat and only one sequence of failures have been used in the proposed academic case study. But the demarche is extendable to multi-threat and multi-sequences of failures.

3. The concept of resilience

In spite of the apparent simplicity of the concept of "resilience", it represents a high complexity in terms of: finding a generic unique definition, encapsulating different disciplinary definitions in a mathematical model-pattern and identifying appropriate metrics.

In material science, "resilience" is the ability of a given material to absorb the energy under elastic deformation. Subsequently, the "proof resilience" is the maximum energy per unit volume that can be absorbed without creating an irreversible deformation. In material science, it is just a matter of restoring the initial state once the stressing phase is off. The material should then become "as good as before stressing". However, there is no concerns about "how long self-restoration would take". In material since, two different materials are identical from material resilience stand point if their "proof resilience" values are identical, even if one can be self-restored in 10 seconds while the other needs 10 minutes. For this "material resilience", a mathematical model and a precise metric (Joule per cubic meter, Jm^{-3}) exist.

In psychological and behavioural sciences, specialists will rather describe "resilience" not as a "quality/ability" but as a process. They may describe resilience as: "as the process of effectively negotiating, adapting to, or managing significant sources of stress or trauma", [38]. Luthar et al. [8], referred to it as a "dynamic process encompassing positive adaptation within the context of significant adversity". We may notice also from Luthar et al. [7, 8], that this dynamic process has a non-deterministic quality. That means that this dynamic process does not encompass the same adaptive pattern in response to the repetitive action of the same stressing vector. The absence of the "deterministic" quality, lets us suppose that it is a "stochastic" process.

We are sharing G. Windle's concerns, [38], of developing an "operational definition of resilience". In our stand point, an operational definition should cover these qualities:

- elasticity; back to "as good as before", after the stressing phase,
- dynamic process; evolving with time,
- stochastic; non-deterministic behavioral patterns.

These are the three qualities that we will be considering in the following assessment of the study case.

4. Study case

This academic case is dealing with a "Water Supply Disruption - WSD" defined by the "loss of water distribution quality in terms of: acceptable pressure and acceptable flow rate, during an unacceptable time-interval.

Under the threat of an "extreme flooding" event, a sequence of some cumulated events would result in the hazardous consequence named WSD. We focus on only possible sequence of event and use the result to assess the "resilience" of the "Water Supply Service". Obviously, a complete resilience assessment requires considering wide range of sequences of failures. However, this task is out of the frame of this paper. The paper is limit to demonstrate the approach using the dynamic modelling of a sequence of events to assess the resilience of a given system/process.

4.1. Description of the sequence

The WSD is the result of the occurrence of four sequential elementary events, defined as:

- Event (E1); a pipe corrosion higher than the admissible limit
- Event (E2); pipe break, resulting in a significant water leakage and pressure drop in the network.
- Event (E3); failure to localise the broken pipe.
- Event (E4); failure to repair (/replace) and to restore the water supply services.

One assumes that the "loss of flow" and the "pressure drop" in the network are immediately detected by the surveillance system butg the exact localisation is not immediate. The WSD is considered if water supply service is not recovered within 2 hours (Polish standards).

Based on the basic failure data given in the following section, a probabilistic resilience assessment is performed. The assessment should allow us to determine the probability distribution as a function in the recovery-time of the WSS.

4.2. Resilience model description

We are particularly interested in the sequence that ends by the "success of the restauration of the supply". We think that its dynamic qualities represent a good measure of the resilience of the network.

The proposed model determines "the occurrence probability of the whole sequence of 4-identified events, within a given interval of time T", $P_n(T)$. $P_n(T)$ integrates the occurrence characteristics of the basic events, the vulnerability of each to a given threat and the time interval before recovery.

4.3. Sequence probability

Briefly, we use the model that has been developed and described with details in [2]. The model is valid for sequences of events described by stochastic Poisson processes. Accordingly, the occurrence probability $P_4(T)$, within an interval T, of the sequences is described by:

$$P_4(T) = \int_0^T e^{-\lambda_1 \xi_1} \lambda_1 d\xi_1 \int_{\xi_1}^T e^{-\lambda_2 \xi_2} \lambda_2 d\xi_2 \dots \int_{\xi_3}^T e^{-\lambda_4 \xi_4} \lambda_4 d\xi_4 \tag{1}$$

where,

$e^{-\lambda_1 \xi_1} \lambda_1 d\xi_1$: is the probability of not exceeding the admissible limit of corrosion, within the interval

$[0, \xi_1]$ and then exceeding it within the infinitesimal $\Delta\xi_1$, with the constant occurrence rate λ_1.

$e^{-\lambda_2\xi_2}\lambda_2 d\xi_2$: is the probability of no pipe rupture in the network because of the corrosion, within the interval $[\xi_1, \xi_2]$ and then occurs within $\Delta\xi_2$, with the constant rupture rate λ_2.

$e^{-\lambda_3\xi_3}\lambda_3 d\xi_3$: is the probability of localisation failure within the interval $[\xi_2, \xi_3]$ and then successful localisation within $\Delta\xi_3$, with the constant localisation rate λ_3.

$e^{-\lambda_4\xi_4}\lambda_4 d\xi_4$: is the probability of unsuccessful repair within the interval $[\xi_3, \xi_4]$ and then a successful repair within $\Delta\xi_4$, with the constant repair rate λ_4.

Obviously, this sequence of events ends by the recovery of the WSS.

4.4. Threat description

We consider one hypothetical threat which is a “severe flooding” event due heavy rain over 2 full days with an exceptional daily precipitation rate of 120 mm. It is not yet a severe destructive flood compared to the great one of summer 1997 in Poland. But, it is still an exceptional precipitation rate compared to the average annual precipitation rate of 618 mm in Poland, based on records over the period 1951-1985 [6].

4.5. Data and rationales

The required basic failure data are: the occurrence rate of exceeding the unacceptable corrosion level, the occurrence rate of corrosion-stressed cracking, the localisation-detection rate of the leak and the reparation (replacement) rate of the cracked pipe. The different rates are assumed to be constant and global, over the whole network. The used data are not exact data but representative of a global network of a medium size region. They are expressed in “h^{-1}” unit, *Table 1.*

We assumed that heavy long rains leading to a severe flood would result in increasing in ground water level. These combined conditions may produce soil movements and rearrangements in some parts in the soil adding additional mechanical stresses on the corroded pipes in that part. That would be described by an increase in the “pipe rupture” rate.

We assume also that the same combined conditions would add additional stresses on the “leak detection and localisation” process and on the “pipe reparation” process, as well. That effect is described by a decrease in the “detection and localisation process” and “repair process” rates.

4.6. Vulnerability to threat

As preconized in [3], the vulnerability of each basic event to the threat will be described by a constant “vulnerability stress factor, v_i”, such as: the pipe-rupture stress factor ($v_2 = +2$), the localisation process stress factor ($v_3 = -0{,}8$) and the repair process stress factor ($v_4 = -0.9$). The stressed occurrence rates of each event will then be expressed, such as:

- The “pipe stressed rupture rate, λ_2^*” will be such as: $\lambda_2^* = (1+2)\lambda_2$,
- The “stressed localisation rate, λ_3^*” will be such as: $\lambda_3^* = (1-0{,}80)\lambda_3$, and
- The “stressed repair rate, λ_4^*” will be such as: $\lambda_4^* = (1-0{,}90)\lambda_4$.

The stressed rupture rate is then increased by three times, the stressed localisation rate is decreased five times and the stressed repair rate is decreased by 10 times, *Table 1.*

Table 1. Occurrence rates & Vulnerability data used in the study case

List of sequential events	Unstressed Rate (/h)	Vulnerability factor	Stressed Rate (/h)
E1 - Occurrence of the event “exceeding the admissible corrosion level”	$5.00E-5$	0.0	$5.00E-5$
E2 - Occurrence of the event “pipe rupture” in the corroded zone	$4.00E-4$	2.0	$1.20E-3$
E3 - Occurrence of the event “successful localisation”	$4.17E-2$	-0.8	$8.34E-3$
E4 - Occurrence of the event “successful repair”	$4.17E-2$	-0.9	$4.17E-3$

4.7. Measuring resilience

The unique interest of this academic study case, is to illustrate a methodology to assess the resilience of a WSS. Accordingly, we are proposing to assess the resilience using three different but not disjoint stand point of views: the incremental loss of resilience (in stressed situations), the most-likely recovery time and the recovery rate time-profile. All three metrics are based on the “occurrence probability” $P_n(T)$of the sequence of events, within the time-interval of interest. The incremental loss of resilience, Δ_{res} is given by:

$$\Delta_{res} = [P_n^*(\Delta T) - P_n(\Delta T)] * \Delta T \qquad (2)$$

where, $P_n^*(\Delta T)$ and $P_n(\Delta T)$ are the stressed and the unstressed sequence occurrence probabilities, *Figure 1*, respectively, and ΔT is the interval $[T_1, T_2]$ defined in *Table 2*.

This incremental loss occurs with a probability given by: $P_n^*(T_2) - P_n^*(T_1)$, in the interval $[T_1, T_2]$.

As one can see, "the incremental loss of resilience" shows its most-likely value of ~3.4 within the period from 1 to 3 weeks with a probability of $9.5E - 3$. However, the WSS recovery may take longer than 3 weeks, That corresponds to an incremental loss of resilience equal to 130, at a probability of $4.9E - 3$. One peculiar observation is the improvement of the WSS resilience within the first 24 hours, expressed by a negative loss $(-2.4E - 5)$. This is explained by the fact that the pipe ruptured stressed-rate is higher so that pipe-rupture may arrive earlier leading to an earlier localisation and then an earlier recovery.

However, this possibility is very unlikely. It has an occurrence probability of $2.2E - 6$, Table 2. So, it is considered as a "very rare" sub-scenario.

Table 2. Incremental loss of resilience in the WSS under the action of the flood threat

No.	$T_1 - T_2$	Unit	$P_n(\Delta T)$	$P_n^*(\Delta T)$	ΔT *(h)*	$P_n^*(\Delta T) - P_n(\Delta T)$	Δ_{res}	$P_n^*(T_2) - P_n^*(T_1)$
1	$0 - 24$	h	$1.22E - 5$	$2.28E - 6$	24	$\sim -1.0E - 5$	$-2.4E - 5$	$2.2E - 6$
2	$24 - 72$	h	$9.66E - 5$	$1.17E - 4$	48	$\sim 2.0E - 5$	$6.9E - 4$	$1.1E - 4$
3	$3 - 7$	d	$1.34E - 4$	$1.48E - 3$	96	$1.35E - 3$	$1.5E - 1$	$1.3E - 3$
4	$1 - 3$	w	$1.35E - 4$	$1.05E - 2$	336	$1.04E - 2$	3.4	$9.5E - 3$
5	$3 - 53$	w	$1.35E - 4$	$1.56E - 2$	8400	$1{,}55E - 2$	130	$4.9E - 3$

Beside the incremental loss of resilience, one may in parallel use the probability density function, $\rho(t)$, which is defined as: $\rho(t) = \frac{d}{dt} P_n(t)$. In Fig. (2), we compare between the time-profiles of the density probability functions for the: stressed and unstressed situations. One can also observe that the stressed probability density function is lower than the unstressed one during the first 24 hours. However, we can compare the most probable recovery time of the WSS, which is: 30 hours for the unstressed situation and 288 hours (12d) for the stressed situation. This is confirming the previous conclusions when using the incremental loss of resilience measure.

The third measure to be proposed in parallel is to use the recovery rate time-profile, $\lambda^*(t)$, traced in *Figure 3*, and is defined by:

$$\lambda^*(t) = \frac{\rho(t)}{P_n(t)} \qquad (3)$$

where $\lambda^*(t)$ is the recovery rate corresponding to the sequence of events defined above and that ends up by the recovery of the WSS within a given interval of time. *Figure 3* illustrates the time-profile of the recovery rate . One may synthesise the time profile as in the following Table 3. Similar remarks are drawn, as previously, for each time-interval of interest: "the occurrence rate of recovery around an interval of 8 days (192 h) is two decades higher in the stressed situation", *Figure 3*.

Obviously, this is also a useful measure of the "loss of resilience" under the effect of a threat. It expresses loss of resilience in terms of "recovery rate" rather than in terms of "incremental decrease in recovery probability".

Table 3. The likelihood of the WSS recovery as function of time-intervals, *Figure 3*

No	$\lambda^*(t)$	Description	Unstressed	Stressed	The recovery under stressing conditions
1	$> 10^{-1}$	Very likely	$< 30\text{h}$	$< 30\text{h}$	is almost similar to the unstressed situation
2	$> 10^{-2}$	Likely	$30\text{h} - 84\text{h}$	$30\text{h} - 192\text{h}$	Takes longer time at similar likelihood
3	$> 10^{-4}$	Unlikely	$84\text{h} - 192\text{h}$	$192\text{h} - 1100\text{h}$	longer time at similar likelihood but by so far later
4	$> 10^{-6}$	Most unlikely	$192\text{h} - 290\text{h}$	$1100\text{h} - 2000\text{h}$	Time-scale is irrelevant for crisis management
5	$< 10^{-6}$	Impossible	$> 290\text{h}$	$> 2000\text{h}$	Time-scale is irrelevant for crisis management

5. Conclusions & discussion

The continuity of drinking water supply services (WSS) is a vital concern, in all societies. Efforts and resources are combined to enhance its resilience in case of a disruption. The paper scans shortly the national (Poland) and international efforts and its different forms. As all other vital services, the introduction of risk analysis culture is recommended as a proven means in order to enhance resilience, especially facing threats of different origins. Although the resilience concept is a complex one, risk analysis and system reliability cultures have the necessary intellectual resources to stand for the challenge of developing the required resilience concept and the appropriate metrics.

The paper proposes resilience assessment methodology raised on four pillars: specifying threats, identifying disruption scenarios, developing probabilistic dynamic models and proposing appropriate metrics.

The proposed resilience probabilistic dynamic model is based on describing the recovery probability after a disruption as a function of time and of the occurrence probability of basic events in the required order.

The proposed metrics are: the incremental loss of resilience, the recovery probability density function and the recovery rate, all as functions of time.

The paper finally proposes an academic case study demonstrating the demarche. A threat is selected and a sequence of 4 basic events is identified. The vulnerability of each basic event to the threat is described using a simple linear model. Then, the paper uses a probabilistic analytical dynamic model to measure the WSS resilience (in unstressed and stressed crisis situations), using the metrics described above.

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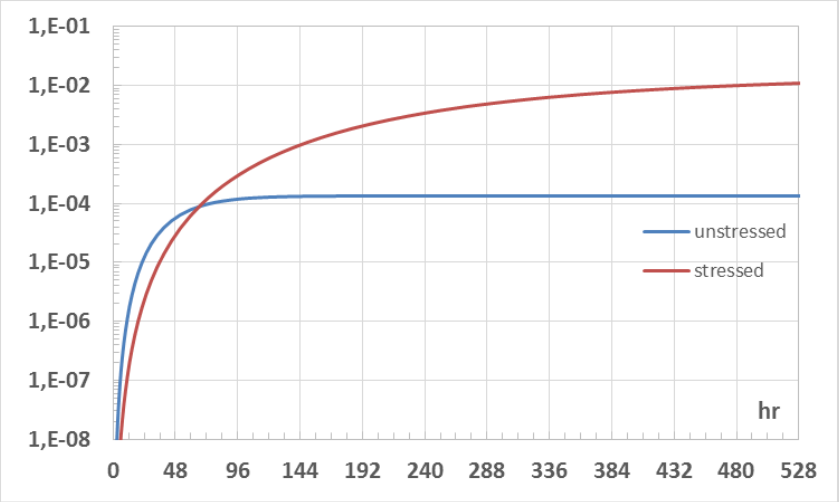

Figure 1. Recovery probability time-profile

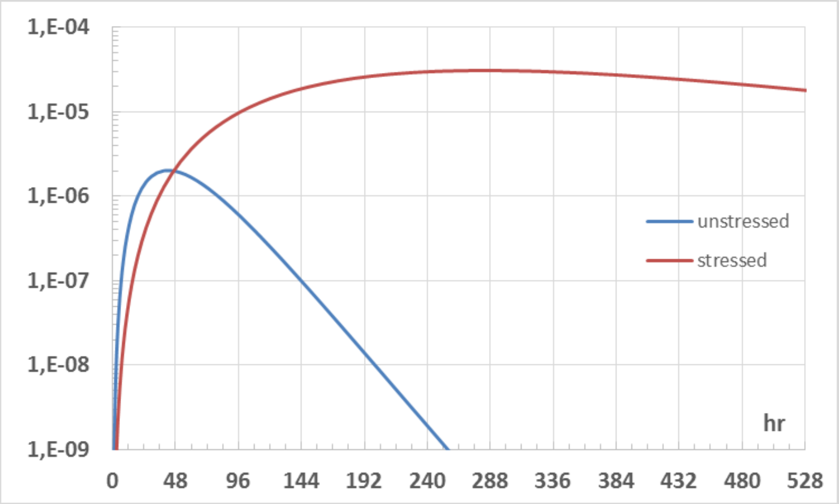

Figure 2. Recovery probability density function time-profile

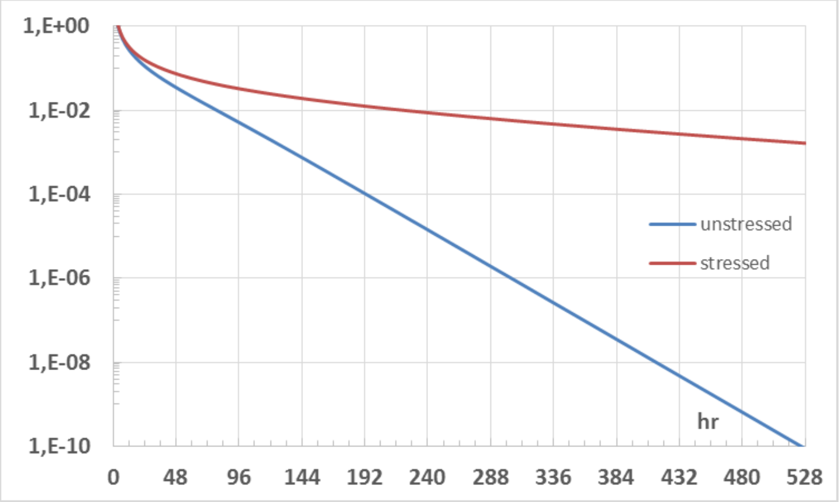

Figure 3. Recovery rate time-profile