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Abstract: Disasters impacts on urban environment are the result of interactions among natural and human systems, which are intimately linked each other. What is more, cities are directly dependent on infrastructures providing essential services (Lifeline Systems, LS). The operation of LS in ordinary conditions as well as after disasters is crucial. Among the LS, drinking water supply deserve a critical role for citizens.

The present work summarizes some preliminary activities related to an ongoing EU funded research project. The main aim of the paper is to define a System Dynamic Model (SDM) to assess the evolution of resilience of a drinking water supply system in case of natural disasters, with particular attention to the role of both 'structural' and 'non-structural' parameters. Reflections are carried out on L'Aquila (Italy) case study, since drinking water infrastructures were significantly stressed during the 2009 earthquake, causing a limited functionality in the aftermath of the event. Furthermore, the reallocation of citizens in temporary shelters determined a change in the demand pattern, requiring a dynamic adaptation of the infrastructure. Based on an innovative approach to resilience, the model was developed also to simulate different emergency management scenarios, corresponding to different disaster management strategies.

1 Introduction

Cities are systems of interacting social groups in densely built spaces served by infrastructures and managed by social and political organizations (Bettencourt, 2015). Therefore, cities are strongly dependent on infrastructures providing essential services, namely Lifeline Systems (LS) that support societal functions, safety, economic prosperity and quality of life (O'Rourke, 2007). Besides, LS are embedded within the urban context and interact dynamically with it (McDaniels et al., 2008; Bettencourt and West, 2010; Bozza et al., 2015), combining physical infrastructures and social networks of interactions among individuals, groups, and institutions (Gasteyer, 2004).

Empirical evidences demonstrated that the dynamic interaction between physical infrastructures and social networks is even tighter in case of the occurrence of a hazardous event, when a city suffers a natural disaster and tries to reconfigure itself (Bozza et al., 2015). The traditional engineering-oriented approaches aiming exclusively at reducing the physical vulnerability of the infrastructures proved to be inadequate to address the complexity of the socio-technical interaction (Bruneau et al., 2003; Davies, 2015). In order to overcome these limits, resilience thinking approaches account for the community/infrastructures interconnections, bridging the static and dynamic components of disasters across pre and post event context (Miles, 2015).

Resilience thinking in natural disaster management has become a central driver in the strategies and policies of urban planners, technical practitioners, decision-makers, NGOs and institutions (e.g. United Nations Office for Disaster Risk Reduction, 2007; World Bank, 2011; European Commission, 2012). Originated in environmental systems (Davies, 2015), the concept of resilience became relevant for engineered domains, including LS (e.g. O'Rourke, 2007; McDaniels et al., 2008; Agarwal, 2015). It can be defined as the ability of infrastructural systems to absorb the shocks of extreme events such as natural disasters. Resilience can be achieved by enhancing the ability of an infrastructure to perform during and after a hazard, as well as through emergency response and recovery strategies (Chang et al., 2008).

The shift from risk management approach to resilience management paradigm was crucial in the field of LS for multiple reasons. On the one side, several works discussed the unsuitability of risk management approaches in LS protection during natural disasters (e.g. Bruneau et al., 2003; Gay and Sinha, 2013; UNISDR, 2014; Comes and Van de Walle, 2014; Reinhorn and Cimellaro, 2014; Cavallo and Ireland, 2014; Davies, 2015). This is mainly due to the complexity of LS, characterized by strong and dynamic interdependencies with urban, natural and social systems, and thus often described as "System of Systems" (e.g. Cavallo and Ireland, 2014; Filippini and Silva, 2014). On the other side, resilience thinking increases the capability of the system to deal with the unforeseeable (Park et al., 2013; Davies, 2015). It addresses the complexities of integrated systems and the uncertainty of future threats (Linkov et al., 2014), emphasizing the system ability: i) to anticipate and absorb potential disruptions, ii) to develop adaptive means to accommodate changes, iii) to establish response behaviors aimed at either building the capacity to withstand the disruption or recover as quickly as possible after an impact (Francis and Bekera, 2014).

Starting from these premises, this work aims at developing an innovative approach to LS resilience assessment, capable to account for the dynamic and complex nature of its interacting elements. To this aim, a System Dynamic Modelling (SDM) approach is adopted. The work intents to demonstrate the SDM suitability for LS resilience assessment and management through the implementation of the method in a real case study, related to the drinking water infrastructure resilience during L'Aquila (Italy) earthquake (2009).

2 State of the art

Resilience is a process rather than a static concept (Francis and Bekera, 2014; Labaka et al., 2015). Designing policies and strategies to build resilience in urban systems claims for a deep understanding of the multifaceted nature of the influencing elements and of the complex multi-actor processes involving social, economic, political and physical dimensions across diverse scales (Helfgott et al., 2014; Dahlberg et al., 2015).

Significant efforts are mentioned in the scientific literature aiming at developing analytical tools to quantitatively assess the infrastructural resilience (e.g. Alderson et al., 2015). Several authors suggested to use specific functions (e.g. Attoh-Okine et al. 2009, Reed et al. 2009 and Henry et al. 2012) as metrics of resilience. Francis and Bekera (2014) worked on infrastructural resilience, implementing a framework based on three key resilience capacities (adaptive capacity, absorptive capacity, recoverability) to determine a resilience factor. The authors combined subjective expert knowledge with assessments of recoverability, through variables depending on performance levels and time to recovery. Referring more specifically to water supply systems, several quantitative methodologies for resilience assessment were proposed, mainly based on the analysis of network characteristics (e.g. Todini 2000; Mugume et al., 2015)

A very well-known paradigm for infrastructural resilience assessment is the TOSE approach (Bruneau et al., 2003). The most interesting feature of this approach is the integration of four dimensions: Technical, Organizational, Social and Economic (e.g. Bruneau et al., 2003; O'Rourke, 2007; Tierney and Bruneau, 2007; Cimellaro et al., 2010). The *technical* dimension of resilience refers to the ability of interconnected physical systems to perform at acceptable/desired level. The *organizational* dimension denotes the capacity of organizations to manage the critical facilities and take actions that contribute to enhance resilience. The *social* dimension of resilience measures to what extent communities could contribute with their behavior to contain the reduction of critical service in case of emergency. Similarly, the *economic* dimension of resilience refers to the capacity to reduce both direct and indirect economic losses. The TOSE approach was widely used in several analyses and, recently, for performing a comparison between L'Aquila earthquake and Canterbury earthquake (Kongar et al., 2015) with respect to the infrastructural systems involved.

Bruneau (2003) and Tierney and Bruneau (2007) suggested the use of a 'resilience triangle' (Figure 1) to quantitatively describe resilience, based on a measure of time-varying system performances Q(t). Given a specific event, the loss of resilience can be measured by the size of the expected degradation in performances over time. Indeed, it can be represented through the area delimited by the curve Q(t). Q(t)describes both the loss of functionality from damage and disruption and the pattern of restoration and recovery (i.e. time to recovery). Resilience-enhancing measures aim at reducing the size of the resilience triangle.

Figure 1. Approximately here

Moving in such direction, System Dynamics Modeling (SDM) is an operative approach for helping reveal the temporal behavior of complex systems (Neuwirth et al., 2015), with several applications in environmental decision-making, especially in the field of hydrology and water resources management (e.g. Ahmad and Simonovic, 2000; Khan et al., 2009; Gastelum et al, 2010).

A System Dynamic (SD) approach aims at providing insight into non-linear system behavior for assisting informed decision-making by stakeholders and policy-makers. SD is a formal method of system description, which facilitates feedback analysis via a simulation model of the effects of alternative system structures and control policies of system behavior (Simonovic, 2009). Forrester (1961, 1968, 1987) introduced the SD methodology sought to involve clients in the process of model construction within strategic problems in business. Additionally, SD has become popular when its general principles of feedback were presented under the label of system thinking (Barlas, 1996). The SD structure, built up with stocks, flows and causes-effects chains, describes the behavior of the system through feedback loops (Sterman, 2000). It can be fundamental to building and integrating conceptual models (Vennix, 1996) during group modelling activities.

The system formalization provides a better understanding of what drives system behavior and support examining future dynamics based on a given set of assumptions. In this way, modeling system behavior over time can provide insight into significant relationships, reveal patterns, expose sources of undesirable system behavior, and help avoid unforeseen consequences of future policy implementations (Neuwirth et al., 2015). Three main SD features make such methodology particularly suitable for resilience assessment: i) the ability to address how structural changes in one part of a system might affect the behavior of the system as a whole; ii) combined predictive (determining the behavior of a system under particular input conditions) and learning (the discovery of unexpected system behavior under particular input conditions) functionality; and iii) active involvement of stakeholders in the modelling process.

This work mainly describes a methodology to assess the resilience of LS, with specific reference to drinking water supply systems, adopting a multi-dimensional and dynamic perspective. An SD model has been developed and tested in order to identify and analyze the main elements fostering or hampering resilience. Secondly, the model has been used to evaluate the impact of actions and strategies for resilience improvement on the dynamic evolution of the system. Finally, it has been used to identify critical feedbacks, and to evaluate their influence on the implementation of policies aiming to enhance LS resilience, assessing their evolution with time.

3 Materials and methods

The methodology described in this work is based on the integration between SDM and TOSE approach. It aims at assessing the resilience of drinking water supply infrastructure accounting for the dynamic evolution of the infrastructure itself and of the urban system in which it operates during emergency.

3.1 Vulnerability assessment model

A basic input for the SD model described in the following is represented by the vulnerability level of the infrastructural system. It is estimated through a probabilistic tool based on Bayesian Belief Networks (BBN). Full details on the methodology are available in Pagano et al. (2013, 2014a, 2014b). The vulnerability assessment model requires the integration of different classes of data: physical (related to infrastructural characteristics), environmental (e.g. seismicity) and operative (e.g. hydraulic variability, maintenance). The model provides specific outputs to estimate the probabilistic vulnerability values for each element of the network. For the purposes of the SD model, an overall value of system vulnerability needs to be defined. Specifically, referring to the values of the state 'high' of the variable 'breaking vulnerability', the maximum value on the whole network is taken into account. As it will be described, the role of the estimated network vulnerability contributes to the *technical* dimension of resilience in the SD, conditioning the level of service provided by the infrastructure. The following Figure 2 represents the BBN used for the vulnerability assessment, and describes how it is conceptually included in the SD model.

Figure 2. Approximately here

3.2 Resilience assessment based on SDM: model building process

The SD model was built to analyze the resilience of drinking water supply systems accounting for the complexity and dynamic interactions among the four main elements of the TOSE approach. The model recognizes and simulates feedback mechanisms, which could affect the resilience of a water system and/or the effectiveness of resilience-enhancing policies. As discussed further in the text, the developed model could be used to support water utilities in the selection and critical analysis of the most suitable strategies to improve resilience, thus reducing potential failures of drinking water supply in case of disasters. A preliminary version of the model was discussed by Pagano et al. (2015). The model was developed and implemented in STELLA® (ISEE Systems Inc.).

According to Davies and Simonovic (2011), the SDM development process was structured according to the following phases: i) understanding the system and its boundaries; ii) identifying the key variables; iii) describing the processes that affect variables through mathematical relationships; iv) mapping the structure of the model; v) simulating scenarios for understanding model behavior. The Figure 3 summarizes the key steps of model building, further described in the present section.

Figure 3. Approximately here

Modeling activities were carried out by integrating scientific knowledge available in literature with expert knowledge (Schön, 1983; Fischer, 2000), elicited through semi-structured interviews, according to participatory work principles. Literature evidences were used to develop the first version of the conceptual model identifying the main cause-effect relationships. The domain experts from the local water utility and the Department of Civil Protection (both national and local agencies), as well as researchers, cooperated in the modeling phases. Some citizens, who were directly involved in the emergency as end users of the water supply service, were also included in modelling activities. Experts were clustered in two different groups (Figure 3) in order to support on one hand the phase of conceptual model building and on the other the definition of the stock and flow model, with the consequential calibration and validation. Full details on the involved stakeholders and the provided information are in the Table 1.

Table 1. Approximately here

The process of group model building starts from the conceptual model definition, representing the sum of cause-effect chains influencing the stock and flow model (Vennix, 1996). In order to gather the fundamental individual and collective knowledge, the domain experts integrated the conceptual model, adding or deleting variables and modifying links. The modelling process ended when no new concepts and/or relationships emerged after a number of interviews and researchers supported the global model design. Following the approach adopted by Pagano et al. (2014), the interviews were carried out limiting bias in expert knowledge collection. Based on Page et al. (2012), particular attention was made on problem framing (to reduce subjectivity and ambiguity), availability issues (the tendency to overestimate the magnitude of recent/familiar events) and anchoring (systematic underestimation of uncertainty/variability).

The obtained conceptual scheme is depicted in Figure 4. The dimensions of resilience were defined adapting the general idea suggested by Bruneau et al. (2003) to a drinking water supply system.

Figure 4. Approximately here

The scheme was built in order to deal separately with the four basic dimensions of resilience. Then the reciprocal influences among variables were identified. For instance, some organizational capabilities (i.e. the availability of human resources, the availability of a good knowledge concerning the infrastructure and the environment) may have a direct influence on the technical dimension of resilience (i.e. they support a quicker and effective response to technical issues connected to the level of service).

The experts were asked to describe the main variables and to properly connect them according to the expected influences. They were also asked to provide a quantitative interpretation of all the considered variables (even non-physical ones, such as knowledge level) and of their possible states. Finally, they were asked to describe the potential dynamic evolution of the variables, the main causes of these changes and the potential effects.

Afterwards, the conceptual model was used as basis for the development of the stock-and-flow model. A first subset of variables was defined referring to the conceptual model in Figure 4, i.e. level of knowledge, available economic resources, water demand (from both population on site and population in shelter camps), level of service/loss of service. Such variables were modeled as *stocks*, according to the SDM methodology, since they describe the accumulation or depletion of both physical and non-physical resources. Another subset of variables was defined and modeled as ‘conveyors’ using the collected knowledge. Those variables are related to either externally specified conditions (e.g. ‘intensity of the hazard’), or to actions/policies that can be implemented and may have an influence on resilience levels (e.g. increasing the training level of employees, implement monitoring activities, availability of GIS and database).

The general structure of the model was then discussed with the expert sub-group, who reviewed the variables and their relationships. Additionally, a quantitative calibration was performed referring to the L'Aquila earthquake case study. As in most emergency conditions, data were not readily available/accessible, and affected by significant uncertainties (Van der Keur et al. 2016). A few key stocks were selected for calibration (e.g. 'water deficit', 'population on site', 'available economic resources'), and their simulated dynamic evolution plotted. Experts were asked to identify for each variable a scatter plot to build an expected trend. The comparison between the expected and the predicted trend allowed the calibration of the key equations used in the model. Small deviations were attributed to the difficulties in collecting reliable data. Nevertheless, the experts considered these deviations as minor.

3.3 Resilience assessment based on SDM: model description

The complete model of resilience is represented in the following Figure 5.

Figure 5. Approximately here

As stated previously, LS play a crucial role in keeping alive the social networks within a community in case of disaster by continuing to provide crucial services (Ouyang and Wang, 2015). This role also emerged, and was discussed by the experts involved, in a severe emergency such as L'Aquila earthquake. Therefore, the main goal of the model is to assess the capability of the infrastructure to provide a satisfactory level of service in case of a disaster. To this aim, the model mainly aims at providing information on the water deficit during emergency and in the immediate aftermath, based on a comparison between water inflow and water demand.

Specific sub-models, identified by purple boxes were defined in order to deal with key issues contributing to resilience according to the TOSE conceptualization. Although most of the sub-models are mutually interconnected, they can be also run and analyzed independently.

Referring to the global model, the 'inflow' volume is primarily conditioned by the water that can be conveyed using the existing infrastructure (according to its residual 'level of service'). This depends on the expected 'failures' (sub-model 'Technical dimension 1 – Failures', Figure 6), which are related both to the damage ‘creation rate’ and to the ‘repair rate’. The former is influenced by ‘hazard intensity’ and by ‘maintenance’ activities, but also significantly by the ‘infrastructure physical vulnerability’ (black conveyor in Figure 6). This variable is linked with the Bayesian vulnerability assessment model described in the sub-section 3.1. The ‘repair rate’ depends instead on the ‘available economic resources’ and ‘human resources ratio in emergency’, and is fostered by the available ‘level of knowledge’. All these variables derive by other sub-models.

Figure 6. Approximately here

During emergencies, the inflow volume is generally integrated using alternative sources (‘volume provided by alternative water sources’), such as wells or ‘other available volumes’ (e.g. tanks). ‘Emergency water’ sources are activated as well (‘emergency vehicles or ‘bottled water’), that are needed to compensate the reduction of available water volumes (sub-model ‘Technical dimension – 2 Additional water volumes’, Figure 7).

Figure 7. Approximately here

From a technical point of view, the model is thus capable to simulate the impacts on infrastructural resilience originated by changes in its functionality. On the one hand, the effect of failures and topological modifications after a disastrous event (e.g. breaks and failures, network adaptation measures); on the other hand, imposed alterations on flow regime and adaptation capabilities.

The model shows also how the capabilities to react quickly to a disastrous event and to rapidly recover functionality do not depend only on the infrastructural characteristics. Economic and organizational elements are crucial as well. From an organizational point of view (sub-model ‘Organizational dimension’, Figure 8), the model describes the impacts on the system resilience due to the development of a full understanding of the infrastructural system, the surrounding environment and the hazard (‘infrastructural knowledge’, ‘environmental knowledge’ and ‘hazard or event knowledge’ respectively). This goal is achieved through the enhancement of information acquisition (e.g. ‘field surveys’, ‘monitoring and forecasting’, ‘infrastructure monitoring’) and sharing capabilities (e.g. ‘availability of GIS and database’, ‘cooperation with other institutions’). Moreover, the model displays how the timeliness and the effectiveness of the involvement of ‘human resources in emergency’ is of utmost importance. To this aim, ‘training level’ plays also a crucial role as well as ‘concern and cooperation’ attitude.

Figure 8. Approximately here

The model shows also (sub-model ‘Economic dimension’, see Figure 9) the role of the interdependencies between the ‘available economic resources’ for the organization and the capability of the infrastructure to cope with ‘failures’. It displays that the reduction of the population using the water services (due to delocalization in other cities or in the shelter camps) results in a decrease of the available economic resources (‘incomes’). Consequently, the organization may have not enough resources to deal with the ‘costs’ associated to emergency. The model accounts for both the internal economic resourcefulness and the ‘emergency economic resources’ than can be activated after the occurrence of a disaster.

Figure 9. Approximately here

From the social point of view (sub-model ‘Societal dimension’, Figure 10), the model is able to simulate the spatial/temporal dynamic of the local population (‘Population on site’, ‘population delocalized’, ‘population in the shelter camps’) as a function of the expected damage on buildings (‘total buildings’, ‘collapsed’ and ‘damaged’); consequently, the required level of service (‘Water demand’) is changed, also considering the potential ‘reduction ratio’ strategies and the ‘community awareness’. The model still lacks the capability to simulate changes in community’s behaviors - e.g. water consumption – in case of emergency. More data are required to overcome this drawback of the model.

Figure 10. Approximately here

The green variables in the model and sub-models represent the set of actions that could be implemented to enhance system resilience. The following Table 2 provides an overview of the measures that are used in this work to describe the resilience of water supply systems.

Table 2. Approximately here

3.4 Overview of the case study

L'Aquila province (central Italy) was struck by an earthquake (6.3 magnitude) on the 6th of April 2009. The physical event was relatively moderate, but it revealed the very high vulnerability of lives, livelihoods, building stock and institutions (Alexander, 2014). More than 300 people were killed and 1500 injured, about 100000 buildings were damaged and 67000 people left homeless (Alexander, 2010). L'Aquila old city was declared unsafe, made off-limits with military control and the community was moved out of destroyed and damaged buildings. The Italian government opted for a direct transition from homelessness to secure accommodation (e.g. tent camps or coastal tourist hotels) (Alexander, 2010). During the recovery phase, two different strategies of relocation were enacted: small settlements - called MAPs - and large new towns - CASE Project (Calvi & Spaziante, 2009; Forino, 2015).

Although the emergency management of LS provided a rapid and resilient response to the earthquake (Dolce and Di Bucci, 2015), an important water-pipe, within the "Gran Sasso Aqueduct" failed because crossing the surface trace of a fault activated during the earthquake (Rossetto et al., 2011; Dolce and Di Bucci, 2015). The steel joint of the pipeline (diameter 600 mm; pressure 25–30 atm) slipped off, and the cause of damage was identified as co-seismic rupture of the Paganica fault that crossed the pipe. No significant damage was observed to the main distribution and storage system, whereas in the minor distribution system slippage/breakage of the joints and breaking of cast iron pipes were the most commonly observed damages (Kongar et al., 2015).

The interviews with the technicians working for the local water utility (Gran Sasso Acqua S.p.A.) confirmed that several minor breaks occurred locally (e.g. in pipes serving single buildings), and caused severe problems to the functionality of the urban drinking water supply network. The location of citizens (e.g. their movement to temporary shelters, or their delocalization) determined significant variations to the demand pattern, and thus the need to adapt the characteristics of the drinking water supply. Several decisions made for managing emergency conditions were also particularly complex, and serious issues related to the drinking water supply service provision were raised.

4 Results

4.1 SDM and scenarios development

The developed SDM was implemented to assess the resilience of L'Aquila drinking water supply system. The SDM is meant to support decision-makers to identify potential actions aiming to improve the capability of the system to promptly react in case of natural disasters, providing crucial services to the affected community. In order to evaluate and compare the effectiveness of the different actions, the 'water deficit' was adopted as measure of system performances. It assesses the capabilities of the water infrastructure to provide the required amount of water in order to satisfy the community's needs in the aftermath of the disastrous event.

Four different scenarios were simulated using the SDM coupled with the BBN model for physical vulnerability assessment. Table 3 summarizes the main differences among scenarios. The set of variables used to characterize the different scenarios was defined accounting for the results of the sensitivity analysis of the model and the experts' opinions. Scenarios were used to perform a 'what-if' analysis, starting from a baseline condition (*Scenario 0*) which directly reflects the state of the variables during the earthquake in 2009. The 'what-if' analysis supports in measuring how changes in a set of independent variables may influence dependent variables in a simulation model.

Particularly, the goal was to anticipate the potential evolutions of the system, under the same external stress, but assuming variations in technical, organizational, social and economic conditions. This analysis was highly relevant to identify the impacts of the implementation (or absence) of specific strategies to enhance system's resilience in all its dimensions.

Table 3. Approximately here

The baseline scenario, identified in the following as *Scenario 0*, represents the state of the infrastructure and of the socio-organizational-economic conditions that characterized the study area during the 2009 earthquake. According to the results of the meetings with institutions and citizens, one of the main issue was that the ‘community awareness’ was rather low, since no information about the emergency procedures was shared prior the disastrous event. ‘Reduction ratio’ was set to 0.5 since there was the need to reduce water demand, but a basic level of service was guaranteed just after the event. From an organizational point of view, internal ‘concern and cooperation’ and ‘cooperation with other institutions’ were pretty high (0.8), although the ‘training level’ of the personnel was not sufficient (0.3). The water utility had also enough ‘available economic resources’ to cope with the emergency, at least in the aftermath of the event. From the technical perspective, the ‘maintenance’ level of the system was sufficient (0.5), and additional water sources (wells) were activated in the emergency. The ‘infrastructure physical vulnerability’ was globally rather high (0.8), but a good ‘knowledge of critical points’ had been developed. The vulnerability value was assessed referring to the BBN-based vulnerability model and the final results are depicted in the following Figure 11. The figure represents, through both a chromatic and a numerical scale, the estimated physical vulnerability of the whole aqueduct. The probability value associated to the state ‘high’ of the variable ‘breaking vulnerability’ is taken into account and plotted. The global level of vulnerability is moderately low, although some critical points can be identified, mainly depending on the fact that the infrastructure is located in an area characterized by several criticalities (e.g. the presence of active faults).

Figure 11. Approximately here

The ‘water deficit’ in this scenario is represented in Figure 12, and compared with the results of the other scenarios briefly described in the following. Although the level of service does not experience a dramatic decrease, the time needed to fully recover the infrastructure functionality is rather long (approximately thirty days). This means that during this period the conditions of the affected population are worsened due to the limited access to this crucial service. The baseline scenario was used also to validate the model. The *Scenario 1* is characterized by a reduction of some of the most important variables of the model (see Table 2 for further details). This scenario mainly shows how a decrease in organizational skills – i.e. ‘cooperation and cooperation’, ‘knowledge of critical points’ and ‘training level’ – may have a dramatic influence on the response of the system, its physical vulnerability being the same. System performances rapidly falls down, and no alternative water sources are supposed to be available. The recovery phase is strongly hampered assuming that limited economic resources are available. The already limited economic resources become even poorer due to the incapability to provide a service to the community, leading the system toward a reinforcing negative loop resulting in rapid deterioration of the infrastructure. This reinforcing loop is the cause of the rapid decrease of the ‘water deficit’ in this scenario. The *Scenario 2* simulates a decrease of ‘infrastructure physical vulnerability’ through expensive structural interventions. Indeed, considering both an increase in the ‘maintenance’ level, and a subsequent reduction in the ‘infrastructure physical vulnerability’, the effect on ‘water deficit’ is definitely positive and the recovery phase results significantly shortened. The *Scenario 3*, at last, describes an integrated strategy where infrastructural improvement actions are supported by also by a better ‘knowledge of critical points’, ‘training level’ of the personnel and enhancement of ‘community awareness’. In this scenario, the rapidity of the system recovery is very high. In particular, both the knowledge and the availability of economic resources allows the water utility to quickly adapt the system to the changing conditions (e.g. the need to connect the shelter camps to the main networks), without reducing the level of service provided to the community. The comparison between system performances in *Scenario 2* and *Scenario 3* allows us to demonstrate once more the crucial role of the socio-economic and organizational elements.

Figure 12. Approximately here

4.2 Sensitivity Analysis

For the purposes of the present work, sensitivity analysis (SA) was performed with respect to both single parameters and clusters (Mateus and Franz, 2015), through the Sensitivity Specs dialog box available in STELLA® (ISEE Systems Inc.). The sensitivity of the system was firstly investigated focusing on the impact of variations of the variable 'infrastructure physical vulnerability' (from 0.1 to 1, increment by 0.1). The analysis was performed referring to the *Scenario 0*. The following Figure 13 suggests that the variable has a key influence on the technical dimension of resilience ('water deficit'), and significantly influences both its magnitude and the time required for recovery.

Figure 13. Approximately here

An additional SA was performed with respect to the variable 'hazard intensity' (from 0.1 to 1, increment by 0.1), leading to a better understanding of how external stress may condition the response of the system. The SA to 'hazard intensity' was firstly performed considering the *Scenario 0* (Figure 14), showing that the magnitude of the hazard highly affects the resulting 'water deficit'. The SA was also performed referring to the *Scenario 3* (Figure 15). It points out the relevance of both infrastructural and organizational improvements for a fixed level of hazard. If both infrastructural and organizational features are improved, the time for recovery may reduce significantly irrespective of the hazard level.

Figure 14. Approximately here

Figure 15. Approximately here

Lastly, a cluster of variables was analyzed within an additional SA, with the aim of quantifying to what extent an improvement (or a worsening) in all organizational features and skills could contribute to changes in the water deficit, the other conditions being the same (*Scenario 0*). In this case, all the variables belonging to the organizational dimension were modified simultaneously (from 0.1 to 1, increment by 0.1). The results are summarized in the following Figure 16, and clearly show how organizational skills may significantly contribute either to foster or hamper the recovery phase after an extreme event.

Figure 16. Approximately here

5 Discussion

The scenarios obtained through the SDM were discussed with the experts. According to their opinion, one of the main aspects of the model is that it can be profitably used as a decision support system for defining and comparing resilience-enhancing measures. A water utility could be supported in the identification of the main weaknesses in its own structure and organization, or in performing an optimal allocation of the available resources at different time steps. Similarly, emergency managers may be helped in identifying and selecting the most effective strategies to cope with disasters. To this aim, the SDM supports managers to dynamically investigate the impacts of such decisions on the level of service provided in the aftermath of the event, and to identify the hidden feedbacks and loops that may facilitate or hamper recovery processes. In order to facilitate the discussion with experts, the main variables of the model were divided in *control variables* and *action variables*. The following Table 4 summarizes the main *control variables* that can be used to describe the time-dependent evolution of system performance. The control variables were defined as *stocks* in the model. Table 5, instead, contains the main *action variables*, which represent fundamental factors and policies that can be selected to improve resilience conditions. A variation in an *action variable* corresponds to a potential change in the main related *control variables*.

Table 4. Approximately here

Table 5. Approximately here

The involved experts considered useful the model capability to simulate the dynamic evolution of the different elements influencing the system resilience. Compared to other methods for resilience assessment, capable to analyse “snapshots” of the situation, the SDM accounts for the dynamic nature of the interconnections among the different variables in case of emergency. Just to provide an example, the model describes how the lack of economic and organizational resources can activate a negative reinforcing loop “pushing down” the system faster than in case of linear cause-effect connections. The lack of economic resources does not allow the water utility to implement timely and effective recovery actions, provoking a dramatic decrease of the provided service and, thus, an even more dramatic decrease of the economic resources due to the lack of users. That is, the level of service and the economic resources are connected by a reinforcing loop that could spiral-down the system performance.

The availability of economic resources is also associated to the activation of a positive feedback loop. Indeed, the economic resourcefulness is directly associated to the increase of knowledge level, which strongly contributes to both avoiding further reductions of service and to increase the repair rate of the system, which is responsible for the reduction of the onset of new failures and damages. This effect triggers a positive impact, i.e. the reduction of the costs for the water utility, which makes available, as a result, further economic resources for additional interventions. This feedback significantly accelerates the recovery process, as it was acknowledged by the experts.

The evolution of resilience is also associated to complex concurrent effects that arise in different time steps. The trend of population on site, for example, has a twofold influence. In the short term, the reduction of population due to the delocalization and sheltering rates determines a reduction of the water demand within the urban system, thus reducing the stress on the infrastructure. In the medium/long term, the reduction of population directly turns into a loss of customers and in reduced fees. This determines negative cascading effects, such as the inability to promptly start recovery operations and to significantly reduce the failure rate of the system.

Besides being useful for performing a dynamic analysis, the adoption of SDM is therefore justified by its capacity to model feedbacks, time delays, and non-linear effects, as well as by the possibility to improve system understanding. Furthermore, it allows effective scenario analyses, through the possibility of changing multiple variables concurrently, which clearly reflects the interconnectedness between the variables in complex systems.

Particularly, the analysis of the scenarios developed using the SDM allowed to demonstrate that the main elements characterizing the TOSE approach are not isolated. They are rather strongly interconnected through a dense and complex web of feedbacks. Tools capable to enhance the understanding of this complex network are crucial to support decision makers in governing the resilience of LS in urban areas.

6 Conclusions

The present paper summarizes research activities developed within an ongoing EU funded research project, aiming at defining a quantitative model to assess the evolution of resilience of drinking water supply systems in case of natural disasters. Reference is made to a complex resilience paradigm, namely the TOSE approach, which jointly considers the role of both ‘structural’ and ‘non-structural’ parameters, contributing to the four basic dimensions of resilience (technical, organizational, social, economic).

The resilience assessment model, which was developed through SDM, was implemented in L’Aquila (Italy) 2009 Earthquake case study, in strict cooperation with the local water utility.

Although further refinements and applications of the model are required, its preliminary development revealed a significant potential as a decision support system, which can be used in case of disasters potentially affecting LS, mainly due to the capability of quantitatively modelling the complex feedback mechanisms and interconnectedness lying behind such system. The developed SD model demonstrated its capabilities to simulate the dynamic evolution of different elements influencing system resilience.

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Tables

Stakeholder	Type	Number of units	Activities	Provided Information
Civil Protection Agency	Technicians	2 (National) + 4 (Local)	Conceptual model building, discussion of results, calibration and validation	Technical issues and societal dynamics; impact of emergency procedures; dynamic evolution of emergency
Water utility (GSA S.p.A.)	Technicians	4	Conceptual model building, discussion of results, calibration and validation	Technical, organizational and economic dynamics; impact of ordinary and emergency procedures; strategies and alternative to cope with emergency
Community	Users	10	Discussion of results and validation	Societal dynamics, dynamic evolution of emergency
IRSA-CNR and Technical University of Bari	Researchers	6	Support to conceptual model building, discussion of results, calibration, validation and sensitivity analysis	Identification of variables and states; analysis of relationships and feedbacks; definition of causal loops; Stock and flow model building; scenario development

Table 1. Summary of the domain experts involved and overview of their role in model building activities

	Performance criteria			
	Robustness	Redundancy	Resourcefulness	Rapidity
Technical	**Def**. Maximize availability of operational water supply after the event.	**Def**. Replacement inventories.	**Def**. Models to assess network vulnerability and damage.	**Def**. Maximize provision of target water supply level.
	Variables. Level of service; Volume provided by alternative water sources; Emergency water	**Variables**. Volume provided by alternative water sources	**Variables**. Infrastructural knowledge	**Variables**. Dynamic evolution of: Level of service; Volume provided by alternative water sources; Emergency water
Organizational	**Def**. Emergency organization and infrastructure in place; critical functions identified	**Def**. Alternative water supplies available	**Def**. Plans for mobilizing supplies and personnel; emergency strategies	**Def**. Maximum restoration of water supply
	Variables. Level of knowledge; Human resources in emergency; Level of knowledge	**Variables**. Volume provided by alternative water sources	**Variables**. Level of knowledge; Available economic resources	**Variables**. Dynamic evolution of: Volume provided by alternative water sources
Social	**Def**. Uninterrupted water supply for fire-fighting	**Def**. Alternative water supplies for post-event fire-fighting	**Def**. No form of rationing needed to meet minimum potable water supply needs	**Def**. Potable water service uninterrupted after event
	Variables. Level of service.	**Variables**. Volume provided by alternative water sources	**Variables**. Water demand; Reduction ratio; reduction ratio in shelter camps.	**Variables**. Dynamic evolution of: Level of service; Volume provided by alternative water sources; Emergency water
Economic	**Def**. Businesses with water after the event	**Def**. Alternative water supplies for all key businesses	**Def**. Economic resources available to cope with the disaster	**Def**. Economic activities re-established in 1 day
	Variables. Level of service; Available economic resources.	**Variables**. Volume provided by alternative water sources	**Variables**. Level of service; Available economic resources.	**Variables**. Dynamic evolution of: Level of service; Available economic resources.

Table 2. Performance criteria of water supply systems. The definitions suggested by Bruneau et al. (2003) are adapted referring to the variables of the proposed model that could be used as indicators.

Variable	**SCENARIO 0**	**SCENARIO 1**	**SCENARIO 2**	**SCENARIO 3**
Community awareness	0.2 (low)	0.2 (low)	0.2 (low)	0.7 (medium-high)

Reduction ratio	0.5 (medium)	0.8 (low)	0.5 (medium)	0.5 (medium)
Maintenance	0.5 (medium)	0.4 (medium-low)	0.7 (medium-high)	1 (high)
Concern and cooperation	0.8 (high)	0.3 (low)	0.8 (high)	0.8 (high)
Cooperation with other institutions	0.8 (high)	0.3 (low)	0.8 (high)	0.8 (high)
Knowledge of critical points	0.7 (medium-high)	0.3 (low)	0.7 (medium-high)	1 (high)
Availability of wells	1 (yes)	0 (no)	1 (yes)	1 (yes)
Infrastructure physical vulnerability	0.8 (high)	0.8 (high)	0.5 (medium)	0.5 (medium)
Training level	0.3 (low)	0.3 (low)	0.3 (low)	1 (high)
Available economic resources (Initial state)	Medium-low	Null	Medium-low	High

Table 3. Summary of the main variables considered, and of their value, in the four modeled scenarios. The numerical values of the variables (ranging from 0 to 1) are proposed along with a qualitative description of their meaning

'Control' variable	**Description**
Water deficit	Defines the relation between the total volume of available water (deriving from the infrastructure and from emergency sources) and the water demand for the population to be served.
Level of service	Expresses the residual level of service, mainly depending on the current conditions of the infrastructure, on breaking and repair rate, on scheduled interruptions.
Volume provided by alternative water sources	Defines the availability of additional volumes of water activated during emergency
Emergency water	Considers the volume of water provided, during emergency, by vehicles and as bottled water
Collapsed buildings	Defines the ratio of the total buildings which are collapsed, and are therefore no longer livable
Damaged buildings	Defines the ratio of the total buildings which are damaged, and therefore temporarily not usable
Population in shelter camps	Expresses the population transferred to shelter camps as a ratio of the total population, depending on the expected buildings' conditions.
Population delocalized	Expresses the population 'permanently' delocalized as a ratio of the total population, depending on the expected buildings' conditions.
Water demand	Amount of water required by population remaining in houses and by population moving to shelter camps. It could be affected by the adoption of rationing strategies.
Human resources in emergency	Defines the number of workers of the water utility, who are directly involved in EM.
Failure rate	Expresses the rate of failures, as a function of both damage rate and repair rate.

Economic resources	Amount of available economic resources, as a combination of both ordinary resources and emergency subsidies.
Level of knowledge	Defines the overall available level of knowledge for the water utility.
Environmental knowledge	Expresses the level of knowledge available on the environment surrounding the infrastructural system.
Infrastructural knowledge	Expresses the level of knowledge available on the infrastructural system.
Hazard or event knowledge	Expresses the level of knowledge available on the hazard occurred and its impacts.

Table 4. 'Control' variables that can be monitored to analyze aspects connected to resilience

'Action' variable	Action/Strategy
Bottled water	Increase provision, and varying temporal distribution of volumes of bottled emergency water
Number of vehicles (internal/external)	Use of additional vehicles for conveying water or improvement of relationships with neighboring utilities
Daily functioning hours (well)	Increase (if necessary and sustainable) the duration of daily pumping during emergency
Reduction ratio of water supplied per capita	Reduce the water supplied per capita in order to reduce the water deficit
Training level	Increase the emergency management capabilities of employees through e.g. courses and practice
Concern and cooperation	Foster cooperation, team spirit and cohesion within the organization
Maintenance	Increasing maintenance for reducing infrastructural failures
Fee	Increasing or reducing fees can vary available economical resources
Emergency economic resources A	Availability of resources for emergency (e.g. national or EU funds)
Redundancy in information management	Foster information sharing and diffusion; consider multiple data availability
Monitoring and forecasting	Implementing control systems for infrastructures as well as early warning
Knowledge of critical points	Implementation of vulnerability assessment tools to identify major problems
Field surveys	Optimization of surveys, and of distribution of employees
Availability of GIS and database	Adoption of GIS systems and development of database for collecting information
Collection of feedback from the users	Implementation of systems (e.g. questionnaires, phone calls…) for getting users' feedbacks on the level of service
Cooperation with other institutions	Development of relationships with other institutions for data and knowledge sharing

Table 5. Variables that can be improved for increasing resilience through specific actions/strategies

***Manuscript (marked version with track changes)**

1 Introduction

Cities are systems of interacting~~ people and~~ social groups in densely built spaces served by infrastructures and managed by social and political organizations (Bettencourt, 2015). Therefore, cities are strongly dependent on infrastructures providing essential services, namely Lifeline Systems (LS) that support societal functions, safety, economic prosperity and quality of life (~~e.g.~~ O'Rourke, 2007~~; NIAC, 2013~~). Besides, LS are embedded within the urban context and interact dynamically with it (~~e.g. Mc Daniels~~McDaniels et al., 2008; Bettencourt and West, 2010; Bozza et al., 2015), combining physical infrastructures ~~(e.g. transportation, supply of electricity, water supply, management and treatment)~~ and social networks ~~and~~of interactions among individuals, groups, and institutions (Gasteyer, 2004). ~~Guaranteeing the reliability of LS under all conditions, even after natural disasters, is therefore of utmost importance.~~

Empirical evidences demonstrated that the dynamic interaction between physical infrastructures and social networks is even tighter in case of the occurrence of a hazardous event, when a city ~~suffer~~suffers a natural disaster and tries to reconfigure itself (Bozza et al., 2015). The traditional engineering-oriented approaches aiming exclusively at reducing the physical vulnerability of the infrastructures proved to be inadequate to address the complexity of the socio-technical interaction (~~e.g.~~ Bruneau et al., 2003; Davies, 2015). In order to overcome these limits, resilience thinking approaches account for the community/infrastructures interconnections, bridging the static and dynamic components of disasters across pre and post event context~~. A static model of resilience identifies and organizes critical variables, whereas a dynamic model represents how and why such variables change across time and space~~ (Miles, 2015).

Resilience thinking in natural disaster management has become a central driver in the strategies and policies of urban planners, technical practitioners, decision-makers, NGOs and institutions (~~Starr et al., 2003;~~e.g. United Nations Office for Disaster Risk Reduction, 2007; ~~Birchall and Ketilson, 2009; Thompson et al., 2009;~~ World Bank, 2011; European Commission, 2012).~~ The notion of resilience~~

~~in natural disaster management has several different interpretations and understandings, which highlight the complexity in using it as an all-encompassing word (Dahlberg et al., 2015).~~ Originated in environmental systems (Davies, 2015), the concept of resilience became relevant for engineered domains, including LS (e.g. O'Rourke, 2007; ~~Mc Daniels~~McDaniels et al., 2008; ~~Stephenson, 2010;~~ Agarwal, 2015). It can be ~~basically~~ defined as the ability of ~~specific~~ infrastructural systems to absorb the shocks of extreme events such as natural disasters. Resilience can be achieved by enhancing the ability of an infrastructure to perform during and after a hazard, as well as through emergency response and recovery strategies (~~e.g.~~ Chang et al., 2008).

The ~~change~~shift from risk management approach to resilience management paradigm was ~~a~~ crucial ~~shift~~ in the field of LS for ~~several~~multiple reasons. On the one side, ~~the risk management approach requires a complete knowledge of all potential hazards and a full understanding of the interconnections among different LS (Davies, 2015). It is typically based on past events and trends analysis. Several~~ several works ~~evidenced~~discussed the unsuitability of ~~such approach~~risk management approaches in ~~order to protect LS against~~LS protection during natural disasters (e.g. Bruneau et al., 2003~~; Cimellaro et al., 2010~~; Gay and Sinha, 2013; UNISDR, 2014; Comes and Van de Walle, 2014; Reinhorn and Cimellaro, 2014; Cavallo and Ireland, 2014; Davies, 2015). This is mainly due to the complexity of LS, characterized by strong and dynamic interdependencies with urban, natural and social systems~~. In order to highlight the complexity of LS, many authors describe them~~, and thus often described as "System of Systems" (e.g. Cavallo and Ireland, 2014; Filippini and Silva, 2014). On the other side, resilience thinking increases the capability of the system to deal with the unforeseeable (Park et al., 2013; Davies, 2015). It addresses the complexities of ~~large~~ integrated systems and the uncertainty of future threats (Linkov et al., 2014), emphasizing the system ability: i) to anticipate and absorb potential disruptions, ii) to develop adaptive means to accommodate changes, iii) to establish response behaviors aimed at either building the capacity to withstand the disruption or recover as quickly as possible after an impact (Francis and Bekera, 2014).~~ Mainly, resilience thinking approaches aim at increasing the capability of the system to deal with the unforeseeable (e.g. Park et al., 2013, Davies, 2015).~~

Starting from these premises, this work aims at developing an innovative approach to LS resilience assessment, capable to account for the dynamic and complex nature of its interacting elements. To this aim, a System Dynamic Modelling (SDM) approach is adopted. The work ~~aims~~intents to demonstrate the SDM suitability for LS resilience assessment and management through the implementation of the method in a real case study, related to the drinking water infrastructure resilience during L'Aquila (Italy) earthquake (2009).

2 State of the art

~~As underlined in the previous section, resilience~~Resilience is a process rather than a static concept (~~e.g.~~ Francis and Bekera, 2014; Labaka et al., 2015). Designing policies and strategies to build resilience ~~of the human, natural and~~in urban systems claims for a deep understanding of the multifaceted nature of the ~~elements~~ influencing ~~the resilience~~ elements and of the complex multi-actor ~~process~~processes involving social, economic, political and physical dimensions across diverse scales (Helfgott et al., 2014; Dahlberg et al., 2015).

Significant efforts are mentioned in the scientific literature aiming at developing analytical tools ~~capable~~ to quantitatively assess the infrastructural resilience (e.g. Alderson et al., 2015). Several authors suggested to use ~~synthetic~~specific functions ~~to measure infrastructural resilience, such as~~ (e.g. Attoh-Okine et al. ~~(~~2009~~) who introduced a belief function framework as resilience index. Further~~, Reed et al. ~~(~~2009~~) proposed a quality curve for describing structural performances, mainly depending on the full capacity of the structural system, on the post-event capacity~~ and ~~on a parameter derived empirically from restoration data following the event. Lastly,~~ Henry et al. ~~(~~2012) ~~developed a time-dependent function as~~as metrics of resilience. Francis and Bekera (2014) worked on infrastructural resilience, implementing a framework based on three key resilience capacities (adaptive capacity, absorptive capacity, recoverability) to determine a resilience factor. The authors combined subjective expert knowledge with assessments of recoverability, through variables depending on performance levels and time to recovery. Referring more specifically to water supply systems, several quantitative ~~metric of system resilience.~~methodologies for resilience assessment were proposed, mainly based on the analysis of network characteristics (e.g. Todini 2000; Mugume et al., 2015)

~~Referring more specifically to water supply systems, some authors proposed quantitative methodologies~~A very well-known paradigm for infrastructural resilience assessment ~~based on the analysis of network characteristics. For instance, Todini (2000) worked on the resilience at urban level implementing a vector optimization problem with cost and resilience as two objective functions and Mugume et al. (2015) used simplified synthetic networks in pipe failure scenarios.~~

~~Further activities were performed with the aim of proposing more complex resilience assessment frameworks. Among the others, Francis and Bekera (2014) proposed a resilience assessment framework, consisting of five components: system identification, vulnerability analysis, resilience objective setting, stakeholder engagement and resilience capacities. The basic idea is expressing the resilience through a factor, depending on three resilience performance levels and on time to recovery. Furthermore, resilience has been defined as a probabilistic concept combining subjective expert knowledge of the underlying event generating process with assessments of recoverability, hardness, and adaptability. To evaluate resilience actions through an entropy-weighted decision support metric, a value formulation is introduced, including the resilience factor, system fragility and the probability of disruption.~~

~~According to Labaka et al. (2015) the existing resilience frameworks have mainly a theoretical nature and crisis managers have difficulties to select the optimum activities or policies. The principles of resilience noted in the literature are limited to describe their meaning and advantages without providing practical actions for proper implementation.~~

~~A very well-known method to assess LS resilience~~ is the TOSE approach (Bruneau et al., 2003). The most interesting feature of this approach is the integration of four dimensions: Technical, Organizational, Social and Economic (e.g. Bruneau et al., 2003; O’Rourke, 2007; Tierney and Bruneau, 2007; Cimellaro et al., 2010). The *technical* dimension of resilience refers to the ability of interconnected physical systems to perform at acceptable/desired level. The *organizational* dimension denotes the capacity of organizations to manage the critical facilities and take actions that contribute to enhance resilience. The *social* dimension of resilience measures to what extent communities could contribute with their behavior to contain the reduction of critical service in case of emergency. Similarly, the *economic* dimension of resilience refers to the capacity to reduce both direct and indirect economic losses ~~(Bruneau et al., 2003; Chang et al., 2008).~~

. The TOSE approach was widely used in several analyses and, recently, for performing a comparison between L’Aquila earthquake and Canterbury earthquake (Kongar et al., 2015) with respect to the infrastructural systems involved.

Bruneau (2003) and Tierney and Bruneau (2007) suggested the use of a ‘resilience triangle’ (~~see Figure 1) to describe resilience, representing~~Figure 1) to quantitatively describe resilience, based on a measure of time-varying system performances $Q(t)$. Given a specific event, the loss of resilience can be measured by the size of the expected degradation in performances over time. Indeed, it can be represented through the area delimited by the curve $Q(t)$. $Q(t)$describes both the loss of functionality from damage and disruption and the pattern of restoration and recovery ~~over~~(i.e. time~~.~~ to recovery). Resilience-enhancing measures aim at reducing the size of the resilience triangle.

Figure 1. Approximately here

~~The multi-dimensional approach to resilience assessment has been adopted by several other authors. Labaka et al. (2015), to mention one of them, demonstrated that crisis in LS management could be~~

~~originated due to the lack of integration among the different dimensions composing the resilience concept.~~

Moving in such direction, System Dynamics Modeling (SDM) is an operative approach for helping reveal the temporal behavior of complex systems (Neuwirth et al., 2015), with several applications in environmental decision-making, especially in the field of hydrology and water resources management (e.g. Ahmad and Simonovic, 2000; Khan et al., 2009; Gastelum et al, 2010~~; Neuwirth et al. 2015).~~).

A System Dynamic (SD) approach aims at providing insight into non-linear system behavior for assisting informed decision-making by stakeholders and policy-makers. SD is a ~~rigorous~~formal method of system description, which facilitates feedback analysis via a simulation model of the effects of alternative system structures and ~~the control policies of system behavior (Simonovic, 2009).~~ control policies of system behavior (Simonovic, 2009). Forrester (1961, 1968, 1987) introduced the SD methodology sought to involve clients in the process of model construction within strategic problems in business. Additionally, SD has become popular when its general principles of feedback were presented under the label of system thinking (Barlas, 1996). The SD structure, built up with stocks, flows and causes-effects chains, describes the behavior of the system through feedback loops (Sterman, 2000). It can be fundamental to building and integrating conceptual models (Vennix, 1996) during group modelling activities.

The system formalization provides a better understanding of what drives system behavior and support examining future dynamics based on a given set of ~~assumption~~assumptions. In this way, modeling system behavior over time can provide insight into significant relationships, reveal patterns, expose sources of undesirable system behavior, and help avoid unforeseen consequences of future policy implementations (Neuwirth et al., 2015). Three main SD features make such methodology particularly suitable for resilience assessment: i) the ability to address how structural changes in one part of a system might affect the behavior of the system as a whole; ii) combined predictive (determining the behavior of a system under particular input conditions) and learning (the discovery of unexpected system behavior under particular input conditions) functionality; and iii) active involvement of stakeholders in the modelling process.

~~SD has been rarely implemented in the field of infrastructural systems. Ouyang (2014) adopted a SD based approach to: i) model their dynamic and evolutionary behavior by capturing important causes and effects under disruptive scenarios; ii) capture the effects of policy and technique factors to reflect the system evolution in the long term; iii) provide the investment recommendations, incorporating multi-attribute utility functions to compare alternative infrastructure protection strategies and iv) help build consensus among stakeholders.~~

~~According to the work of Labaka et al. (2015), it is clear that resilience is composed of different dimension and also that, if such dimensions are analyzed independently, crisis could be originated due to the lack of their integration.~~

~~Within such framework, this~~This work mainly describes a methodology to assess the resilience of LS, with specific reference to drinking water supply systems, adopting a multi-dimensional and dynamic perspective. An SD model has been developed and tested in order to identify and analyze the main elements fostering or hampering resilience. Secondly, the model has been used to evaluate the impact of actions and strategies for resilience improvement on the dynamic evolution of the system. Finally, it has been used to identify critical feedbacks, and to evaluate their influence on the implementation of ~~actions or~~ policies aiming to enhance LS resilience, assessing their evolution with time.

3 Materials and methods

The methodology described in this work is based on the integration between SDM and TOSE approach. It aims at assessing the resilience of drinking water supply infrastructure accounting for the dynamic evolution ~~in emergency~~ of the infrastructure itself and of the urban system in which it operates~~.~~ during emergency.

3.1 Vulnerability assessment model

A basic input for the SD model described in the following is represented by the vulnerability level of the infrastructural system. It is estimated through a probabilistic tool based on Bayesian Belief Networks (BBN). Full details on the methodology are available in Pagano et al. (2013, 2014a, 2014b). The vulnerability assessment model requires the integration of different classes of data: physical (related to infrastructural characteristics), environmental (e.g. seismicity) and operative (e.g. hydraulic variability, maintenance). The model provides specific outputs to estimate the probabilistic vulnerability values for each element of the network. For the purposes of the SD model, an overall value of system vulnerability needs to be defined. Specifically, referring to the values of the state ‘high’ of the variable ‘breaking vulnerability’, the maximum value on the whole network is taken into account. As it will be described, the role of the estimated network vulnerability contributes to the *technical* dimension of resilience in the SD, conditioning the level of service provided by the infrastructure. The following Figure 2 represents the BBN used for the vulnerability assessment, and describes how it is conceptually included in the SD model.

Figure 2. Approximately here

3.2 Resilience assessment based on SDM: model building process

The SD model was built to analyze the resilience of drinking water supply systems accounting for the complexity and dynamic interactions among the four main elements of the TOSE approach. The model recognizes and simulates feedback mechanisms, which could affect the resilience of a water system and/or the effectiveness of resilience-enhancing policies. As discussed further in the text, the developed model could be used to support water utilities in the selection and critical analysis of the most suitable strategies to improve resilience, thus reducing potential failures of drinking water supply in case of disasters. A preliminary version of the model was discussed by Pagano et al. (2015). The model was developed and implemented in STELLA® (ISEE Systems Inc.).

According to Davies and Simonovic (2011), the SDM development process was structured ~~in~~according to the following~~ main~~ phases: i) understanding the system and its boundaries; ii) identifying the key variables; iii) describing the processes that affect variables through mathematical relationships; iv) mapping the structure of the model; v) simulating scenarios for understanding model behavior. The Figure 3 summarizes the key steps of model building, further described in the present section.

Figure 3. Approximately here

Modeling activities were carried out by integrating scientific knowledge available in literature with expert knowledge (Schön, 1983; Fischer, 2000), elicited through semi-structured interviews~~.~~ ~~Experts~~ , according to participatory work principles. Literature evidences were used to develop the first version of the conceptual model identifying the main cause-effect relationships. The domain experts from the local water ~~utilities~~utility and the ~~National~~ Department of Civil Protection~~,~~ (both national and local agencies), as well as ~~academics and~~ researchers, ~~were~~ cooperated in the modeling phases. Some citizens, who were directly involved in ~~this~~ the emergency as end users of the water supply service, were also included in modelling activities. Experts were clustered in two different groups (Figure 3) in order to support on one hand the phase of conceptual model building and on the other the definition of the stock and flow model, with the consequential calibration and validation. Full details on the involved stakeholders and the provided information are in the Table 1.

Table 1. Approximately here

~~. The collected~~The process of group model building starts from the conceptual model definition, representing the sum of cause-effect chains influencing the stock and flow model (Vennix, 1996). In order to gather the fundamental individual and collective knowledge~~ was meant to:~~, the domain experts integrated the conceptual model, adding or deleting variables and modifying links. The modelling process ended when no new concepts and/or relationships emerged after a number of interviews and researchers supported the global model design. Following the approach adopted by Pagano et al. (2014), the interviews were carried out limiting bias in expert knowledge collection. Based on Page et al. (2012), particular attention was made on problem framing (to reduce subjectivity and ambiguity), availability issues (the tendency to overestimate the magnitude of recent/familiar events) and anchoring (systematic underestimation of uncertainty/variability).

- ~~Structuring the complex set of relationships and feedbacks among the different kinds of variables contributing to resilience – i.e. technical, organizational, societal, economic;~~
- ~~Assessing the impact of both ordinary management procedures and emergency actions on resilience;~~
- ~~Modelling the dynamic evolution of an emergency situation and the key steps in disaster management;~~
- ~~Describing the major issues and the most suitable strategies for increasing resilience.~~

~~In order to handle the complexity of the relations among variables, a simplified~~The obtained conceptual scheme is depicted in Figure 4. The dimensions of resilience were defined adapting the general idea suggested by Bruneau et al. (2003) to a drinking water supply system.

Figure 4. Approximately here

~~was developed (Figure 2).~~ The scheme ~~dealt~~was built in order to deal separately with the four basic dimensions of resilience. Then the reciprocal influences among variables were identified. For instance, some organizational capabilities (i.e. the availability of human resources, the availability of a good knowledge concerning the infrastructure and the environment) may have a direct influence on the technical dimension of resilience (i.e. they support a quicker and effective response to technical issues connected to the level of service).

The ~~dimensions of resilience were defined adapting to the general idea suggested by Bruneau et al. (2003) to a drinking water supply system.~~

~~Figure 2. Approximately here~~

~~The involved~~ experts were asked to ~~identify~~describe the main variables and to properly connect them according to the expected influences. They were also asked to provide a quantitative interpretation of all the considered variables (even non-physical ones, such as knowledge level) and of their possible states. Finally, they were asked to describe the potential dynamic evolution of the variables, the main causes of these changes and the potential effects.

~~The collected knowledge~~ Afterwards, the conceptual model was ~~then structured in a~~used as basis for the development of the stock-and-flow model. A first subset of variables was defined referring to the conceptual model ~~(~~in Figure 4, i.e.~~g.~~ level of knowledge, available economic resources, water demand ~~[~~(from both population on site ~~+~~and population in shelter camps~~],~~), level of service/loss of service~~)~~.. Such variables were modeled as ~~'stocks'~~*stocks*, according to the SDM ~~theory~~methodology, since they describe the accumulation or depletion of both physical and non-physical resources. Another subset of variables was defined and modeled as 'conveyors' using the collected knowledge. Those variables are related to either externally specified conditions (e.g. ~~the~~ 'intensity of the ~~hazard~~hazard'), or to actions/~~strategies~~policies that can be implemented and may have an influence on resilience levels (e.g. increasing the training level of employees, implement monitoring activities, availability of GIS and database).

The general structure of the model was then discussed with the expert sub-group, who reviewed the variables and their relationships. Additionally, a quantitative calibration was performed referring to the L'Aquila earthquake case study. As in most emergency conditions, data were not readily available/accessible, and affected by significant uncertainties (Van der Keur et al. 2016). A few key stocks were selected for calibration (e.g. 'water deficit', 'population on site', 'available economic resources'), and their simulated dynamic evolution plotted. Experts were asked to identify for each variable a scatter plot to build an expected trend. The comparison between the expected and the predicted trend allowed the calibration of the key equations used in the model. Small deviations were attributed to the difficulties in collecting reliable data. Nevertheless, the experts considered these deviations as minor.

3.3 Resilience assessment based on SDM: model description

The complete model of resilience is represented in the following Figure ~~3.~~5.

Figure 5. Approximately here

~~Figure 3. Approximately here~~

As stated previously, LS play a crucial role in keeping alive the social networks within a community in case of disaster by continuing to provide crucial services~~, e.g. drinking water supply~~ (Ouyang and Wang, 2015). This role also emerged, and was discussed by the experts involved, in a severe emergency such as L'Aquila earthquake. Therefore, the main goal of the model is to assess the capability of the infrastructure to provide a satisfactory level of service in ~~the aftermath of the disaster. To this aim, the model defines the water balance during emergency and in the immediate aftermath, based on a comparison between water provision and water demand. Initially, the inflow volume is represented by the water that can be conveyed using the existing infrastructure. It depends on the expected failure rate, which is related both to the damage creation mechanisms and to the repair rate. The damage creation mechanisms is influenced by the infrastructural physical vulnerability, shown in black in Figure 3. This variable is linked with the Bayesian vulnerability assessment model described in Pagano et al. (2014). Going further into details, the model implements Bayesian Belief Network (BBN) accounting for a wide range of parameters (physical, environmental and operational) which contribute to affect the conditions of pipes and their response to external stresses. More details concerning the development of the model and its implementation~~

~~for assessing physical vulnerability of the water infrastructures are available in Pagano et al. (2014).~~case of a disaster. To this aim, the model mainly aims at providing information on the water deficit during emergency and in the immediate aftermath, based on a comparison between water inflow and water demand.

Specific sub-models, identified by purple boxes were defined in order to deal with key issues contributing to resilience according to the TOSE conceptualization. Although most of the sub-models are mutually interconnected, they can be also run and analyzed independently.

Referring to the global model, the ‘inflow’ volume is primarily conditioned by the water that can be conveyed using the existing infrastructure (according to its residual ‘level of service’). This depends on the expected ‘failures’ (sub-model ‘Technical dimension 1 – Failures’, Figure 6), which are related both to the damage ‘creation rate’ and to the ‘repair rate’. The former is influenced by ‘hazard intensity’ and by ‘maintenance’ activities, but also significantly by the ‘infrastructure physical vulnerability’ (black conveyor in Figure 6). This variable is linked with the Bayesian vulnerability assessment model described in the sub-section 3.1. The ‘repair rate’ depends instead on the ‘available economic resources’ and ‘human resources ratio in emergency’, and is fostered by the available ‘level of knowledge’. All these variables derive by other sub-models.

Figure 6. Approximately here

During emergencies, the inflow volume is generally integrated using alternative sources~~,~~ (‘volume provided by alternative water sources’), such as wells or ‘other available ~~backup volumes~~volumes’ (e.g. tanks). ‘Emergency water’ sources are activated as well (‘emergency vehicles or ‘bottled ~~water~~water’), that are needed to compensate the reduction of available water volumes~~. The~~ (sub-model ‘Technical dimension – 2 Additional water volumes’, Figure 7).

Figure 7. Approximately here

From a technical point of view, the model is thus capable to simulate the impacts on infrastructural resilience originated by changes in its functionality. On the one hand, ~~impacts determined by~~the effect of failures and topological modifications after a disastrous event (e.g. breaks and failures, network adaptation measures~~),~~); on the other hand, imposed alterations on flow regime and adaptation capabilities ~~(e.g. the capability to provide water in the shelter camps).~~.

The model shows also how the capabilities ~~of the system~~ to react quickly ~~react~~ to a disastrous event and to rapidly recover ~~its functionalities~~functionality do not depend only on the infrastructural characteristics. Economic and organizational elements are crucial as well. From an organizational point of view~~,~~ (sub-model ‘Organizational dimension’, Figure 8), the model describes the impacts on the system resilience due to the development of a full understanding of the infrastructural system, the surrounding environment and the hazard~~.~~ (‘infrastructural knowledge’, ‘environmental knowledge’ and ‘hazard or event knowledge’ respectively). This goal is achieved through the enhancement of information acquisition (e.g. ‘field surveys’, ‘monitoring and forecasting’, ‘infrastructure monitoring’) and sharing ~~tools~~capabilities (e.g. ‘availability of GIS~~).~~ and database’, ‘cooperation with other institutions’). Moreover, the model ~~shows~~displays how the timeliness and the effectiveness of the involvement of ‘human resources in ~~emergency~~emergency’ is of utmost importance. To this aim, ‘training ~~activities play~~level’ plays also a crucial role as well as ‘concern and cooperation’ attitude.

Figure 8. Approximately here

The model shows also (sub-model ‘Economic dimension’, see Figure 9) the role of the interdependencies between the ~~economic resources~~ ‘available economic resources’ for the organization and the capability of the infrastructure to ~~recovery from the disastrous event~~cope with ‘failures’. It displays that the reduction of the population using the water services (due to delocalization in other cities or in the shelter camps) results in a decrease of the available economic resources~~.~~ (‘incomes’). Consequently, the organization ~~has~~may have not enough resources to deal with the ‘costs’ associated to emergency~~ management~~. The model accounts for both the internal economic resourcefulness and the ‘emergency ~~funds~~economic resources’ than can be activated after the occurrence of a disaster.

Figure 9. Approximately here

From the social point of view~~,~~, (sub-model ‘Societal dimension’, Figure 10), the model is able to simulate the spatial/temporal dynamic of the local population ~~and,~~(‘Population on site’, ‘population delocalized’, ‘population in the shelter camps’) as a function of the expected damage on buildings (‘total buildings’, ‘collapsed’ and ‘damaged’); consequently, ~~of~~ the required level of service (‘Water demand’) is changed, also considering the potential ‘reduction ratio’ strategies and the ‘community awareness’. The model still lacks the capability to simulate changes in community’s behaviors - e.g. water consumption – in case of emergency. More ~~date~~data are required to overcome this drawback of the model.

Figure 10. Approximately here

The green variables in the model ~~(Figure 3)~~and sub-models represent the set of actions that could be implemented to enhance system resilience. The following Table ~~1 shows~~2 provides an overview of the measures that are used in this work to describe the resilience of water supply systems.

~~Table 1. Approximately here~~

~~Once developed, the model was validated in two steps. Firstly, it was discussed through the cooperation of another subset of experts, who were asked to analyze the variables and to confirm/change the relationships proposed and the related equations. Secondly, it was applied to a real case study, namely the well-known L’Aquila earthquake in 2009, in order to verify the results obtained from a quantitative point of view, thus supporting the calibration phase.~~

Table 2. Approximately here

3.~~2~~4 Overview of the case study

L’Aquila province (central Italy) was struck by an earthquake (6.3 magnitude) on ~~6 April 2009. The L’Aquila urban matrix is shaped by the historical center and 59 neighborhoods lying outside.~~the 6th of April 2009. The physical event was relatively moderate, but it revealed the very high vulnerability of lives, livelihoods, building stock and institutions ~~in the Apennine Mountains~~ (Alexander, 2014). More than 300 people were killed and 1500 injured, about 100000 buildings were damaged and 67000 people left homeless (Alexander, 2010~~; 2014), due to the severe damage to buildings and LS. The damage to structures and infrastructures was detected over a broad area of approximately 600 square kilometers, including the downtown of L’Aquila and several rural villages (Kongar et al., 2015). Seventy percent of the historical heritage and residential buildings were severely damaged or destroyed (Kaplan et al., 2010).~~

~~Furthermore, the~~). L’Aquila old city was declared unsafe, made off-limits with military control and the community was moved out of destroyed and damaged buildings. ~~What is more, the old city symbolizes the cultural and socio-economic core since the XII century with a notable historical heritage (Forino, 2015). However, the~~The Italian government opted for a direct transition from homelessness to secure accommodation (e.g. tent camps or coastal tourist hotels) (Alexander, 2010). During the recovery phase, two different strategies of relocation were enacted: small settlements~~,~~ - called MAPs~~, were filled in damaged preexisting settlements~~ - and large ~~‘~~new ~~towns’, called~~towns - CASE Project~~, were constructed~~ (Calvi & Spaziante, 2009; Forino, 2015). ~~Specifically, both delocalization strategies represent paradigmatic top-down reconstruction actions (Alexander, 2013), and the chosen sites were outside the L’Aquila city boundaries, causing considerable problems for the community.~~

Although the emergency management of LS provided a rapid and resilient response to the earthquake (Dolce and Di Bucci, 2015), an important water-pipe, within the “Gran Sasso Aqueduct” failed because crossing the surface trace of a fault activated during the earthquake (Rossetto et al., 2011~~,~~; Dolce and Di Bucci, 2015). The steel joint of the pipeline (diameter 600 mm; pressure 25–30 atm) slipped off, and the cause of damage was identified as co-seismic rupture of the Paganica fault that crossed the pipe. No significant damage was observed to the main distribution and storage system, whereas in the minor distribution system slippage/breakage of the joints and ~~the~~ breaking of cast iron pipes were the most commonly observed damages (Kongar et al., 2015).

The interviews with the technicians working for the local water utility (Gran Sasso Acqua S.p.A.) confirmed that several minor breaks occurred locally (e.g. in pipes serving single buildings), and ~~determined~~caused severe problems to the functionality of the urban drinking water supply network. The location of citizens (e.g. their movement to temporary shelters, or their delocalization) determined significant variations to the demand pattern, and thus the need to adapt the characteristics of the drinking water supply. Several decisions made for managing emergency conditions were also particularly complex, and serious issues related to the drinking water supply service provision were raised. ~~Just to provide an example, in some cases a partial practicability of buildings was granted by the municipality, mainly with the aim of supporting the recovery of economic activities even if the houses in the same building were not practicable. This was particularly critical, mainly due to presence of multiple damages within single buildings, and required a careful and detailed local investigation on damages and leaks, to avoid further problems and inefficiencies due to the loss of huge volumes of water.~~

4 Results

4.1 SDM and scenarios development

The developed SDM was implemented to assess the resilience of L'Aquila drinking water supply system. ~~Moreover, the~~The SDM is meant to support decision-makers to identify potential actions aiming to improve the capability of the system to promptly react in case of natural ~~disaster~~disasters, providing crucial services to the affected community. In order to evaluate and compare the effectiveness of the different actions, the 'water ~~balance~~deficit' was adopted as measure of ~~the~~ system ~~resilience~~performances. It assesses the capabilities of the water infrastructure to provide the required amount of water in order to satisfy the community's needs in the ~~immediate~~ aftermath of the disastrous event.

Four different scenarios were simulated using the SDM coupled with the BBN model for physical vulnerability assessment ~~(results are represented in Fig. 5).~~. Table ~~2~~3 summarizes the main differences among ~~the~~ scenarios.

~~Table 2. Approximately here~~

The set of variables ~~to be~~ used to characterize the different scenarios was defined accounting for the results of the sensitivity analysis of the model and the experts' opinions. ~~The sensitivity analysis allowed us to identify the most influential variables in the model. Experts were also required to rank the variables according to their importance.~~Scenarios were used to perform a 'what-if' analysis, starting from a baseline condition (*Scenario 0*) which directly reflects the state of the variables during the earthquake in 2009. The 'what-if' analysis supports in measuring how changes in a set of independent variables may influence dependent variables in a simulation model. Particularly, the goal was to anticipate the potential evolutions of the system, under the same external stress, but assuming variations in technical, organizational, social and economic conditions. This analysis was highly relevant to identify the impacts of the implementation (or absence) of specific strategies to enhance system's resilience in all its dimensions.

Table 3. Approximately here

The baseline scenario, identified in the following as *Scenario 0*, represents the state of the infrastructure and of the socio-organizational-economic conditions that characterized the study area during the 2009 earthquake. ~~The~~ According to the results of the meetings with ~~local~~ institutions and ~~members~~citizens, one of the ~~communities were used to define the values for~~main issue was that the

~~model variables, and then adopted for a preliminary calibration of the model. The~~ ‘community awareness’ was rather low, ~~considering that~~since no information about the emergency procedures was shared prior the disastrous event. ‘Reduction ratio’ ~~refers~~was set to 0.5 since there was the need to reduce ~~the~~ water demand ~~through adaptations of the consumers’ behaviours in case~~, but a basic level of service was guaranteed just after the event. From an organizational point of view, internal ‘concern and cooperation’ and ‘cooperation with other institutions’ were pretty high (0.8), although the ‘training level’ of the personnel was not sufficient (0.3). The water utility had also enough ‘available economic resources’ to cope with the emergency~~. In~~, at least in the aftermath of the ~~earthquake, a reduction of water consumption was induced in the city by water losses due to a multiplicity of local breaks. Similarly, water supply limitations were imposed in the shelter camps, since temporary infrastructures were built based on the existing network and properly adapted to the original functioning scheme.~~event. From the technical perspective, the ~~maintenance level was acceptable, whereas the infrastructural~~‘maintenance’ level of the system was sufficient (0.5), and additional water sources (wells) were activated in the emergency. The ‘infrastructure physical vulnerability’ was globally rather high (0.8), but a good ‘knowledge of critical points’ had been developed. The vulnerability ~~was rather high. The latter~~ value was assessed referring to the BBN-based vulnerability model ~~(Pagano et al., 2014). The~~ and the final results ~~of the vulnerability assessment, performed according to the Bayesian tool described in the previous sections,~~ are depicted in the following Figure~~. 4~~ 11. The figure represents, through both a chromatic and a numerical scale, the estimated physical vulnerability of the whole aqueduct. ~~Particularly, the~~The probability value associated to the state ‘high’ of the variable ‘breaking vulnerability’ is taken into account and plotted. The global level of vulnerability is moderately low, although some critical points can be identified~~. This is~~, mainly ~~due to~~depending on the fact that the infrastructure ~~can be considered recent (it was built in 1997) and well maintained and monitored, but it~~ is located in an area characterized by several criticalities (e.g. the presence of active faults). ~~According to the~~

~~available data, the model is capable to identify, among the most critical pipes of the system, those damaged during the earthquake.~~

Figure ~~4~~11. Approximately here

~~Finally, three important variables related to the organizational issues were taken into account, i.e. the cooperation with the other institutions, the knowledge of the critical points of the infrastructure and the training level of the personnel.~~ The ‘water ~~balance~~deficit’ in this scenario is represented in Figure ~~5~~12, and compared with the results of the other scenarios briefly described in the following. Although the level of service does not experience a dramatic decrease, the time needed to fully recover the infrastructure functionality is rather long (~~almost~~approximately thirty days). This means that during this period the conditions of the affected population are worsened due to the limited access to this crucial service. The baseline scenario was used also to validate the model. ~~To this aim, the results of the SDM simulation were discussed with the water utility managers involved in the emergency management during the 2009 earthquake. According to their opinion, the evolution of the variable “water balance” was reasonably coherent with their experiences. Small deviations from the actual situation during the emergency were due to the difficulties in collecting all required data. Nevertheless, the experts considered these deviations as minor.~~The *Scenario 1* is characterized by a ~~decrease~~reduction of some of the most important variables of the model~~.~~ (see Table 2 for further details). This scenario mainly shows how a decrease ~~of some~~in organizational ~~capabilities~~skills – i.e. ‘cooperation~~,~~ and cooperation’, ‘knowledge of critical points’ and ‘training ~~– cannot be compensated by~~level’ – may have a ~~reduction~~dramatic influence on the response of the system, its physical vulnerability~~. The level of service~~ being the same. System performances rapidly ~~fall~~falls down~~ due to the lack of~~, and no alternative water sources~~. Moreover, the~~ are supposed to be available. The recovery phase is strongly hampered ~~by the very~~assuming that limited economic resources ~~and organizational capabilities of the water utility. Moreover, the~~are available. The already limited economic resources become even poorer due to the incapability to provide a service to the community, leading the system toward a reinforcing negative loop resulting in rapid deterioration of the infrastructure. This reinforcing loop is the cause of the rapid decrease of the ‘water ~~balance~~deficit’ in this scenario. The ~~comparison between the system performance in~~ *Scenario 2* simulates a decrease of ‘infrastructure physical vulnerability’ through expensive structural interventions. Indeed, considering both an increase in the ‘maintenance’ level, and ~~*Scenario 3* allows us to demonstrate once more the crucial role of~~a subsequent reduction in the ‘infrastructure physical vulnerability’, the ~~socio-economic~~ effect on ‘water deficit’ is definitely positive and ~~organizational elements.~~the recovery phase results significantly shortened. The *Scenario* ~~2, characterized by a decrease of~~ 3, at last, describes an integrated strategy where infrastructural ~~vulnerability through expensive maintenance interventions is less positive then the *Scenario 3*, where these interventions~~improvement actions are supported by ~~improvements in the~~ also by a better ‘knowledge ~~sharing about the infrastructure,~~ of critical points’, ‘training level’ of the personnel and enhancement of ‘community ~~awareness~~awareness’. In this scenario, the rapidity of the system recovery is very high. In particular, both the knowledge and the availability ~~of detailed knowledge of the infrastructure and~~ of economic resources allows the water utility to quickly adapt the system to the changing conditions (e.g. the need to connect the shelter camps to the main networks), without reducing the level of service provided to the community. The comparison between system performances in *Scenario 2* and *Scenario 3* allows us to demonstrate once more the crucial role of the socio-economic and organizational elements.

Figure 12. Approximately here

4.2 Sensitivity Analysis

For the purposes of the present work, sensitivity analysis (SA) was performed with respect to both single parameters and clusters (Mateus and Franz, 2015), through the Sensitivity Specs dialog box available in STELLA® (ISEE Systems Inc.). The sensitivity of the system was firstly investigated focusing on the impact of variations of the variable ‘infrastructure physical vulnerability’ (from 0.1

to 1, increment by 0.1). The analysis was performed referring to the *Scenario 0*. The following Figure 13 suggests that the variable has a key influence on the technical dimension of resilience ('water deficit'), and significantly influences both its magnitude and the time required for recovery.

Figure 13. Approximately here

An additional SA was performed with respect to the variable 'hazard intensity' (from 0.1 to 1, increment by 0.1), leading to a better understanding of how external stress may condition the response of the system. The SA to 'hazard intensity' was firstly performed considering the *Scenario 0* (Figure 14), showing that the magnitude of the hazard highly affects the resulting 'water deficit'. The SA was also performed referring to the *Scenario 3* (Figure 15). It points out the relevance of both infrastructural and organizational improvements for a fixed level of hazard. If both infrastructural and organizational features are improved, the time for recovery may reduce significantly irrespective of the hazard level.

Figure 14. Approximately here

Figure 15. Approximately here

Lastly, a cluster of variables was analyzed within an additional SA, with the aim of quantifying to what extent an improvement (or a worsening) in all organizational features and skills could contribute to changes in the water deficit, the other conditions being the same (*Scenario 0*). In this case, all the variables belonging to the organizational dimension were modified simultaneously (from 0.1 to 1, increment by 0.1). The results are summarized in the following Figure 16, and clearly show how organizational skills may significantly contribute either to foster or hamper the recovery phase after an extreme event.

Figure 16. Approximately here

~~Figure 5. Approximately here~~

5 Discussion

The scenarios obtained through the SDM were discussed with the experts~~ in emergency management and water infrastructures management~~. According to their opinion, one of the main aspects of the model is that it can be profitably used as a decision support system for defining and comparing resilience-enhancing measures~~ during all phases of risk management.~~

. A water utility could be supported in the identification of the main weaknesses in its own structure and organization, or in performing an optimal allocation of the available resources at different time steps. Similarly, emergency managers may be helped in identifying and selecting the most effective strategies to cope with disasters. To this aim, the SDM ~~support~~supports managers to dynamically investigate the impacts of such decisions on the level of service provided in the aftermath of the event, and to identify the hidden feedbacks and loops that may facilitate or hamper recovery processes. In order to facilitate the discussion with experts, the main variables of the model were divided in ~~'control'~~*control variables* and ~~'action'~~*action variables*. The following Table ~~3~~4 summarizes the main ~~'control'~~*control variables* that can be used to describe the time-dependent evolution of system performance. The control variables were defined as ~~'stocks'~~*stocks* in the model. Table ~~4~~5, instead, contains the main ~~'action'~~*action variables*, which represent fundamental factors and policies ~~drivers~~ that can be selected to improve resilience conditions. A variation in an ~~'action'~~*action variable* corresponds to a potential change in the main related ~~'control'~~*control variables*.

Table ~~3~~4. Approximately here

Table ~~4~~5. Approximately here

The involved experts considered useful the model capability to simulate the dynamic evolution of the different elements influencing the system resilience. Compared to other methods for resilience assessment, capable to analyse "snapshots" of the situation, the SDM accounts for the dynamic nature of the interconnections among the different variables in case of emergency. Just to provide an example, the model describes how the lack of economic and organizational resources can activate a negative reinforcing loop “pushing down” the system faster than in case of linear cause-effect connections. The lack of economic resources does not allow the water utility to implement timely and effective recovery actions, provoking a dramatic decrease of the provided service and, thus, an even more dramatic decrease of the economic resources due to the lack of users. That is, the level of service and the economic resources are connected by a reinforcing loop that could spiral-down the system performance.

The availability of economic resources is also associated to the activation of a positive feedback loop. Indeed, the economic resourcefulness is directly associated to the increase of knowledge level, which strongly contributes to both avoiding further reductions of service and to increase the repair rate of the system, which is responsible for the reduction of the onset of new failures and damages. This effect triggers a positive impact, i.e. the reduction of the costs for the water utility, which makes available, as a result, further economic resources for additional interventions. This feedback significantly accelerates the recovery process, as it was acknowledged by the experts.

The evolution of resilience is also associated to complex concurrent effects that arise in different time steps. The trend of population on site, for example, has a twofold influence. In the short term, the reduction of population due to the delocalization and sheltering rates determines a reduction of the water demand within the urban system, thus reducing the stress on the infrastructure. In the medium/long term, the reduction of population directly turns into a loss of customers and in reduced fees. This determines negative cascading effects, such as the inability to promptly start recovery operations and to significantly reduce the failure rate of the system.

Besides being useful for performing a dynamic analysis, the adoption of SDM is therefore justified by its capacity to model feedbacks, time delays, and non-linear effects, as well as by the possibility to improve system understanding. Furthermore, it allows effective scenario analyses, through the possibility of changing multiple variables concurrently, which clearly reflects the interconnectedness between the variables in complex systems.

Particularly, the analysis of the scenarios developed using the SDM allowed to demonstrate that the main elements characterizing the TOSE approach are not isolated. They are rather strongly interconnected through a dense and complex web of feedbacks. Tools capable to enhance the understanding of this complex network are crucial to support decision makers in governing the resilience of LS in urban areas.

6 Conclusions

The present paper summarizes research activities developed within an ongoing EU funded research project, aiming at defining a quantitative model to assess the evolution of resilience of drinking water supply ~~system~~systems in case of natural disasters. Reference is made to a complex resilience paradigm, namely the TOSE approach, which jointly considers the role of both ‘structural’ and ‘non-structural’ parameters, contributing to the four basic dimensions of resilience (technical, organizational, social, economic).

The resilience assessment model, which was developed through SDM, was implemented in L’Aquila (Italy) 2009 Earthquake case study, in strict cooperation with the local water utility. Although further refinements and applications of the model are required, its preliminary development revealed a significant potential as a decision support system, which can be used in case of disasters potentially ~~impacting lifelines~~affecting LS, mainly due to the capability of quantitatively modelling the complex feedback mechanisms and interconnectedness lying behind such ~~a complex~~ system. The developed SD model demonstrated its capabilities to simulate the dynamic evolution of ~~the~~ different elements influencing ~~the~~ system resilience.

Acknowledgements

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Tables

Stakeholder	**Type**	**Number of units**	**Activities**	**Provided Information**
Civil Protection Agency	Technicians	2 (National) + 4 (Local)	Conceptual model building, discussion of results, calibration and validation	Technical issues and societal dynamics; impact of emergency procedures; dynamic evolution of emergency
Water utility (GSA S.p.A.)	Technicians	4	Conceptual model building, discussion of results, calibration and validation	Technical, organizational and economic dynamics; impact of ordinary and emergency procedures; strategies and alternative to cope with emergency

Community	Users	10	Discussion of results and validation	Societal dynamics, dynamic evolution of emergency
IRSA-CNR and Technical University of Bari	Researchers	6	Support to conceptual model building, discussion of results, calibration, validation and sensitivity analysis	Identification of variables and states; analysis of relationships and feedbacks; definition of causal loops; Stock and flow model building; scenario development

Table 1. Summary of the domain experts involved and overview of their role in model building activities

	Performance criteria			
	Robustness	Redundancy	Resourcefulness	Rapidity
Technical	**Def**. Maximize availability of operational water supply after the event.	**Def**. Replacement inventories.	**Def**. Models to assess network vulnerability and damage.	**Def**. Maximize provision of target water supply level.
	Variables. Level of service; Volume provided by alternative water sources; Emergency water	**Variables**. Volume provided by alternative water sources	**Variables**. Infrastructural knowledge	**Variables**. Dynamic evolution of: Level of service; Volume provided by alternative water sources; ~~WU emergency~~Emergency water
Organizational	**Def**. Emergency organization and infrastructure in place; critical functions identified	**Def**. Alternative water supplies available	**Def**. Plans for mobilizing supplies and personnel; emergency strategies	**Def**. Maximum restoration of water supply
	Variables. Level of knowledge; Human resources in emergency; Level of knowledge	**Variables**. Volume provided by alternative water sources	**Variables**. Level of knowledge; Available economic resources	**Variables**. Dynamic evolution of: Volume provided by alternative water sources
Social	**Def**. Uninterrupted water supply for fire-fighting	**Def**. Alternative water supplies for post-event fire-fighting	**Def**. No form of rationing needed to meet minimum potable water supply needs	**Def**. Potable water service uninterrupted after event
	Variables. Level of service.	**Variables**. Volume provided by alternative water sources	**Variables**. Water demand; Reduction ratio; reduction ratio in shelter camps.	**Variables**. Dynamic evolution of: Level of service; Volume provided by alternative water sources; Emergency water
Economic	**Def**. Businesses with water after the event	**Def**. Alternative water supplies for all key businesses	**Def**. Economic resources available to cope with the disaster	**Def**. Economic activities re-established in 1 day
	Variables. Level of service; Available economic resources.	**Variables**. Volume provided by alternative water sources	**Variables**. Level of service; Available economic resources.	**Variables**. Dynamic evolution of: Level of service; Available economic resources.

Table ~~1~~2. Performance criteria of water supply systems. The definitions suggested by Bruneau et al. (2003) are adapted referring to the variables of the proposed model that could be used as indicators.

Variable	SCENARIO 0	SCENARIO 1	SCENARIO 2	SCENARIO 3
Community awareness	0.2 (low)	0.2 (low)	0.2 (low)	0.7 (medium-high)
Reduction ratio	0.5 (medium)	0.8 (low)	0.5 (medium)	0.5 (medium)
Maintenance	0.5 (medium)	0.4 (medium-low)	0.7 (medium-high)	1 (high)
Concern and cooperation	0.8 (high)	0.3 (low)	0.8 (high)	0.8 (high)
Cooperation with other institutions	0.8 (high)	0.3 (low)	0.8 (high)	0.8 (high)
Knowledge of critical points	0.7 (medium-high)	0.3 (low)	0.7 (medium-high)	1 (high)
Availability of wells	1 (yes)	0 (no)	1 (yes)	1 (yes)
~~Infrastructural~~Infrastructure physical vulnerability	0.8 (high)	0.8 (high)	0.5 (medium)	0.5 (medium)
Training level	0.3 (low)	0.3 (low)	0.3 (low)	1 (high)
Available economic resources (Initial state)	Medium-low	Null	Medium-low	High

Table ~~2~~3. Summary of the main variables considered, and of their value, in the four modeled scenarios. The numerical values of the variables (ranging from 0 to 1) are proposed along with a qualitative description of their meaning

'Control' variable	Description
Water ~~balance~~deficit	Defines the relation between the total volume of available water (deriving from the infrastructure and from emergency sources) and the water demand for the population to be served. ~~It can be assumed representative of resilience.~~
Level of service	Expresses the residual level of service, mainly depending on the current conditions of the infrastructure, on breaking and repair rate, on scheduled interruptions.
Volume provided by alternative water sources	Defines the availability of additional volumes of water activated during emergency
Emergency water	Considers the volume of water provided, during emergency, by vehicles and as bottled water
Collapsed buildings	Defines the ratio of the total buildings which are collapsed, and are therefore no longer livable
Damaged buildings	Defines the ratio of the total buildings which are damaged, and therefore temporarily not usable
Population in shelter camps	Expresses the population transferred to shelter camps as a ratio of the total population, depending on the expected buildings' conditions.

Population delocalized	Expresses the population ‘permanently’ delocalized as a ratio of the total population, depending on the expected buildings’ conditions.
Water demand	Amount of water required by population remaining in houses and by population moving to shelter camps. It could be affected by the adoption of rationing strategies.
Human resources in emergency	Defines the number of workers of the water utility, who are directly involved in EM.
Failure rate	Expresses the rate of failures, as a function of both damage rate and repair rate.
Economic resources	Amount of available economic resources, as a combination of both ordinary resources and emergency subsidies.
Level of knowledge	Defines the overall available level of knowledge for the water utility.
Environmental knowledge	Expresses the level of knowledge available on the environment surrounding the infrastructural system.
Infrastructural knowledge	Expresses the level of knowledge available on the infrastructural system.
Hazard~~/~~ or event knowledge	Expresses the level of knowledge available on the hazard occurred and its impacts.

Table ~~3~~4. ‘Control’ variables that can be monitored to analyze aspects connected to resilience

‘Action’ variable	**Action/Strategy**
Bottled water	Increase provision, and varying temporal distribution of volumes of bottled emergency water
Number of vehicles (internal/external)	Use of additional vehicles for conveying water or improvement of relationships with neighboring utilities
Daily functioning hours (well)	Increase (if necessary and sustainable) the duration of daily pumping during emergency
Reduction ratio of water supplied per capita	Reduce the water supplied per capita in order to ~~satisfy~~reduce the water ~~balance~~deficit
Training level	Increase the emergency management capabilities of employees through e.g. courses and practice
Concern and cooperation	Foster cooperation, team spirit and cohesion within the organization
Maintenance	Increasing maintenance for reducing infrastructural failures
Fee	Increasing or reducing fees can vary available economical resources
Emergency economic resources A	Availability of resources for emergency (e.g. national or EU funds)
Redundancy in information management	Foster information sharing and diffusion; consider multiple data availability
Monitoring and forecasting	Implementing control systems for infrastructures as well as early warning
Knowledge of critical points	Implementation of vulnerability assessment tools to identify major

	problems
Field surveys	Optimization of surveys, and of distribution of employees
Availability of GIS and database	Adoption of GIS systems and development of database for collecting information
Collection of feedback from the users	Implementation of systems (e.g. questionnaires, phone calls…) for getting users’ feedbacks on the level of service
Cooperation with other institutions	Development of relationships with other institutions for data and knowledge sharing

Table ~~4~~5. Variables that can be improved for increasing resilience through specific actions/strategies

***Highlights**

Research highlights :

- A model for resilience assessment of drinking water supply systems is proposed.
- Resilience is modeled in its multi-dimensionality (TOSE approach)
- SDM is used for dynamically modeling resilience during and after a natural disaster.
- An application is proposed through the L'Aquila earthquake (2009) case study

Figure 1

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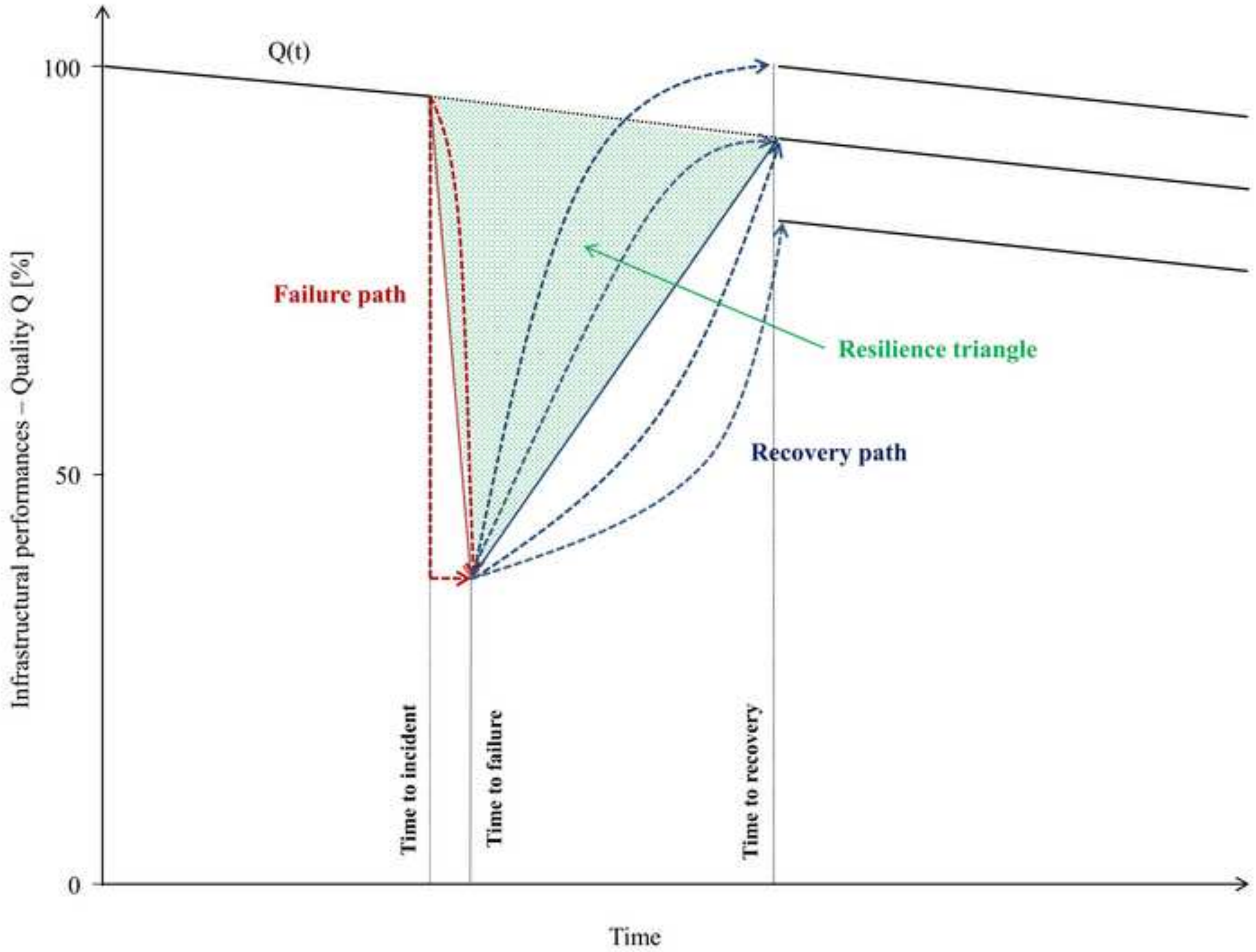
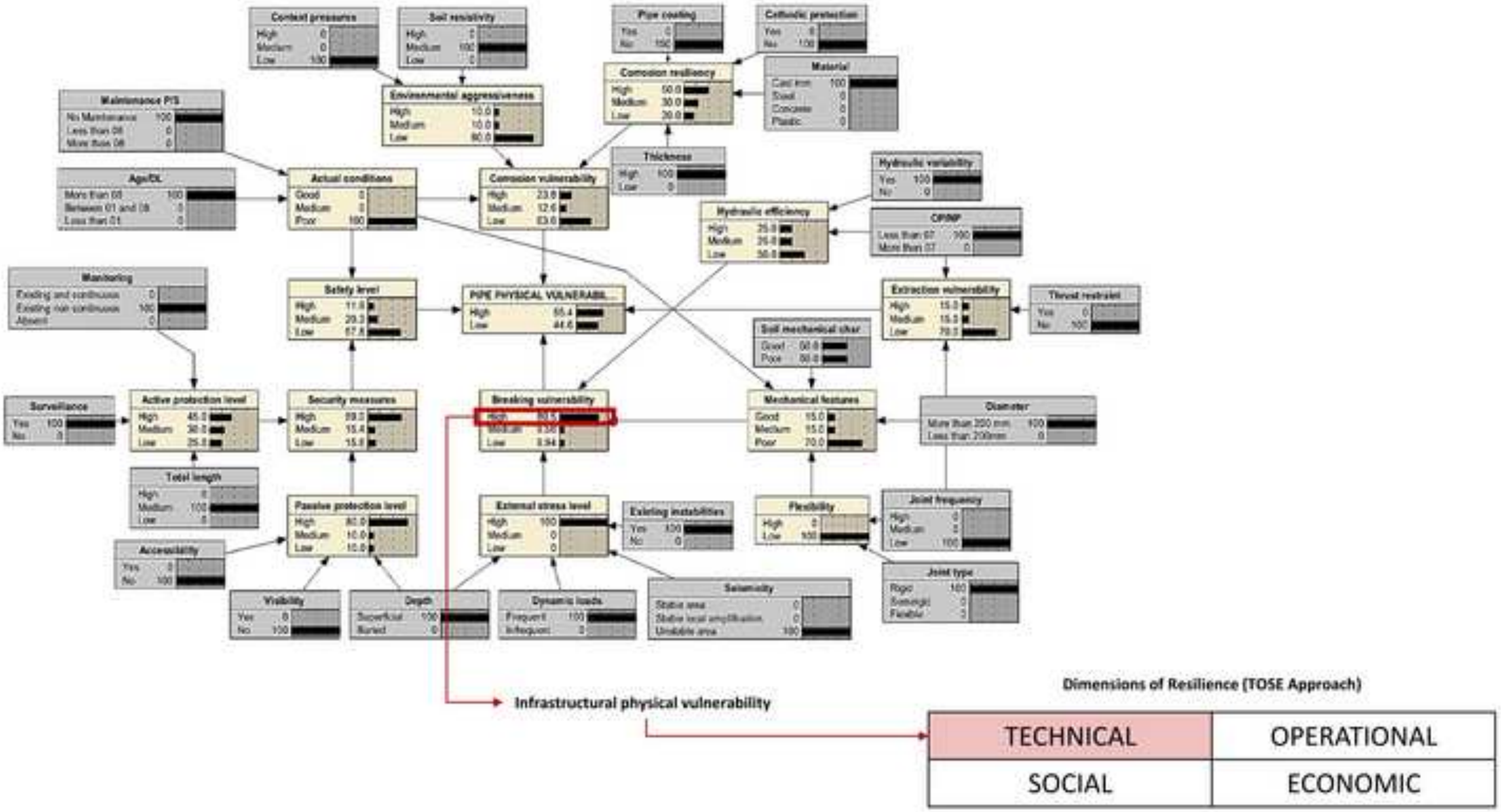


Figure 2


Contact pressures
Soil resistivity
Pipe coating
Cathodic protection
Material
Corrosion resiliency
Environmental aggressiveness
Maintenance P/S
Age/DL
Actual conditions
Corrosion vulnerability
Thickness
Hydraulic variability
Hydraulic efficiency
CP/NP
Monitoring
Safety level
PIPE PHYSICAL VULNERABIL...
Extraction vulnerability
Thrust restraint
Soil mechanical char
Surveillance
Active protection level
Security measures
Breaking vulnerability
Mechanical features
Diameter
Total length
Passive protection level
External stress level
Existing instabilities
Flexibility
Joint frequency
Accessibility
Joint type
Visibility
Depth
Dynamic loads
Seismicity
Infrastructural physical vulnerability
Dimensions of Resilience (TOSE Approach)
TECHNICAL
OPERATIONAL
SOCIAL
ECONOMIC

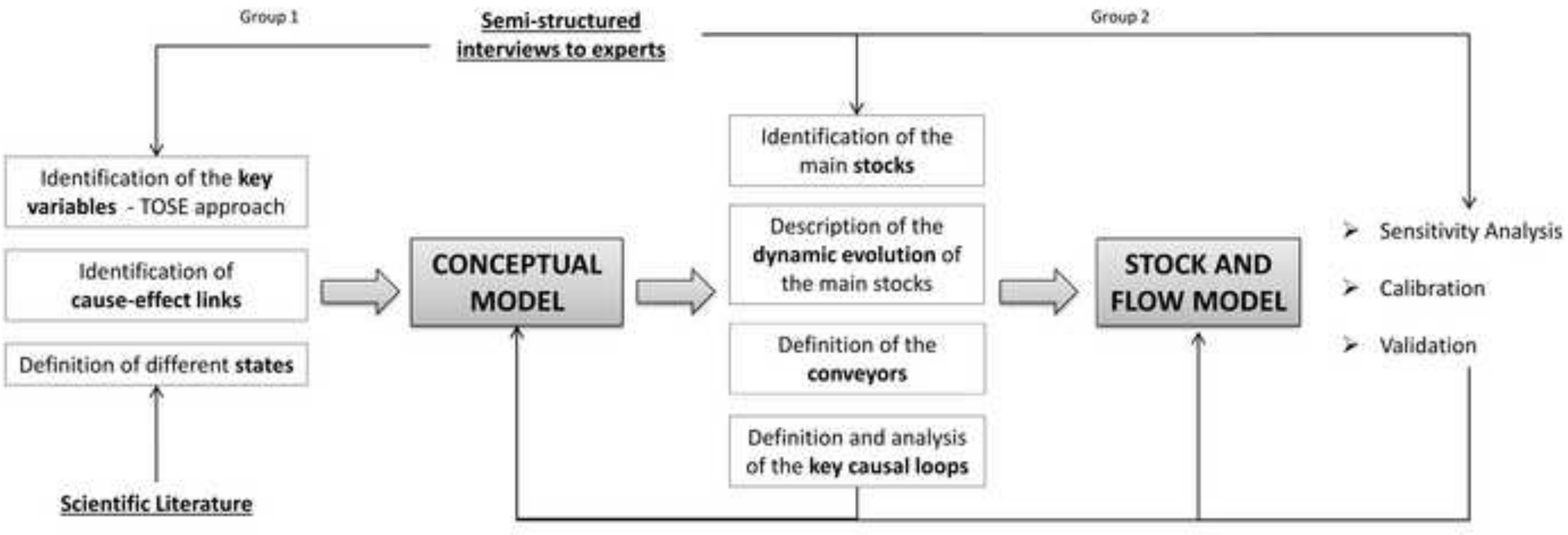

Group 1
Semi-structured interviews to experts
Group 2
Identification of the key variables - TOSE approach
Identification of cause-effect links
Definition of different states
Scientific Literature
CONCEPTUAL MODEL
Identification of the main stocks
Description of the dynamic evolution of the main stocks
Definition of the conveyors
Definition and analysis of the key causal loops
STOCK AND FLOW MODEL
Sensitivity Analysis
Calibration
Validation

Figure 4

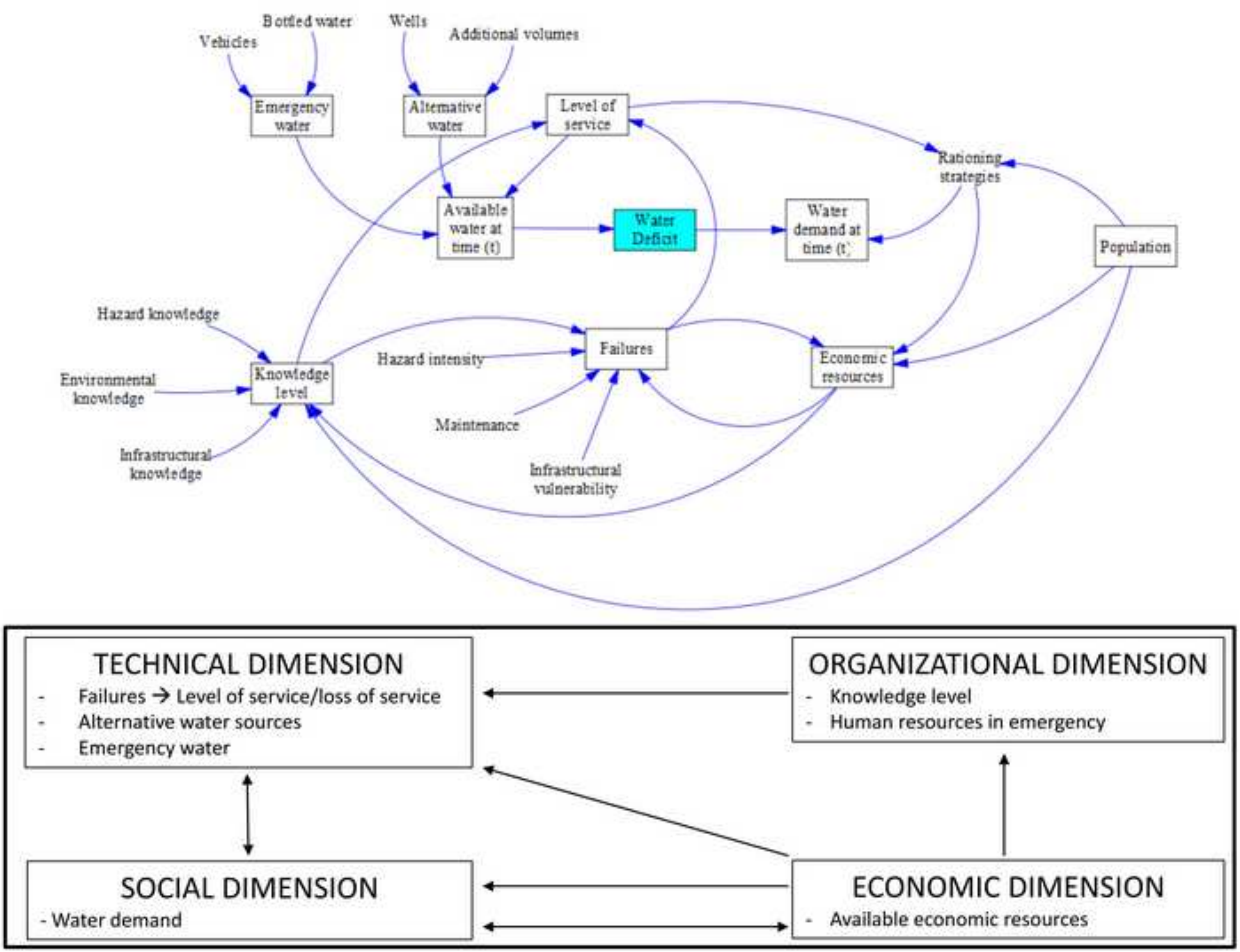

Vehicles
Bottled water
Wells
Additional volumes
Emergency water
Alternative water
Level of service
Rationing strategies
Available water at time (t)
Water Deficit
Water demand at time (t)
Population
Hazard knowledge
Environmental knowledge
Knowledge level
Hazard intensity
Failures
Economic resources
Maintenance
Infrastructural knowledge
Infrastructural vulnerability
TECHNICAL DIMENSION
- Failures → Level of service/loss of service
- Alternative water sources
- Emergency water
ORGANIZATIONAL DIMENSION
- Knowledge level
- Human resources in emergency
SOCIAL DIMENSION
- Water demand
ECONOMIC DIMENSION
- Available economic resources

Figure 5

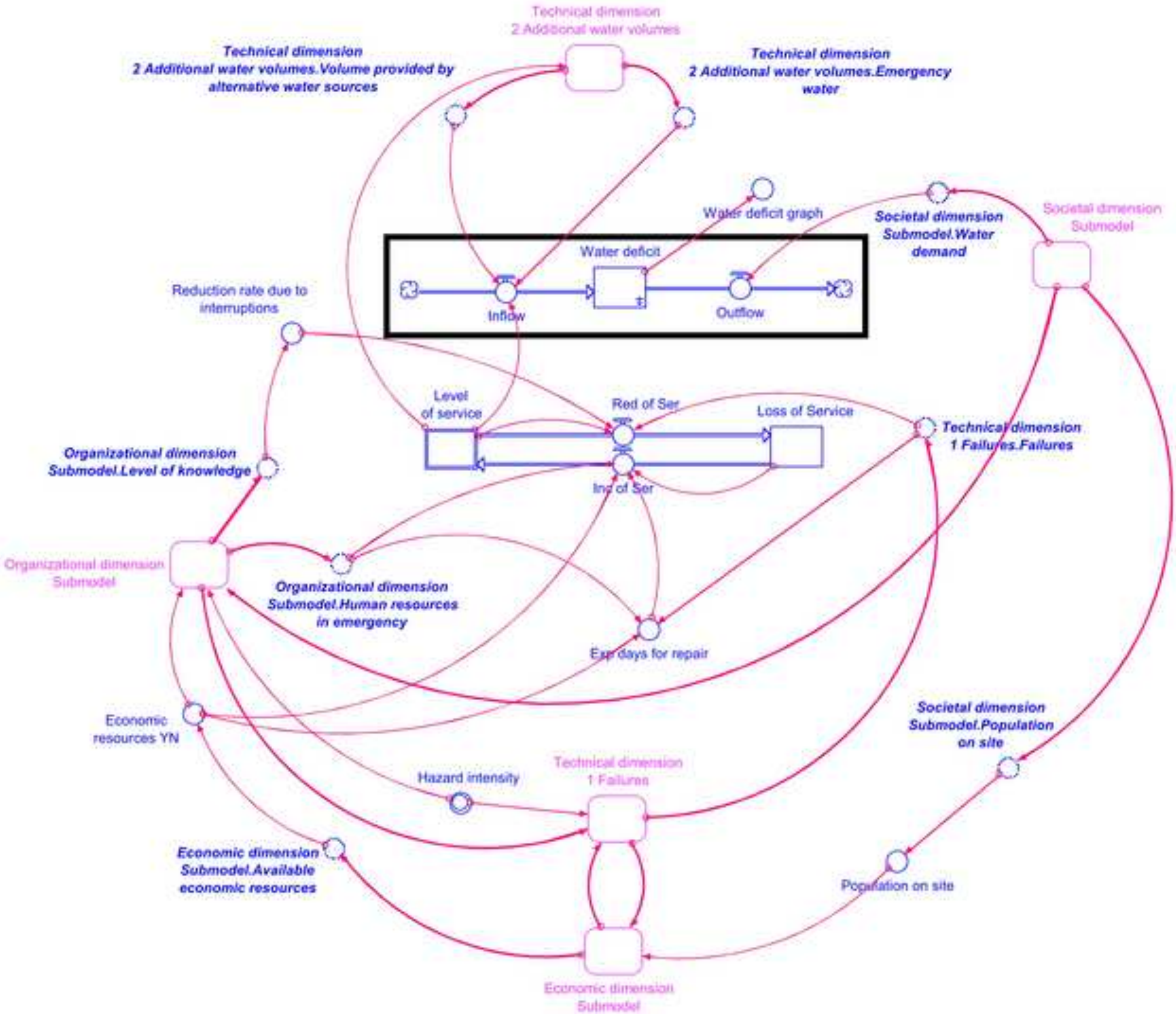

Technical dimension
2 Additional water volumes
Technical dimension
2 Additional water volumes.Volume provided by alternative water sources
Technical dimension
2 Additional water volumes.Emergency water
Water deficit graph
Societal dimension Submodel.Water demand
Societal dimension
Submodel
Water deficit
Inflow
Outflow
Reduction rate due to interruptions
Level of service
Red of Ser
Loss of Service
Technical dimension
1 Failures.Failures
Inc of Ser
Organizational dimension Submodel.Level of knowledge
Organizational dimension
Submodel
Organizational dimension Submodel.Human resources in emergency
Exp days for repair
Economic resources YN
Societal dimension Submodel.Population on site
Hazard intensity
Technical dimension
1 Failures
Economic dimension Submodel.Available economic resources
Population on site
Economic dimension
Submodel

Figure 6

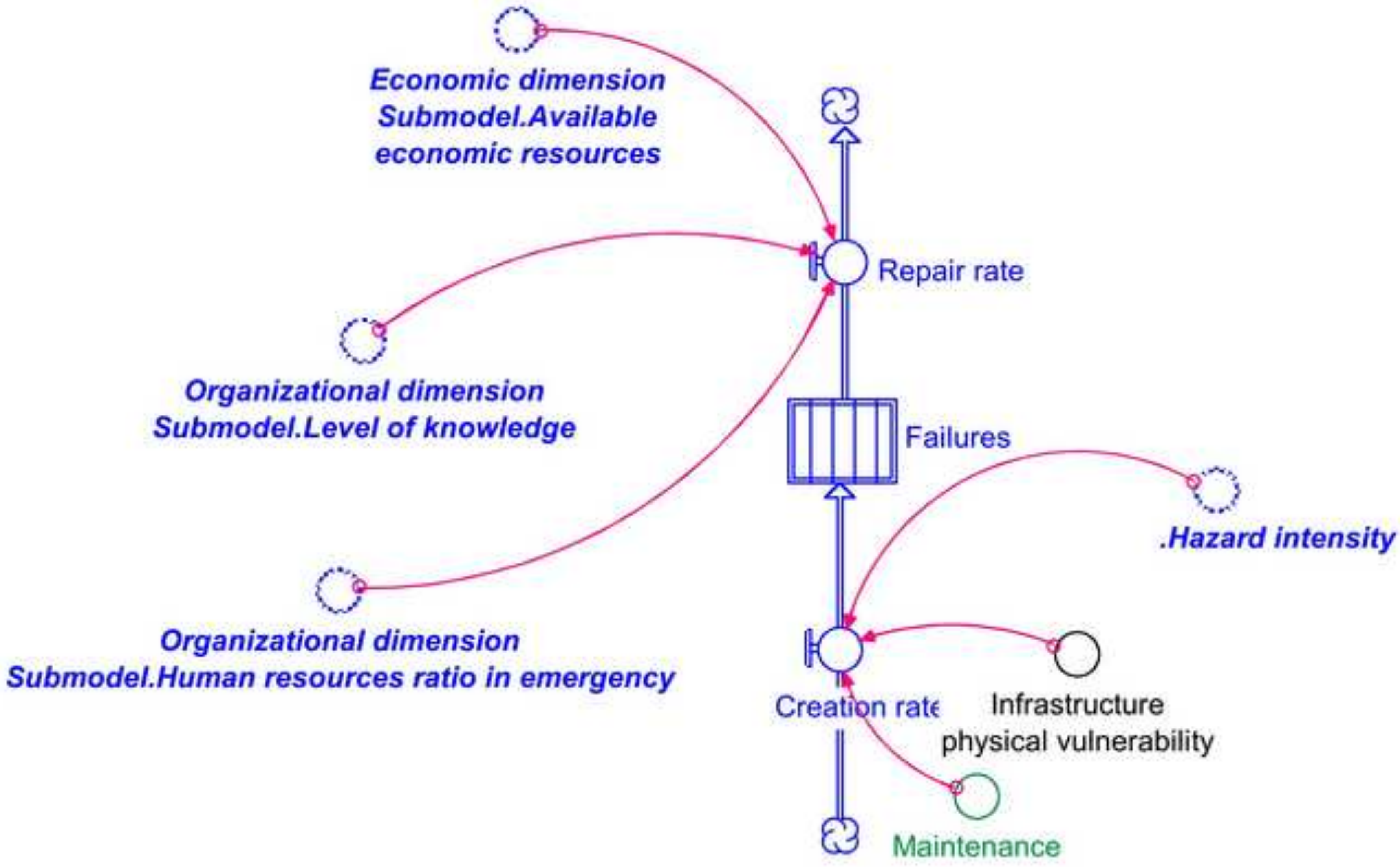

Economic dimension Submodel.Available economic resources
Repair rate
Organizational dimension Submodel.Level of knowledge
Failures
.Hazard intensity
Organizational dimension Submodel.Human resources ratio in emergency
Creation rate
Infrastructure physical vulnerability
Maintenance

Figure 7

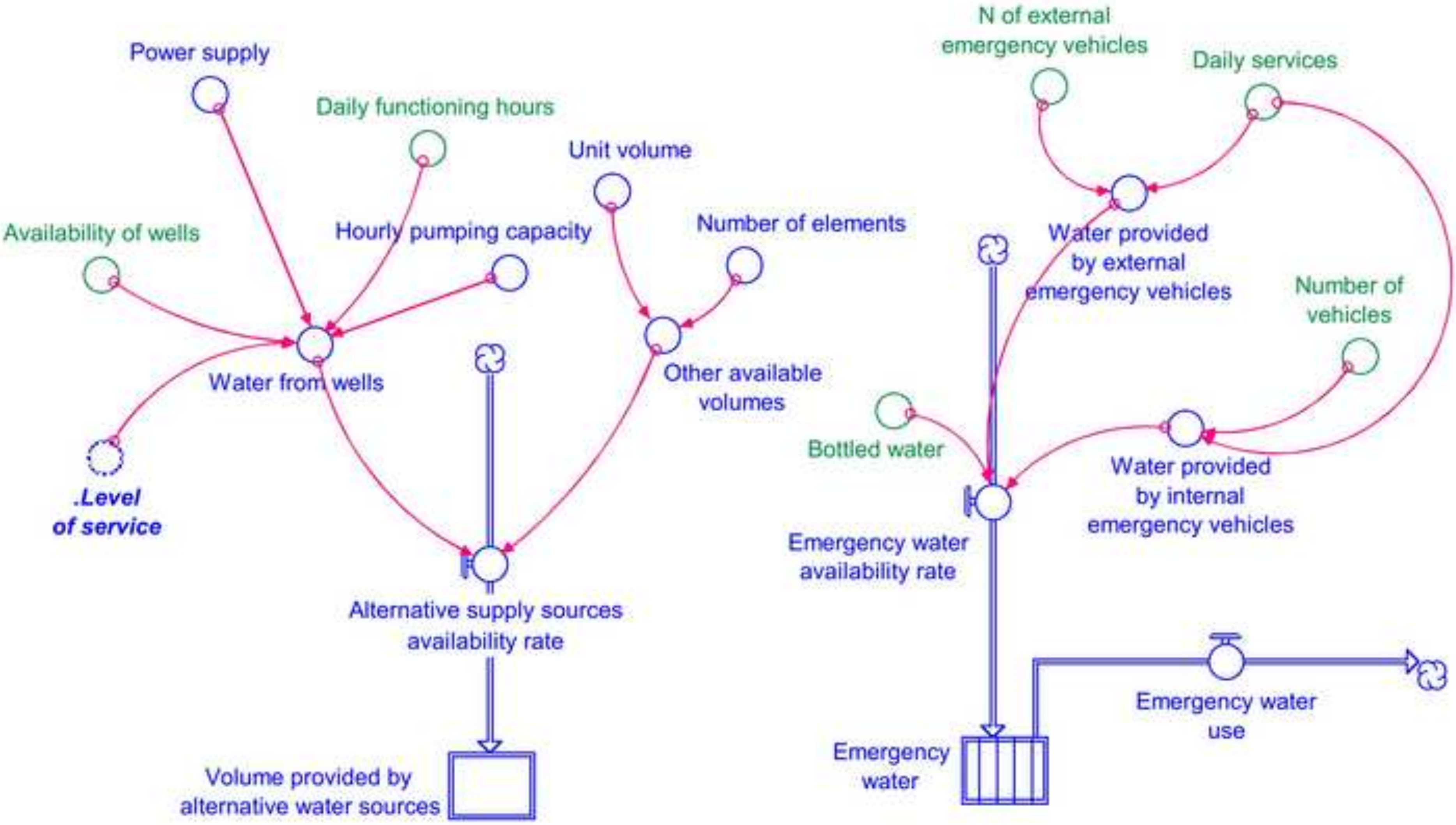

Power supply
Daily functioning hours
Unit volume
Availability of wells
Hourly pumping capacity
Number of elements
Water from wells
Other available volumes
.Level of service
Alternative supply sources availability rate
Volume provided by alternative water sources
N of external emergency vehicles
Daily services
Water provided by external emergency vehicles
Number of vehicles
Bottled water
Water provided by internal emergency vehicles
Emergency water availability rate
Emergency water use
Emergency water

Figure 8

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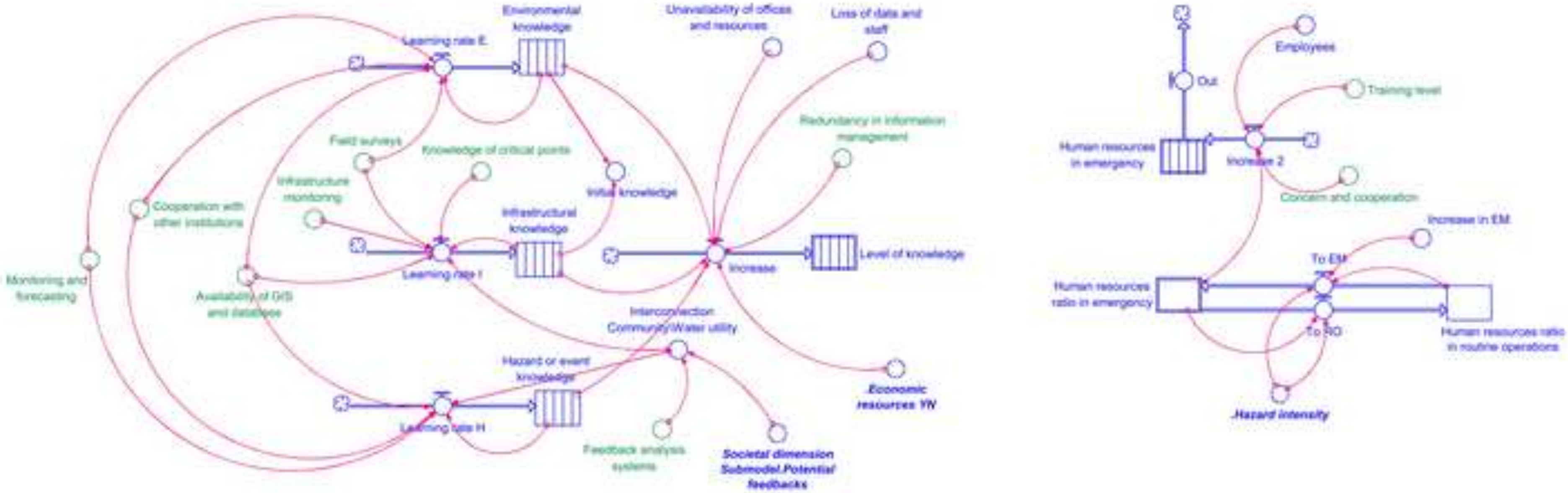

Figure 9

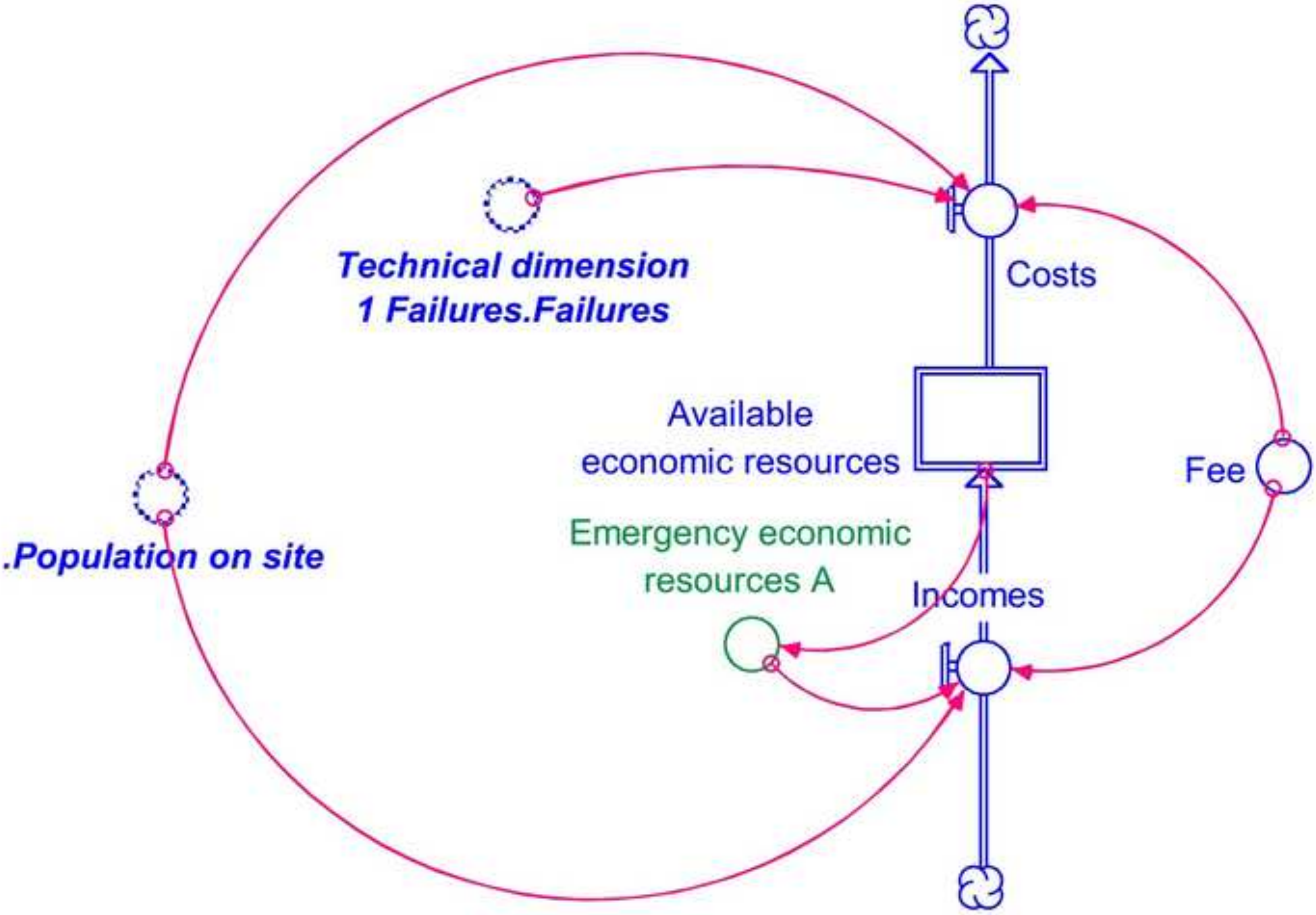
Technical dimension
1 Failures.Failures
Costs
Available
economic resources
Fee
.Population on site
Emergency economic
resources A
Incomes

Figure 10

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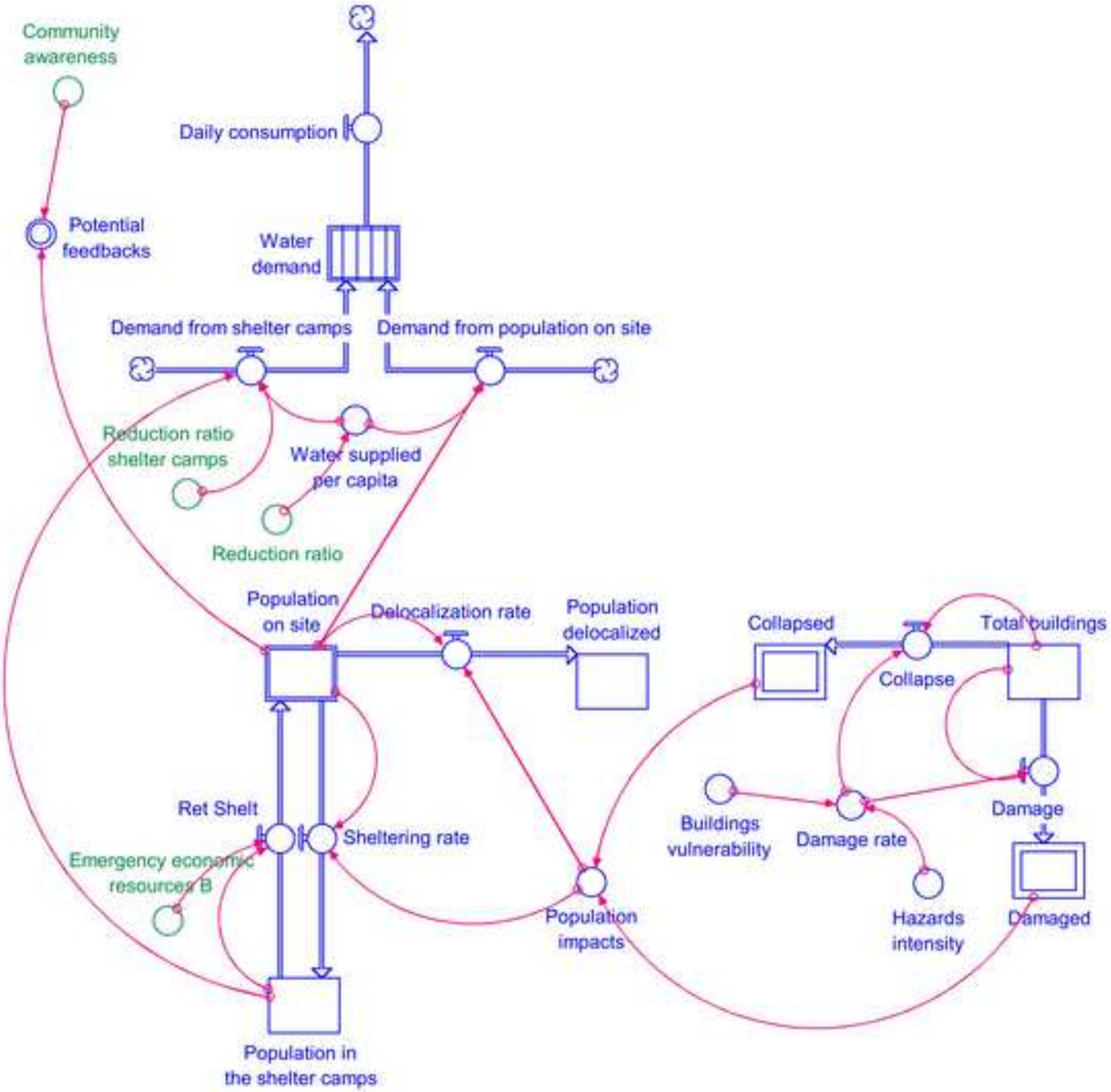

Figure 11

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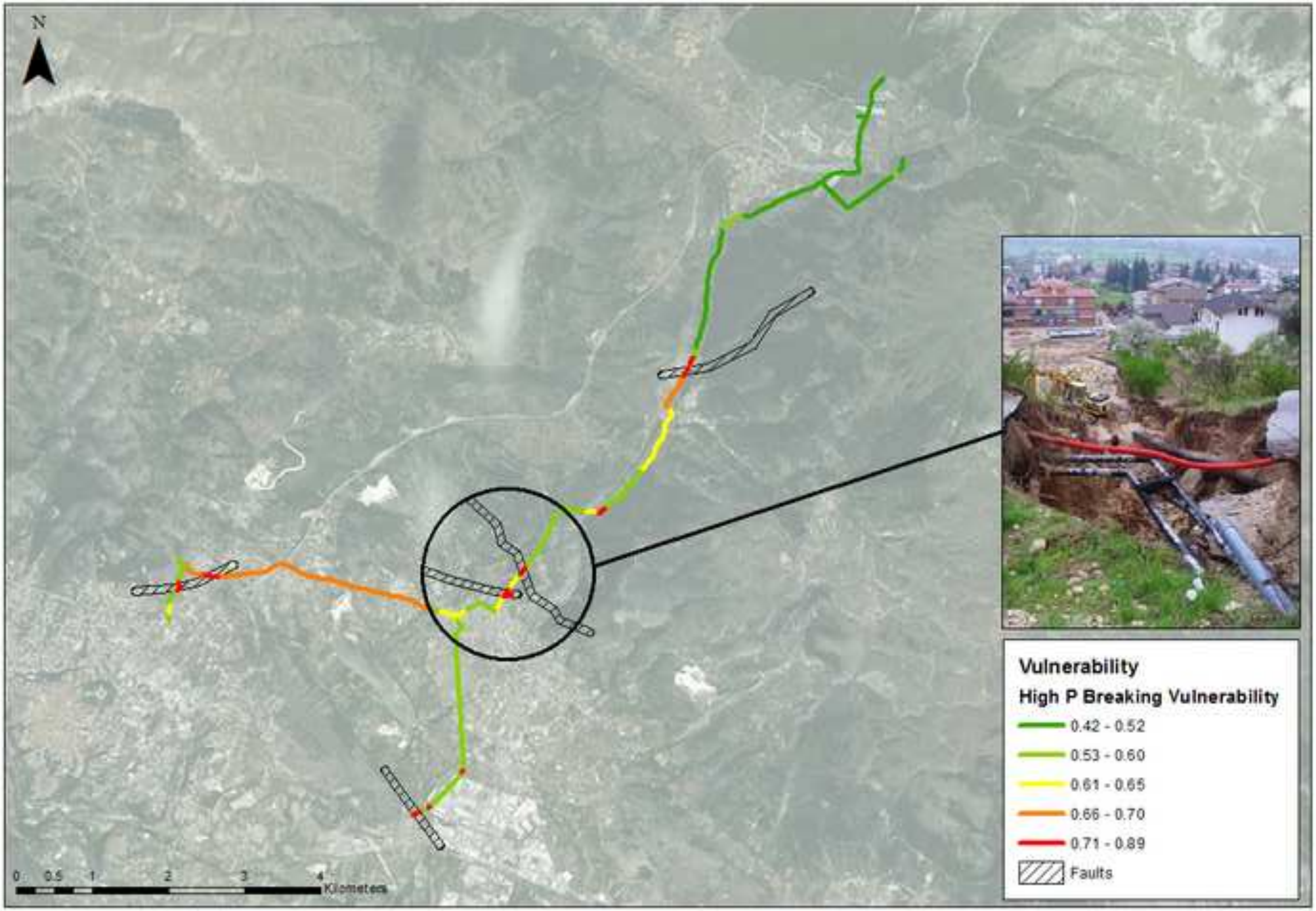

Figure 12

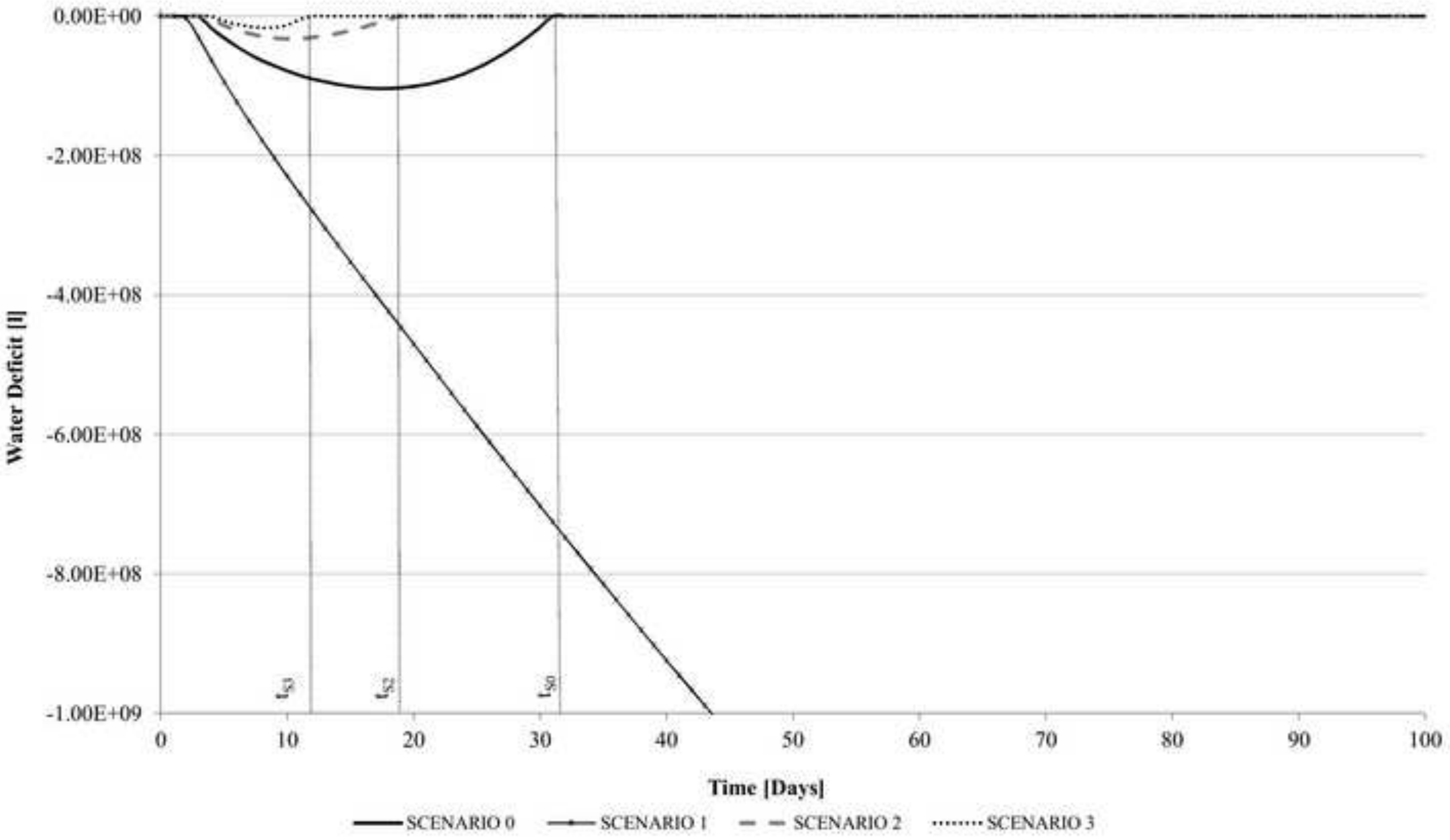
0.00E+00
-2.00E+08
-4.00E+08
-6.00E+08
-8.00E+08
-1.00E+09
Water Deficit [l]
t_{S3}
t_{S2}
t_{S0}
0
10
20
30
40
50
60
70
80
90
100
Time [Days]
SCENARIO 0
SCENARIO 1
SCENARIO 2
SCENARIO 3

Figure 13

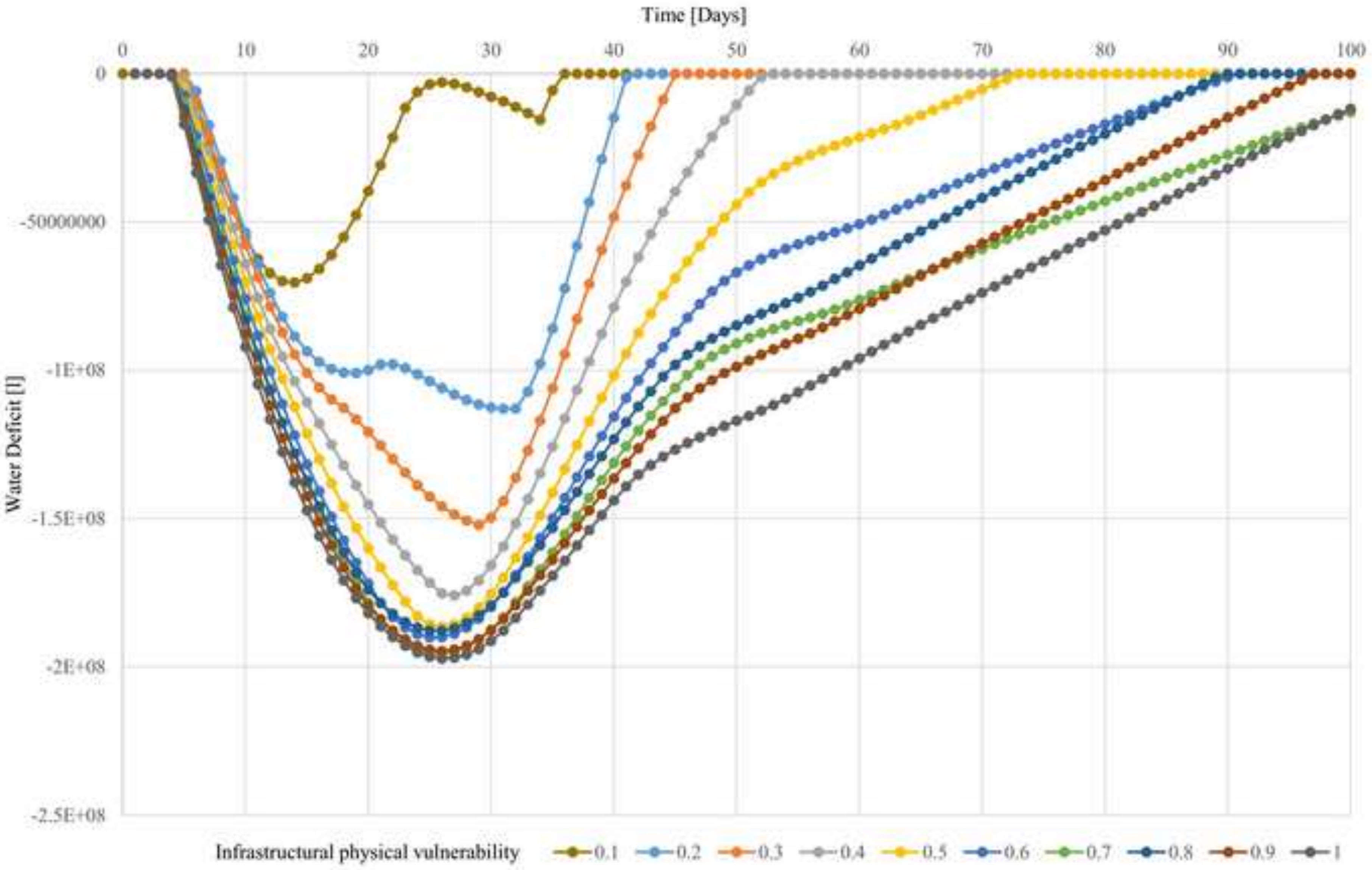
Time [Days]
0
10
20
30
40
50
60
70
80
90
100
Water Deficit [l]
0
-50000000
-1E+08
-1.5E+08
-2E+08
-2.5E+08
Infrastructural physical vulnerability
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 14
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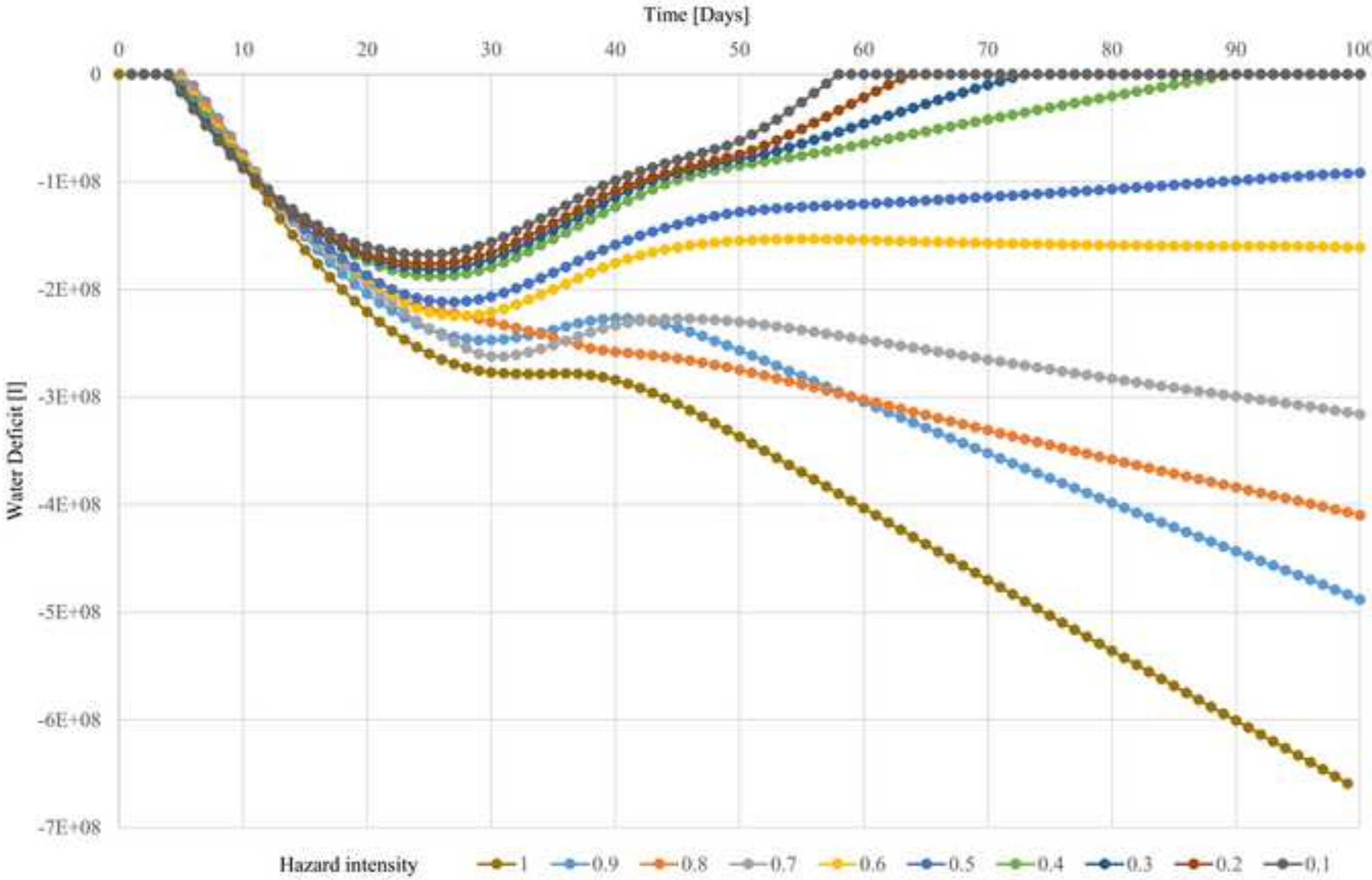

Figure 15

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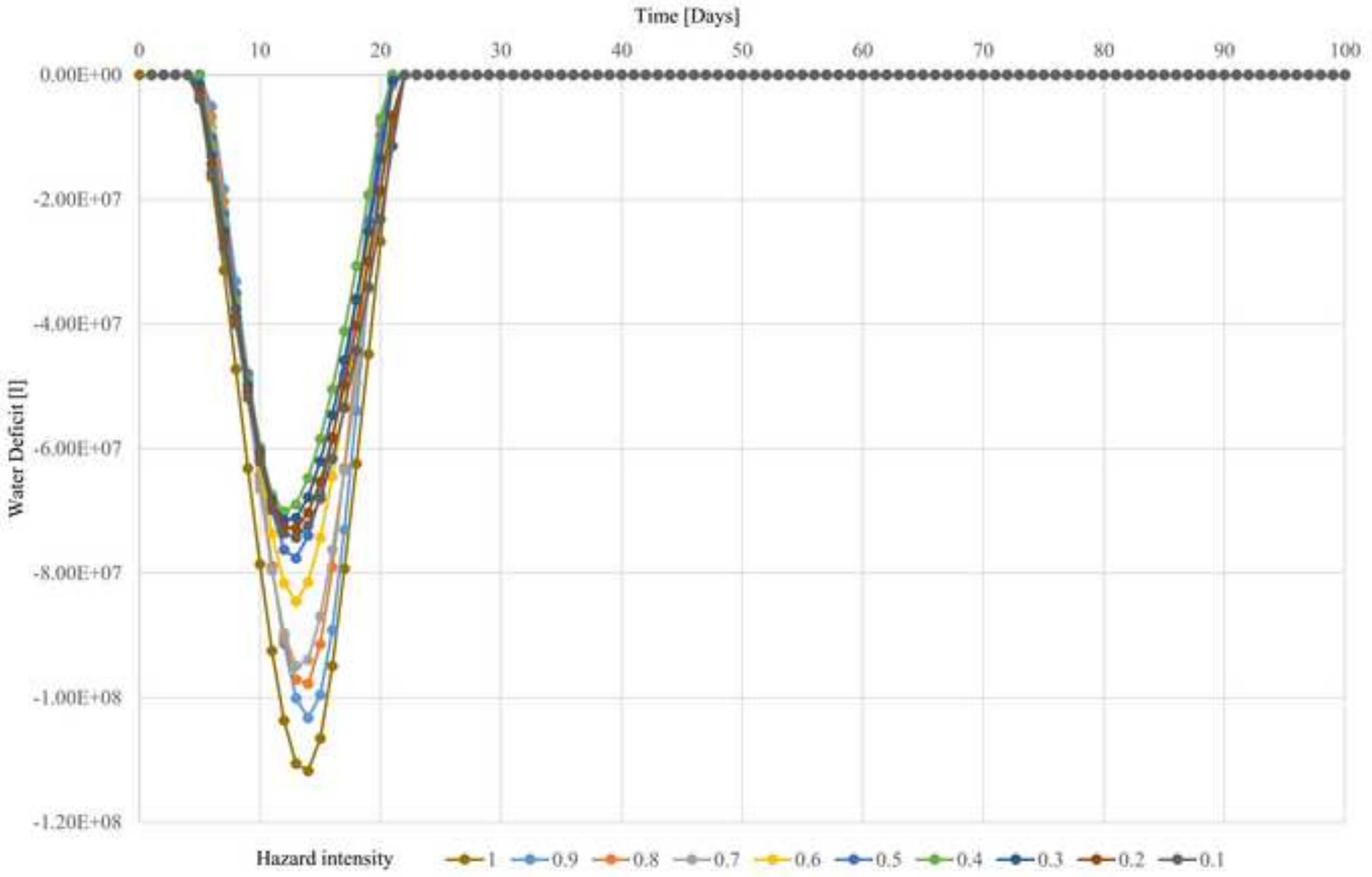

Figure 16

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