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## Socially-integrated resilience in building-level water networks using smart microgrid+net

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### Abstract

Environmental change and natural events can impact on multiple dimensions of human life; economic, social, political, physical (built) and natural (ecosystems) environments. Water distribution networks cover both the built and natural realms and are as such inherently vulnerable to accidental or deliberate physical, natural, chemical, or biological threats. An example of such threats include flooding. The damage to water networks from flooding at the building level can include disrupted supply, pipe damage, sink and sewer overflows, fittings and appliance malfunctions etc. as well as the consequential socio-economic loss and distress. It has also been highlighted that the cost of damage caused by disasters including flooding can be correlated to the warning-time given before it occurs. Therefore, contiguous and continuous preparedness is essential to sustain disaster resilience.

This paper presents an early stage review to: 1. Understand the challenges and opportunities posed by disaster risks to critical infrastructure at the building level. 2. Examine the role and importance of early warnings within the smart systems context to promote anticipatory preparedness and reduce physical, economic, environmental and social vulnerability 3. Review the opportunities provided by smart water microgrid/net to deliver such an early warning system and 4. Define the basis for a socially-integrated framework for resilience in building water networks based on smart water micro grids and micronets. The objective is to establish the theoretical approach for smart system integration for risk mitigation in water networks at the building level. Also, to explore the importance and scope integration of other social-political dimensions within such framework and associated solutions. The findings will inform further studies to address the gaps in understanding the disaster risks in micro water infrastructure e.g. flooding, and; to develop strategies and systems to strengthen disaster preparedness for effective response and anticipatory action for such risks.

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## 1. Introduction

Environmental change and the resulting natural events can impact on multiple dimensions of human life; economic, social, political, physical (built) and natural (ecosystems) environments. Water distribution networks cover both the built and natural realms. As such, they are inherently vulnerable to accidental or deliberate physical, chemical, or biological threats [1]. The damage to water networks from natural and environmental shocks at the building level can include disrupted supply, pipe damage, sink and sewer overflows, fittings and appliance malfunctions etc. as well as the consequential social and economic distress. It has been shown that the cost of damage caused is directly related to the warning-time given before the event occurs. Therefore, continuous preparedness over time is essential to sustain individual and collective disaster resilience [2]. However, monitoring systems remain inadequate to support the anticipatory and timely analysis of disaster events at this scale [3]. The emergency-focused risk management approach also means that risks that arise over a longer time, including hazards that occur infrequently, and which take account of dynamic factors such as climate change, population growth and socio-economic change, are overlooked. Therefore, stakeholders do not always fully understand the overall level of risks necessary to make informed resilient judgements.

Early warning systems are used to improve the efficiency of disaster preparedness and response. However, in its analysis of the technological aspects of the infrastructure, the literature has failed to carry out an investigation of early warning process for other areas [4]. This paper is concerned with the importance of early warning in mitigating the impact of physical and natural events on water distribution networks. This is because a gap has been identified in the consistent, long term approach needed to ensure the timely problem identification, preparedness and solution deploying aspects of risk mitigation in water networks.

### 1.1. Flood risks; challenges and opportunities

Natural events; hydrological, geomorphological or climatological has direct or indirect cause and effect attributable to current and ongoing environmental change. During the past two decades, earthquakes, storms, tsunamis, floods, landslides, volcanic eruption and wildfires have killed millions of people, adversely affected the lives of even more people and resulted in enormous economic damages. 90% of all worldwide natural events – disasters - are water related and it is through water that most of the impact of climate change are felt [5]. In the UK, nearly 1 in 6 properties are currently at risk of flooding, and this number is set to increase as the latest projections indicate the severity and frequency of rainstorms are rapidly on the rise [6]. The impacts will see the cost of flood damage rise fivefold in the UK by 2050, up to £23bn a year [7]. However, flood monitoring systems especially across urban scales remain inadequate to support the timely analysis of flood events [3]. The city system is made up of various components that act as input–output units, including positive or negative feedback loops across spatial levels (Figure 1). Consequently, flood exposure at a certain spatial level is dependent on the interventions implemented at a higher level [8]. At a lower spatial level, the system is composed of interacting parts or subsystems such as buildings, roads and a supporting social economic environment for agents to interact. This is where at-risk residents and property owners can be involved in both the problem identification, preparedness and solution deploying aspects of risk mitigation. In principle, at each spatial level, three types of measures can be put in place to reduce a system's flood vulnerability based on the type of possible responses of a system to floods. These are: reducing exposure; reducing the system's sensitivity and; mitigating the impacts (recovery).

Smart buildings, districts and neighborhoods, and by extension smart cities, is today developed as a potential answer to not just environmental challenges, but challenges created by increased urbanization. It is considered a solution for maintaining necessary supplies of water, energy, communication and transport to meet growing demands in urban centers, and in parallel a mandatory evolution of old and established city infrastructures [9]. And to mainstream climate adaptation across sectors and funding mechanisms [10]. A smart city is characterized by a pervasive use of ICT, which, in various urban domains, help cities make better use of their resources and achieve

resilience to environmental shocks. The challenge for smart cities however remains the question of scale i.e. whole to parts, rather than parts to whole. Also, how best to integrate social capital without the negative impact e.g. invasion of privacy, whilst making the best use of the new kinds of data to create new and usable knowledge.

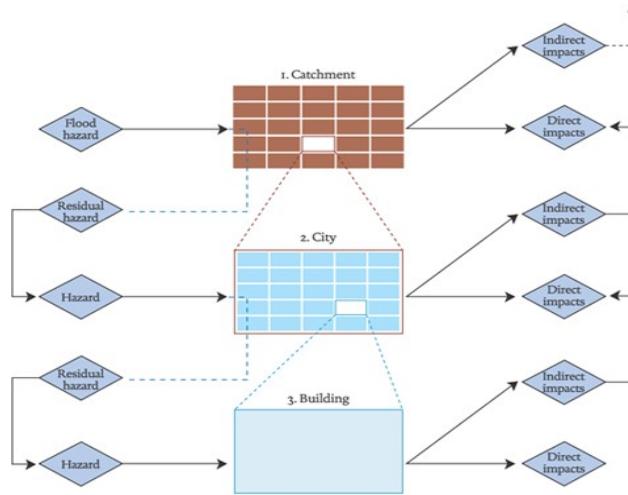


Fig. 1. Flood resilience: travelling across spatial levels; this figure depicts the propagation of a flood wave through the catchment system in case of a failure or overtopping of the primary flood-protection system [8].

Academic and practical studies/actions for mitigating resource challenges, and for maintaining livability through resilience against natural events have also so far been contained within their separate subject realms. And smart systems offer the frame to mitigate this trend and facilitate integrated thinking and action. Within this theoretical and pragmatic scope, it can be possible to improve understanding, create knowledge and inform anticipatory action to mitigate environmental risks. Smart systems provide a ready opportunity to obtain, interpret and disseminate live information about risks and response measures at the building-level. Environmental challenges are not just technical, physical or material. Social and organizational problems associated with multiple and diverse stakeholders, high levels of interdependence, competing objectives and values, and social and political complexity also occur. So knowledge derived from an integrated smart system can inform anticipatory decision-making processes and actions across socio-political domains that could in turn help to reduce physical and social vulnerabilities and resilience. Therefore, the socio-political dimensions of resilience in water networks are reviewed towards the end of this paper.

### 1.2. Why building-level solutions are important?

Critical infrastructures including those at the micro/building-level are intimately linked with the economic, social wellbeing and security of the communities they serve. Hazard mitigation for such lifeline infrastructures as water, electricity, and communications has generally focused on first order effects—designing the systems to resist the loads imparted by extreme natural events, and more recently, malevolent acts such as sabotage and terrorism. However, as these systems become increasingly complex and interdependent, hazard mitigation must also be concerned with the secondary and tertiary failure effects of these systems on each other [11]. Moreover, interdependent infrastructure also mean that failures can have cascading effects up and down the scale, and the building can be at the final but most crucial point of the chain (Figure 2). The resilience of future cities therefore depends on the resilience of its constituent parts and this includes the resilience of existing building stock.

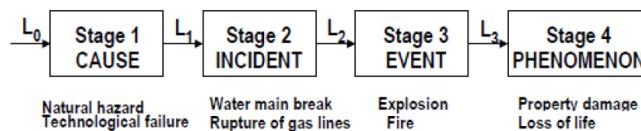


Fig. 2. A model for depicting the linked relationships between hazards and their ultimate outcomes (Baisuck and Wallace 1979; in [11]

## 2. Integrated solutions for resilience in critical water networks at the building level

Critical infrastructures; energy, water, gas, data etc. are a significant aspect of the physical environment. They are defined as a system of systems, designed to support large, complex, widely distributed and mutually supportive networks. A ‘system of systems’ is most commonly described at national level, but also impacts locally. Disasters are experienced in critical infrastructures at all levels of the urban scale: macro (city), meso (neighbourhood) and micro (building) scales but this work focusses on the local (micro) scale as this is less studied. This is where further research is needed to ascertain whether cascading ecological crisis models are fully applicable to situations where the hazards revolve around localized malfunctioning [after: 12].

Interdependent effects occur when an infrastructure disruption spreads beyond itself to cause appreciable impact on other infrastructures, which in turn cause more effects on other infrastructures [13]. This presents enormous challenges when they are submitted to the external stresses which are natural and technological hazards [14]. Despite the common conception that cascading disasters are unexpected low-probability, high-impact events are well rooted in society’s feedback loops [15]. These systems constantly evolve, thus the interconnected infrastructure systems must adapt to it. Hence the understanding of such systems and solutions for better integration of social, economic and political interdependencies is valuable. Such an integrated approach to improve flood resilience should include [16]:

- Better forecasting and early warnings
- Improved modelling and visualisation of impending floods
- Making space for flood water so that it can safely pass through communities and be stored in “sacrificial” flood areas
- Making buildings and infrastructure more resistant and resilient to flooding. This should cover both new and existing buildings. As it is imperative to also consider the significant proportion of buildings, predominantly under-insured houses, that remain vulnerable and prone to supply disruptions due to or as a result of natural events such as flooding
- Improved engagement of the public, business and other stakeholders so that they become part of the solution
- Better preparation for installing temporary measures and for responding to floods
- Improved recovery and better support for those affected

### 2.1. Water microgrids + net for resilience

A water distribution system consists of sources, pipes, and hydraulic control elements connected together to deliver prescribed quantities at desired pressures and qualities. Such systems are subject to a number of different loading conditions (i.e. different patterns of nodal demands) e.g. peak daily demands, series of varying patterns through a day, or critical loads when one or more of its elements gets out of service [1]. Water infrastructure is similarly vulnerable to extreme weather events, resulting in significant impacts to clean water distribution, wastewater treatment, and storm-water management. Therefore, microgrids have recently been proposed as a potential solution to address the increasing number of outages caused by such events [17].

A smart micro water grid (SMWG) is a high-efficiency water management system of sensors, nodes, valves and connectors that integrates information and communication technologies (ICT) for the water distribution systems in individual buildings. This makes it possible for customers within a building to have access to their total water use on a real-time basis and thus be able to make informed decisions related to their water use. At the same time, central water operators will receive real-time water demand information that will make future forecasts more accurate [18]. A micro grid can operate in either grid connected or islanded mode when there are external shocks or faults and/or to gain economic advantage [19]. It also typically deploys mobile sensors in and outside a building to sense discrete events (such as temperature, user activities e.g. energy and water use, and body area network for healthcare) and share this information using the same communication medium, typically, the Internet [20].

The benefit of this approach is primarily its non-intrusive nature but also the sensitivity of these sensors to record events that would normally go unnoticed. Further, the increasing prevalence SMWG will provide both the means and opportunity to efficiently address resilience issues water infrastructure and networks. This however requires a pragmatic technology framework within two hardware realms: smart water micro grids and micronets for the sensing of discrete events within such grids. Like microgrids, a micronet comprises information systems built on top of the

existing water supply network infrastructure or grids. The micro water grid is not necessarily physically differentiated from the distribution network as decentralized water systems are completely segmented from existing legacy infrastructure [17]. The micro net enables such disassociation in order to derive localized data and information.

Advantages of micronets include: ability to be integrated with existing infrastructure with minimal disruption; opportunities for redistribution of supply as well as managed network redundancy to cater for failures and climatic effects e.g. floods and droughts; permits advanced metering and sensing equipment to manage peak demand and loads across singular or a cluster of water microgrids in a particular level; enables forecasting and probabilistic simulations and modelling and lastly; it provides opportunity for early warning systems and anticipatory response to mitigate internal e.g. leakage or external factors e.g. natural events. The practical value of this approach has been shown especially in connection to larger water networks, but their calibration to the local conditions is usually infeasible in small to medium-sized water networks because of their high data demand [21]. Other challenges include: effective data integration; access to autonomous, disaggregated data especially for research; and the cost and reliability of hardware including sensors.

## 2.2. Integrated early warning systems (EWS) based on microgrid+net frameworks

The purpose of an early warning system for water networks is to reduce economic, physical and social losses, as well as impact on health and wellbeing from natural hazards. Early warning systems define the technological infrastructure that can assist in carrying out these tasks. But it goes beyond a technological infrastructure (microgrid), to include supporting data processing and forecasting of natural disasters (micronet). Both are required to deliver information which allow people and organizations to prepare, and for triggering actions that can prevent or mitigate a disaster [4]. For instance, an early warning system for flooding impact on water networks can be used to monitor and manage the flow of water, within and external to the network, and initial alerts if failures are inevitable.

Up to now, water research solutions and developments for water primarily addressed water resource management in order to tackle current and future shortages. But focus is shifting to resolving important aspects of resilience to external shocks. For instance, a flood early warning systems (FEWS) was recently developed by the Urban Flood Project [22] in Denmark to monitor sensor networks installed in flood defenses (dikes, dams, embankments, etc.).



Figure 3: Elements of a socially-integrated early warning system. Adapted from [UN/ISRR in 23]

In this system, information and simulation results are fed into an interactive decision support system that helps dike managers, city authorities and individuals to make informed decisions in case of emergency and in routine dike quality assessment. The prototype system provides smart alerts on three levels: rainfall forecasts (level one); storm activity (level two); and real-time reports from flow gauges (level three). The resulting alerts serve multiple stakeholders i.e. helps relevant authorities to prepare for and minimize the impact of flash flooding; individual users can also access

daily flood hazard maps based on the rainfall forecasts. There is also a planning tool that is proposed to help stakeholders and local authorities to strategically plan their activities by suggesting optimum structural and non-structural measures for the area, in terms of different flood, urban development and fire scenarios associated with climate change [22].

Based on this example and [23], a simplified flooding early warning system at the building-level can also be characterized by four interlinked stages (Figure 3).

From this socially integrated framework, an integrated flood EWS for water networks to consist of hardware and software components can be proposed to include (Figure 4):

- Acquisition of data e.g. hydrological - water flow and pressure, and meteorological – rainfall etc.
- Transmission of the data in real time or at regular intervals
- Storage of the data
- Data communication
- Archiving/recall of the data.

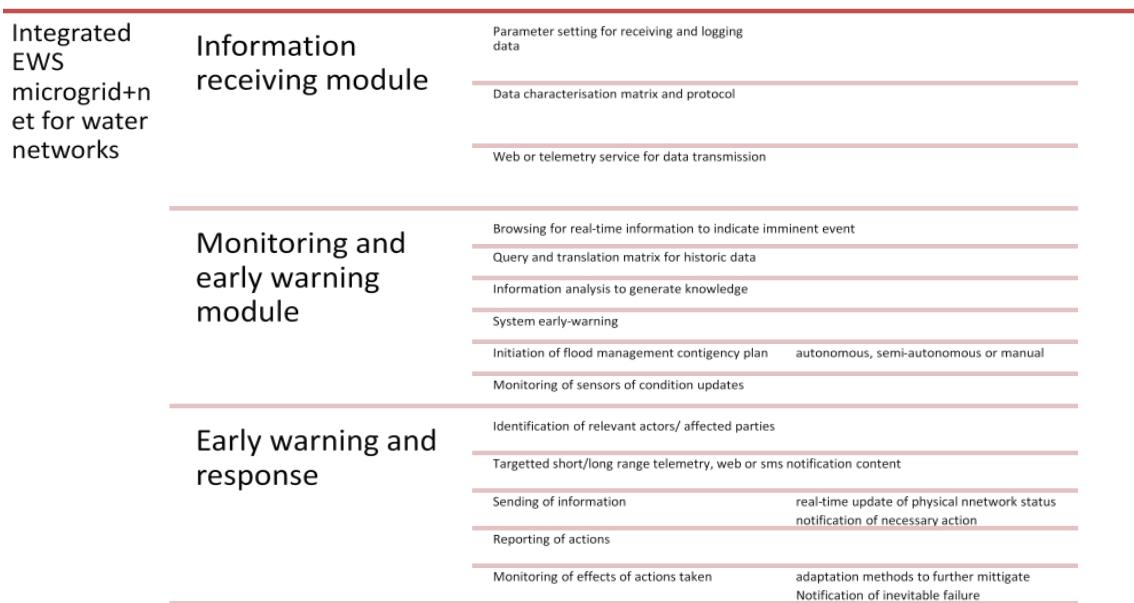


Figure 4: Integrated EWS microgrid + net for water networks (Adapted from [24])

A socially integrative EWS will consist of systems and processes to promote knowledge and adaptive capacity as well as the ability of citizens and governance to respond, and take commensurate action. Therefore, the involvement of key actors' at all key stages of development, deployment and decision making is important. Typically, the decision-making process of early warning comprises a set of tasks, which can be carried out either by specialists - meteorologist, hydrologist, geologist, and disaster management professional in government, private or non-profit organisations. However, the decisions made at this macro scale often have different priorities and effects compared to decisions required to mitigate damage at the micro, building-level. This is an important gap that can be filled by a microgrid+net that is for example integrated with a Building Management System (BMS) or Smart meter. This area is the scope of further studies to be conducted as part of this project.

### 3. Integration of non-physical processes and actors in an EWS microgrid+net for water networks

The concept of resilience recognizes the need to pay attention to the interdependencies between the different strata and functions of infrastructures in urban areas. However, this cannot be achieved independently and without consideration of the inter-connectedness and collaborations across social, economic, political and organizational

domains. A framework based on physical components of a microgrid+net alone is therefore insufficient to achieve comprehensive resilience. Thus, cross dimensional integration, coupled with collaboration among the key actors is required for effective decision making on hazards and risks; vulnerabilities and needs as well as the design and implementation of management and adaptive strategies.

This is supported by [25], whose study highlights the challenge of integrating and synthesizing for resilience without facing the need to decide among contrasting definitions, or omitting causal and functional relationships. Stating the flood risk management could be framed within two coupled cyclic processes to better mainstream sectoral measures with policy implementation (Figure 5). A more detailed breakdown of information and decisions is also proposed by [4].

In addition to common key actors presented in prior studies, the key actors for decision making at the building level to improve water network resilience includes: Water companies, local authorities, regulators, building professionals, building owners/users etc.). All need to be involved in setting the information and decision requirements for what happens in the local water network. And these niche actors need to be proactively engaged so that they can be strategically prepared at the onset of future extreme events if the transitioning opportunities associated with extremes are to be harnessed especially to expedite water system solutions [26].

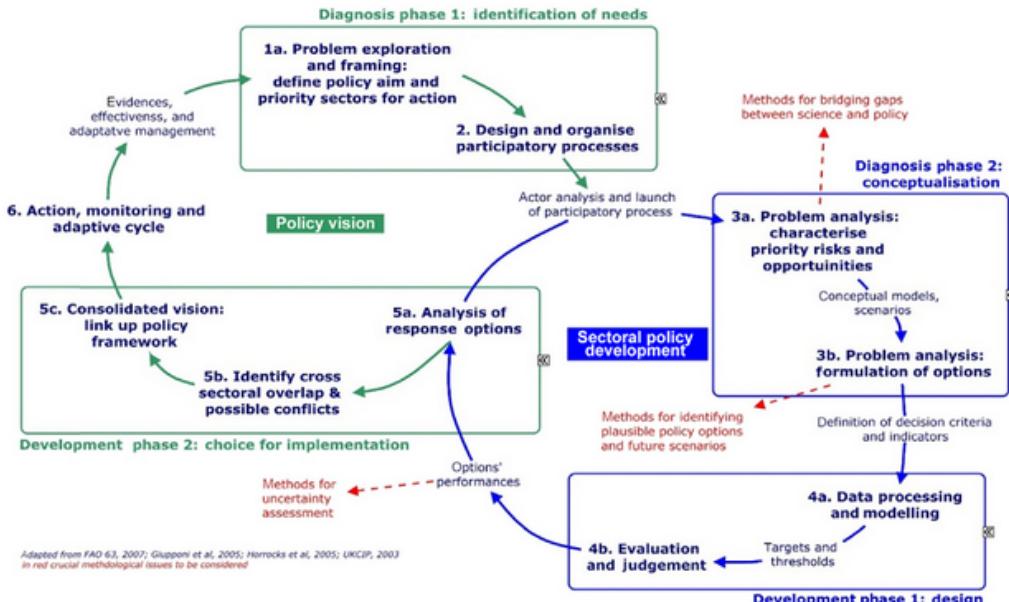


Figure 5: Cyclical decision-making flowchart for climate change adaptation and risk management [25]

#### 4. Conclusion

The increasing trends in natural events highlights the need to increase the resilience of complex infrastructures, as well as the associated socio-economic and political processes. Infrastructure at all urban scales, including at the building level must be built or enhanced to better cope with natural events. This paper presents a review to highlight the importance of early warning systems as an important aspect of resilience preparedness but further argues for the importance of such systems, not just at the city scale but also at the building level. As well as the potential for smart systems such as micro-grids and micronets as the means to deliver resilience through intelligent forecasting methods, resilience risk decision-making support for/by stakeholders and to encourage new approaches to water networks and infrastructure design.

Lastly, the existing concepts of a socially-integrated EWS microgrid+net framework is briefly presented. The next steps aims to work with the key actors in this domain to further develop the framework, and to collaboratively design and develop a pragmatic microgrid+net system.

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