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**Manuscript title:** Towards self-healing in water infrastructure systems

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**Abstract**

With infrastructure systems growing increasingly complex and interdependent, the consequences of a system failure have the potential to be more devastating, and impact more users, than ever before. Self-healing systems, originally proposed as a solution to complexity in software-based systems, are those which can independently identify failure or degradation in the network and generate solutions to restore functionality, allowing the continued provision of services. The benefits of adopting a self-healing approach to infrastructure network management are obvious and abundant; network quality can be assessed and assured, threats can be swiftly identified and dealt with, resources can be assigned to optimise coverage under fluctuating demand, and consumers can have confidence in the stability of the services they use on a daily basis. This paper outlines the potential for self-healing within water infrastructure systems, a sector that has been slow to embrace system-wide approaches. A systematic review of the topic identifies emerging terminology and methods within the water domain, and the extent to which current research aligns with self-healing methodology is discussed. Finally, the steps that can be implemented to shift the water sector towards a self-healing perspective are explored through a case study of leakage management in water pipeline systems.

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## 1. Introduction

Infrastructure systems provide crucial services such as energy, water, transport, and telecommunications. As cities expand and infrastructure networks serve growing numbers of people, these systems have become increasingly complex. Additional complexity, and the associated interdependencies between networks, increases the difficulty of predicting system failure, as well as the propagation of failure throughout the network (Rinaldi, Peerenboom and Kelly, 2001). In order to effectively manage infrastructure systems, systemic approaches, which address failures within the wider context of a complex network, are required.

This research seeks to explore whether the framework of self-healing systems, a systemic approach to the management of software-based systems, can be effectively applied to infrastructure systems. Looking in particular at the water sector, current system management strategies are contrasted with a proposed self-healing framework to establish the benefits of, and potential barriers to, implementation of a self-healing system approach. The first steps that need to be taken to move towards a self-healing methodology are identified and explored.

## 2. Self-healing systems

### *2.1 Origins*

Self-healing has its origins in software-based systems, where IBM's autonomic computing initiative outlined their vision of 'self-managing' systems. Seeking to shift the management of increasingly complex computational systems away from error-prone human operators, IBM proposed integrating this responsibility into the system itself. Self-managing systems were

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further defined by four sub-characteristics; self-configuring, self-healing, self-optimizing, and self-protecting, with self-healing described as the ability of the system 'discover, diagnose, and react to disruptions' (Ganek and Corbi, 2003). While true self-healing is performed in the absence of human intervention, systems that require some degree of interaction with an external agent can instead be described as assisted-healing systems (Ghosh *et al.*, 2007).

### *2.2 Elements of self-healing*

Self-healing cannot be possible without self-awareness. The ability of a system to act, either to prevent or react to failure, is dependent upon understanding that the system is behaving in such a way that intervention is required. Being able to detect and define the state of a system at a given time is thus crucial to self-healing. Conveyed in Figure 1, systems can be categorised as being in one of three states; normal, damaged, and broken. In its normal – or healthy – state, a self-healing system will be able to provide resources or services at standard operating levels. What constitutes 'normal' is not always immediately evident, and may fluctuate under variable operating conditions. In the damaged state, a self-healing system must be able to specify a threshold at which restorative actions are deemed necessary. This threshold may be defined as bounded acceptable values (possibly provided by standards or regulations), a percentage deviation in conditions, or the occurrence of measurable unacceptable behaviours within the system. In the broken state, the system is no longer able to provide acceptable service, and actions to restore system function must be identified and prioritised.

While the status of a self-healing system at a given time can be described by its state, the processes by which a system maintains its current state or moves between states fall into three

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categories: detection, preventative action, and reactive action. In the transition from normal to non-normal states, the system must detect that performance has deviated from normal levels, in order to trigger a self-healing response. This process of detection comprises of monitoring the system and recognising when functionality is compromised. In instances of sudden service loss, the transition to a broken state can be almost instantaneous. An example of this would be when natural disasters sever power lines or broadband cables, burst water pipes, or block roads or railways. However, the transition from a normal state to a broken one can also be a progressive degradation. In this case, the system experiences a 'fuzzy zone' of deterioration, in which it can be difficult to define a discrete line between healthy and unhealthy states (Ghosh *et al.*, 2007). Maintaining a healthy state requires not only an ongoing process of detection, but proactive interventions to prevent any unacceptable change in system parameters that might cause degradation in system performance. Any actions undertaken to prevent deviation from the normal state can be described as preventative, as these are implemented before system performance is compromised. Should such measures fail to prevent transition to a damaged or broken state, the return to a healthy state is achieved through interventions that enable system recovery. Such actions are reactive, as they follow a degradation of system service.

### *2.3 Self-healing vs decision support*

While decision support systems (DSS) can facilitate self-healing processes, the two types of system are not interchangeable. Traditionally, DSS have been thought of as a support to a human decision-maker, rather than as a replacement, and the human-user interface is considered an important component of DSS (Eom *et al.*, 1998). Ghosh et al. (2007) describe

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the decision support typically offered by DSS as passive, with the outcome of the decision-making process ultimately down to the system user. Self-healing systems, however, have the potential to deliver active decision support; they are able to detect and respond to failure in the absence of human intervention. With well-developed system architecture, self-healing systems may also have the capacity to select an optimum remediation strategy and prioritise certain components in repair scheduling (Ghosh *et al.*, 2007). In complex, inter-connected systems, taking the initiative from the user and returning it to the system itself can enable a faster, more effective response to disruption.

This is not to say that DSS cannot play a role in enabling self-healing, particularly in sectors where self-healing systems are in their infancy, with human intervention not yet eliminated from the system. Assisted-healing systems share many core elements with DSS, including the need to detect and define system failure. It is in their approach to active interventions that the two differ, with DSS typically offering advice to a human decision-maker, while assisted-healing systems are able to make their own decisions, but require a human agent to implement their chosen course of action.

### *2.4 Self-healing in infrastructure systems*

Like their computational counterparts, infrastructure systems are becoming increasingly complex. The growing digitalisation of critical infrastructure has intensified the levels of interconnectedness between networks which also interact with the larger economic, environmental, and societal systems within which they reside (Oughton *et al.*, 2018). This creates interdependencies between systems, which can increase the risk of failure across system boundaries, and significantly affects how failure travels through a network. There are three main types of failure propagation in infrastructure networks (Rinaldi, Peerenboom and Kelly, 2001);

- Cascading failures – occurs when a disruption in one infrastructure causes failure in a second infrastructure.
- Escalating failures – occurs when an existing disruption in one infrastructure exacerbates an independent disruption of a second infrastructure, typically by increasing either the severity of the second failure or the time for recovery or restoration.
- Common cause failures – occurs when two or more infrastructure networks are disrupted at the same time, with components within each network failing because of some common cause.

As for complex software-based systems, the management of complex infrastructure networks presents a significant challenge for human operators, who may struggle to anticipate the effects of interdependencies on failure propagation throughout the system. Building self-healing capacity into such a system has many obvious benefits, from the removal of human error to a swift reduction in response times.

The energy sector has already begun to embrace this approach, with self-healing a key characteristic of the smart grid (European Task Force for Smart Grids, 2011). With so many services dependent on a stable power supply, the consequences of failures in power grids have never been greater. A self-healing smart grid is able to detect abnormalities, reconfigure the system in order to isolate disturbances, and minimize disruption by reducing outage frequency and minimizing outage length. Self-healing also gives the smart grid end-to-end resilience, with the ability to detect and override human errors that may have otherwise resulted in outages (Amin, 2013).

The water sector offers further examples of complex and highly interdependent systems, with dynamic interactions between constructed infrastructure networks, the physical environment, and societal pressures. This can result in multi-objective, multidisciplinary challenges, giving rise to unpredictable and emergent behaviours (Simonovic, 2020). However, a self-healing approach to system management is yet to be widely adopted in the water sector. Vertical integration within water supply and distribution networks and limitations of legacy infrastructure are additional challenges faced by this sector that may have contributed to this slower uptake.

### *2.5 Self-healing in a digital ecosystem*

Given that appropriate self-healing interventions have a massive dependency on accurate, timely, and secure information, the digitalisation of infrastructure systems provides both some of the greatest challenges and opportunities for the adoption of self-healing techniques.

Increased digitalisation allows for the possibility of a real-time, or ‘right time’, connection between the infrastructure system and theoretical and mathematical models. ‘Right time’ connections provide data at a sufficient rate to satisfy the needs of the system, for example reservoir levels may be supplied only daily during typical weather conditions, but more frequently during storm events. Access to a reliable data connection, typically provided by a network of sensors, allows the infrastructure system to be accurately modelled in its present state. This data can also be used in scenario modelling, to anticipate potential failures and identify vulnerabilities in the system. Where digitalisation is limited, however, is in the implementation of the knowledge gained through such modelling. For example, in the water sector specifically, at present a human is almost always in the loop to facilitate the connection between the outputs of the system model and the physical system itself. This common digital set-up is illustrated in Figure 2. What digitalisation does offer, however, is the opportunity to minimise the risk associated with this human link in the chain by using data science techniques to take decision making power away from human and adding it to the system model.

An assumption made by many of the proposed techniques in the water sector is the availability of accurate and complete data. Research that utilises real-time data has found that this is not always the case, with one study on leakage detection finding that data corruption issues/logger failures were responsible for 8.2% of alerts issued (Mounce and Boxall, 2010). With buried networks like water distribution pipelines, access to repair or replace sensing hardware is costly and time-consuming. As such, data pre-processing methods are often employed to improve the quality of data inputted into models (Mounce *et al.*, 2017). Unreliable data can, in some cases, increase the responsibility of the human in the loop, who may have to use their discretion to judge whether or not an alert was made in error. In such circumstances, the expertise of the human in the loop is key to success. A healthy digital ecosystem seeks to limit the need for human judgement, both by ensuring reliable data access and by developing models which are able to handle imperfect or unexpected data, increasing confidence in model outputs.

## 3. Self-healing in water systems

### *3.1 Literature search strategy*

A systematic literature review was conducted to assess the state of self-healing within the water industry. With limited adoption of self-healing terminology in the water sector, it was decided that returning to the field of computational systems, where self-healing research originated, would provide a greater range of initial search terms. Papers describing the origins, principles, and development of self-healing systems were therefore used to create a broad list of terms linked to the concept of self-healing (Psaier and Dustdar, 2011) (Ghosh *et al.*, 2007) (Rodosek *et al.*, 2009). These are listed in Table 1.

Secondary targeted searches were conducted to ensure terminology specific to certain processes was included, yielding additional papers on autonomous decision support and system restoration.

### *3.2 Literature findings*

Through the lens of self-healing processes, the current state of system management in water infrastructure is examined, to establish the extent to which current approaches align with a self-healing methodology. To explore this, each paper identified in the search was assessed and classified according to which of the three main stages of self-healing – detection, preventative action, and reactive action – were addressed by the paper's proposed approach to system management. It was immediately evident that there were very few examples of complete self-healing systems. Instead, many focused on tackling issues that sit within a sub-section of a larger system. While limited research spans all three, each component of self-healing is represented within the full pool of papers. The dominant terminology found in each stage, as well as in papers covering multiple components, is presented in Figure 3, along with a selection of the techniques and algorithms employed.

### 3.2.1 Detection techniques in literature

With self-awareness such a crucial element of self-healing, it is promising that detection techniques have been proposed for a large range of applications, including water quality (Karthe *et al.*, 2016), pipe leakage (Mounce *et al.*, 2015), irrigation (Achtaich *et al.*, 2019), and reservoir monitoring (Doi, Norwawi and Ismail, 2020). The position of water infrastructure systems within larger environmental systems means that they are often affected by various environmental factors, such as rainfall, river flow, and groundwater levels, that are challenging to accurately monitor at scale. Integration of forecasting tools into models allows these variables to be considered, whilst also providing opportunities for failure anticipation (Wang *et al.*, 2019) (Wang, 2013). Forecasting of failure can also be facilitated by data from either hydrological forecasts or real-time sensors, with models able to predict the likelihood of failure events such as ice-jam or dry-up in river channels (Wang, 2013), allowing preventative interventions to be introduced. Another form of forecasting, damage forecasting, has been utilised in restorative approaches for networks where failure locations can be numerous and difficult to locate, such as water supply systems following an earthquake. A hydraulic analysis can instead take known information regarding the network and disruption, such as pipe properties and earthquake intensity respectively, to forecast damage within the system, allowing prioritised repair schedules to be developed (Anwar and Dong, 2020) (Choi, Yoo and Kang, 2018) (Han *et al.*, 2020).

For largely closed systems, such as water treatment plants and irrigation systems, or those where data is required from specific sites, such as reservoirs, sensor-based approaches to detection are generally preferred. It is important to note that, in order to facilitate restorative interventions, a self-healing system must not only detect its present state, but define a threshold at which that state is deemed unhealthy. Approaches to this have included defining an unacceptable deviation from previous measurements (Zhou *et al.*, 2018) or training data (Mounce *et al.*, 2017), and using limits defined in standards or legislation.

#### 3.2.2 Detection with preventative action techniques in literature

Effective monitoring can detect minor fluctuations and enable early interventions to prevent a degradation in service. The most popular research direction at the overlap of detection and preventative action is the design of controllers. Many of these are fuzzy self-adaptive controllers, providing greater system autonomy even in fluctuating or uncertain conditions. As might be expected, these are particularly prevalent in multi-variable water/wastewater treatment systems (Qiao, Huang and Han, 2012) (Francisco, Skogestad and Vega, 2015) (Francisco, Vega and Skogestad, 2015) (Li, Peng and Wang, 2012), although controllers can also facilitate the operation of canals (Ding *et al.*, 2009) (Han, 2011) and water supply systems (Ding and Cao, 2010). Preventative action interventions in the absence of detection technologies were found to be relatively rare, again underscoring the importance of system

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awareness in self-healing. The few papers that attempt this have centred on resource allocation in water management, seeking to optimise variables such as cost and reliability and reduce flood risk in a range of potential resource distribution scenarios (Qin *et al.*, 2020). With multiple variables to consider, multi-objective evolutionary algorithms have proven popular for tackling water resource allocation problems (Y. Al-Jawad and M. Kalin, 2019) (Kasprzyk, Reed and Hadka, 2016).

#### 3.2.3 Detection with reactive action techniques in literature

It is at the intersection of reactive interventions and detection methods that decision support systems sit. Whilst human operators are largely still necessary, the actions of operators are guided by insights generated by the system itself. Triggering these actions can be as straightforward as the sending of automated alerts in response to the detected variable crossing beyond a failure threshold (Mounce and Boxall, 2010). Decision support systems operating with high degrees of automation have been applied to pathogen monitoring in drinking water (Karthe *et al.*, 2016), siphon operation for flood mitigation in wetlands and shallow ponds (Qin *et al.*, 2019), and river pollution control (Zhang, Wu and Shang, 2008).

#### 3.2.4 Preventative and reactive action techniques in literature

A notable finding was that preventative and reactive actions are rarely addressed within the same paper. Instead, research has focussed either on preventing failures that can be anticipated, or on restoring the system after unavoidable failure Interestingly, both have been approached from a resource allocation perspective, with the former allocating water across rivers and

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reservoirs, and the latter allocating emergency response resources such as repair crews. It is evident that it is in the area of reactive interventions where water systems still rely on a significant degree of human involvement. With the complexity involved in fixing water infrastructure, particularly underground services, it is likely that many systems in this sector will need to be assisted-healing until advances in enabling technologies can be made. Existing research in this area, however, takes decisions on how to prioritise repairs out of human hands. In disaster response scenarios, approaches vary from a dynamic cost-benefit method (Han *et al.*, 2020) to prioritisation of restoring water supplies to emergency facilities such as hospitals and fire stations (Authors: Li, 2018).

#### 3.2.5 Self-healing techniques in literature

Only two papers were identified that included all the core components of self-healing systems, with detective capabilities in addition to both preventative and restorative interventions. The first tackles irrigation, where the difference between damaged and broken states is typically down to the degree of severity. Recent developments in smart irrigation systems have enabled extensive system monitoring through the Internet of Things. The authors adopted a constraint-based approach, defining the properties that a solution is required to have, rather than a set of specific instructions, and delegating the decision making to a solver (Achtaich *et al.*, 2019). The second is an ambitious attempt at real-time regulation of resources within the Yellow River basin. Access to real-time information on user requirements and channel flow allows for dynamic adjustments in water diversion and reservoir release. The paper is somewhat lacking in detail regarding how decisions are made during periods where river discharge is unable to meet the needs of all users, but it demonstrates well how a systemwide approach can be applied beyond smaller water infrastructure networks to the more challenging systems of river basins, which themselves sit within wider and more complex environmental systems (Wang, 2013).

### *3.3 Data and sensing*

A crucial element of self-healing systems is their ability to detect their present state and distinguish between healthy and failed states. As such, access to up-to-date sensing data regarding the properties and key variables within a network very much underpin the effectiveness of a self-healing system. It was found, however, that many of the techniques considered in this review were yet to be demonstrated on data from a live network. Several alternatives, including historical and benchmark data, were used instead to establish the performance of proposed techniques. While this is often sufficient to demonstrate how active interventions would utilise data to heal the system, this does not address potential challenges in data collection and accuracy.

## 4. Towards self-healing in water systems - A case study of pipe leakage

This section will explore how the water sector might move towards a self-healing approach, looking at the steps this might take. This is done through the case study of pipe leakage in water distribution systems. The problem is presented, as are the steps that can be taken to move from a siloed to systemic approach to addressing this issue, with respect to the current limitations of the infrastructure.

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### *4.1 The issue of pipe leakage*

In England and Wales, an average of 3,170 million litres, or 21% of water put into public supply, were lost to leakage per day between 2018 and 2019. This equates to wastage of 53 litres per person per day (*PR19 final determinations: Securing cost efficiency technical appendix*, 2019). Accurate sensing of leakage is part of the problem, with the majority of the UK's pipe network buried underground, and monitoring is typically performed by point pressure sensors located throughout the network. With a significant proportion of the network consisting of aged infrastructure, sensor coverage is not always extensive, and it is estimated that up to a third of excavations fail to expose the leakage location. Repairing pipes suffering from leakage is also a costly affair, with the required excavations impacting road user, local businesses, and city logistics (Caffoor, 2019).

Ofwat, the body responsible for economic regulation of the privatised water industry in England and Wales, aims to reduce leakage by at least 15% by 2024-25 (*PR19 final determinations: Securing cost efficiency technical appendix*, 2019). In order to meet this target, water companies need not only to extend and upgrade their sensing capabilities, but to address the issue of leakage as a whole system. This means implementing interconnected systems with data following between each stage of the self-healing cycle, rather than adopting fragmented solutions that address individual self-healing processes in isolation.

### *4.2 The current siloes*

The current approaches to tackling leakage in water distribution systems fall into one of four

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categories; improved sensing technologies/coverage, preventative maintenance, leakage detection through analysis of sensor data, and repair scheduling.

- **Installation of sensors.** Increased sensor coverage has formed the bulk of water companies' leakage reduction strategies to date, with Ofwat reporting that the vast majority of companies achieving substantial leakage reductions in 2019-20 had introduced significant programmes to enhance network monitoring (*Service delivery report 2019-2020*, 2020). Acoustic loggers, which detect the sound waves generated by leaks as they travel through the pipe wall, are releasing flow and pressure sensors as the sensing technology favoured by water companies. However, these remain discrete point sensors, and it can be down to engineers to use this data to attempt pinpoint leakage locations. New solutions being developed include in-pipe fibre-optic sensing, which is able to achieve much greater accuracy by providing continuous sensing along the length of the pipe ('Nuron: Make infrastructure make sense', 2017). The installation of new technology in pre-existing buried pipes, however, can be costly and potentially disruptive. Investments have recently been made into research on in-pipe robotics, which seeks to develop small robots capable of inspecting buried pipes from within (Caffoor, 2019). This would potentially allow improved sensing in existing buried infrastructure without the need to perform costly excavations.
- **Preventative maintenance.** Preventative maintenance has the potential to significantly reduce leakage by identifying weak areas in a network and replacing or strengthening these before a leak is able to occur. Most strategies for preventative

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maintenance are either time-based or reliability-based. While there has been limited research on preventative maintenance in pipelines, a tool for assessing the reliability of pipeline elements, both before and after repair, has been proposed in order to inform preventative maintenance strategies (Sun, Ma and Morris, 2009). There has also been some research on predicting leakage in pipe networks. This has focused on prediction using pipe parameters, such as age, diameter, and material, and geographic/geological factors, such as soil type and distance to road, rather than prediction based on flow, pressure, or acoustic sensor data (Jing and Zhi-Hong, 2012) (Leu and Bui, 2016).

- **Leakage detection.** Underpinning the healing of leakage-affected systems is reliable leakage detection. There have been various approaches to analysing sensor data in order to identify potential leaks. A modified Clonalg algorithm has demonstrated success in identifying leaks from pressure sensor data (Eryiğit, 2019), and historical data from flow sensors has been used to train a binary neural network to identify anomalous flows caused by leakage (Mounce *et al.*, 2015) (Mounce *et al.*, 2017). In live networks, ensuring incoming data is of a reliable quality can present a challenge for detection tools. Differentiating between anomalous data indicative of a leak and erroneous sensor readings can also prove difficult.
- **Repair prioritisation and scheduling.** Response strategies for natural disasters, where resources must be spread across a wide heavily disrupted network, have yielded numerous scheduling tools for system repair. With leakage such a prevalent issue across water systems even in day-to-day operations, these tools can be utilised in

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non-disaster scenarios to ensure repairs achieve the greatest impact. Single criteria, multi-criteria, and cost-benefit methods for repair prioritisation and crew scheduling have been developed (Han *et al.*, 2020). Uncertainty in pipe and/or leak location is another factor to consider in repair scheduling.

### *4.3 From siloed to system-based*

It is important to consider how data flows through a self-healing system, in order to allow processes that may initially have been fragmented to come together as a cohesive system. The categories of existing technologies used in the management of pipe leakage can be considered as elements of a greater system, with output data from each element becoming input data for one or more of the following. Figure 4 shows how data could flow between previously separate components within a greater system of leakage management.

In-pipe sensors provide data on water pressure and flow rate, although advanced sensors may also provide temperature or acoustic data. This data could be fed into a leakage detection tool, which may employ machine learning methods or evolutionary algorithms to identify the likelihood, severity, and location, of potential leaks. If a leak is deemed likely or severe enough to warrant intervention, as defined by threshold criteria, the outputs of the leakage detection tool would then become the inputs for a repair planning tool, along with data on availability and location of repair teams and any necessary equipment. Repair scheduling may focus on limiting the time for which the system is operating below normal levels, minimising the amount of water lost, or targeting the most severe leaks first. It may also be necessary to prioritise leakages in key locations, such as those supplying critical infrastructure. A

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multi-criteria approach combining several of these considerations may be required. Once repairs have been carried out, information on the new state of the network, including specifications of any new pipes installed, should be added to a database for preventative maintenance. Preventative maintenance could be guided by leakage prediction techniques, which require pipe parameter and location data. This data is held by water companies. Preventative maintenance strategies would establish the most vulnerable areas of the system, which can then be prioritised for maintenance when resources are available, using scheduling tools.

### *4.4 Steps to implementation*

As may be expected, given the fragmented approach to self-healing in the water sector, perhaps the biggest barrier to more comprehensive adoption of this approach is the need to establish communication across stages of the system. For example, while several works have proposed tools for leakage detection, and others have developed methods to schedule and prioritise repairs, there is no case as yet where outputs of the former have been used as inputs for the latter. The development of centralised information architecture, in order to facilitate effective data sharing, will be crucial in enabling existing techniques to come together into a wider system. While many existing methods could currently be considered decision support tools, integration into this system framework would instead produce a self-managing or assisted-healing system.

A second potential barrier to implementation of such a systemic approach is in the completeness and accuracy of data in the water sector. With many aged assets, records often stretch back over decades, and those for data such as pipe location can vary significantly in accuracy. As this older infrastructure will be a part of the UK's water systems for the foreseeable future, methods must be able to handle uncertainties and even gaps in data if they are to be implemented at network level. Data formatting may also vary, both between organisations and between teams managing different elements of the pipe system. A more systemic approach to data management would see the standardisation of data collection and leakage records, although widespread implementation of such an approach would take time. Therefore, incorporating flexibility into methods will assist in the integration of different datasets.

The final step to self-healing, requires advances in technology. As a system with most assets buried underground and a significant amount of aged infrastructure, the water sector faces more barriers than many other infrastructure sectors when it comes to the implementation of a fully self-healing approach. One technology being developed which may help towards this goal is in-pipe robotics. Although yet to see implementation, recent investments in this area of research may see this change in the future. However, while existing technology may not allow for the repair of pipes without human involvement, a self-managing system would take all but the most physical tasks out of the hands of the operator and make them the responsibility of the system. This has the potential to significantly improve the efficiency of operations by optimising complex problems such as leakage detection and multi-objective repair scheduling.

## 5. Conclusions

The self-healing approach to system management has the potential to improve the reliability

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and autonomy of complex systems, as demonstrated in the fields of computing science and software engineering. As a highly interconnected network, water systems could benefit greatly from the adoption of a self-healing perspective. While existing techniques address individual elements of self-healing in isolation, a shift to system-wide thinking, as well as investment in technology to facilitate efficient data sharing across the sector, is needed to unlock the full potential of self-healing in water infrastructure systems. At the heart of this approach is a pathway for data to move through the system, so that insight generated by one process within the network is able to guide decisions in the next stage of the cycle. Future work may seek to explore how to provide such a data pathway between current techniques for applications such as leakage detection and repair scheduling, to establish the practical barriers to integrating existing processes in a self-healing network. The ideal of a fully self-healing system may not yet be possible for many applications in the water sector, and indeed in other sectors and infrastructure networks. However, shifting from an isolated approach to one that considers each process of self-healing as part of a larger system is an important first step in providing the integrated management that such complex and interdependent systems require.

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**Table 1.**

| | | | |
|---|---|---|---|
| Self heal* | Survivable | Self routing | Self recover* |
| Self protect* | Self repair | Self stabili* | Self adapt* |
| Self configure* | Self reconfigure* | Self optimi* | Artificial immune system |

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**Figure 1.** Self-healing system states and processes. Adapted from (Ghosh *et al.*, 2007)

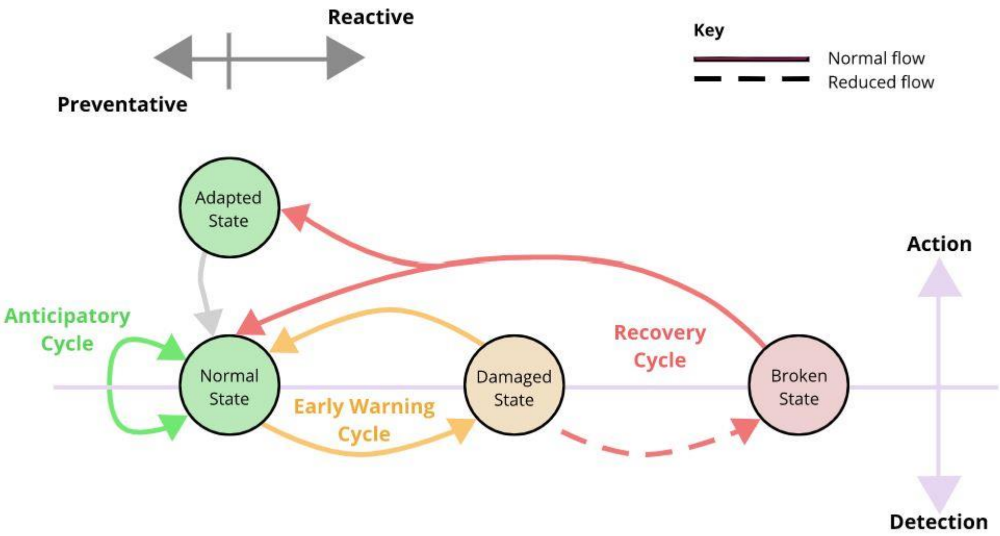

**Figure 2.** A common digital set-up for water infrastructure systems

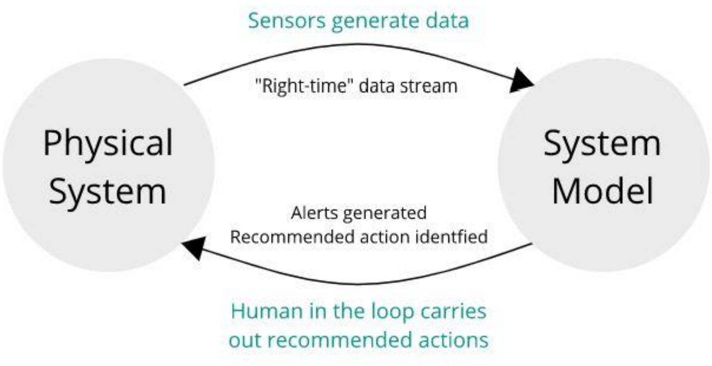

**Figure 3.** Terminology and methods found in review of self-healing in water infrastructure

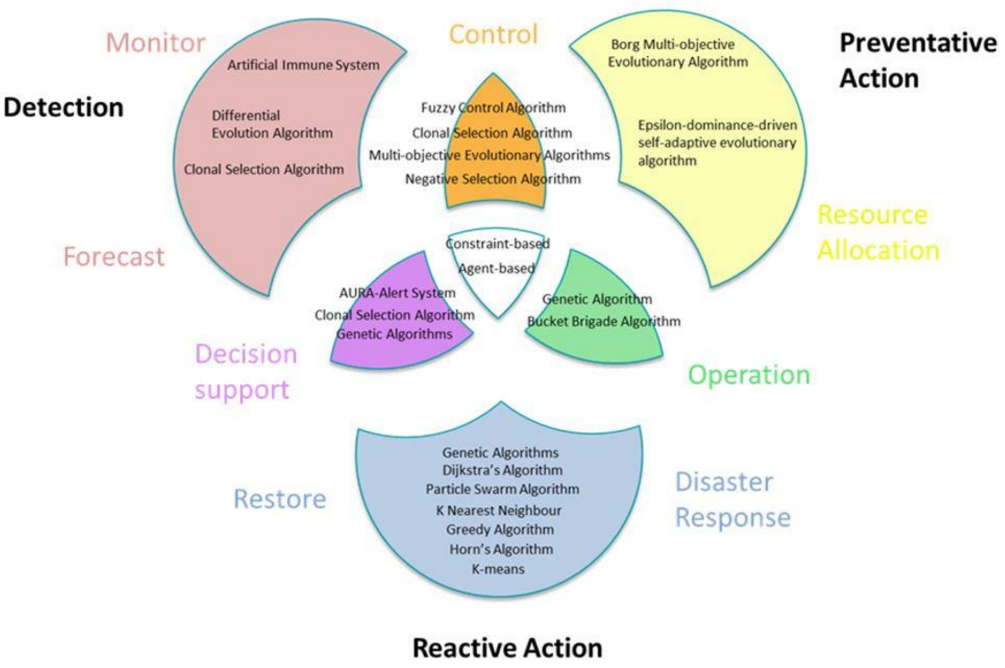

**Figure 4.** Data flows in a systems approach to leakage management