Antifragility, Smart Cities, and Local Urban Governance

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Antifragility is a system property that results in systems becoming increasingly resitant to external shocks by being exposed to them. These systems have the counter-intuitive property of benefiting from uncertain conditions. This paper presents one of the first known applications of antifragility to water infrastructure systems, and outlines the development of antifragility at the city scale through the use of a bi-modal strategy, local governance, and data collection. The data can then be shared between cities to establish what heuristics are effective in the management of water systems in order to develop increasingly robust and antifragile infrastructure. The systems architecture presented results in a management paradigm that is able to deliver reliable water systems despite highly uncertain future conditions.

Keywords: Antifragility, Urban Water, Deep Uncertainty, Climate Adaptation

Introduction

In recent years there has been a large increase in the use of sensor networks to facilitate data collection in a shift towards the implementation of Smart Cities. The information collected through the so-called “Smart City” paradigm is extremely beneficial in informing local decision-makers. This paper postulates that the Smart City concept lends itself to cities becoming antifragile (Taleb, 2012) to climatic and weather shocks over time. By empirically grounding policy making and adaptation, it is possible for cities to become increasingly resistant to the effects of extreme weather conditions over time. This continual evolution is a significant element of the concept of antifragility. Antifragility is a system property originally detailed by Taleb (2012) that results in systems becoming increasingly resistant to external shocks. Antifragile systems have the counter-intuitive property of benefiting from uncertain conditions. By developing antifragility in urban water systems they will have an increased capacity to adapt to the shocks and stresses they are exposed to.

This paper introduces the use of the concept of antifragility to guide infrastructure planning and management in cities. So far, there is only one known example of antifragility applied to infrastructure planning (Bruce Beck 2013). The present paper will discuss how urban water systems can be managed to achieve antifragility.

Water Issues in Urban Areas

Changing Urban Water Challenges

The world is experiencing an extremely rapid rate of change across a spectrum of issues (Friedman 2008). The world’s urban population has rapidly risen from 746 million people in 1950 to 3.9 billion people in 2014 with urbanisation expected to continue (United Nations Department of Economic and Social Affairs Population Division 2014).

Urbanisation leads to high concentrations of demand for natural resources, particularly for water. Additionally, the increased wealth of urban residents leads to increased water demand through water-heavy goods and widespread used of white goods (Lambert & Vassarotti 2013). Australia's growing cities have increased their water usage five-fold through population growth and through the increased demand for "water-heavy" good (IPCC 2014). Similar phenomena are occurring across the world, with half of the world's cities with more than 100,000 inhabitants experiencing water scarcity (ARUP 2014). Concurrently, climate change is changing hydrological conditions for urban areas across the globe. Climate change is projected to exacerbate desertification and water stresses through reductions in incident precipitation and by altering snowmelt patterns (IPCC 2014). These are resulting in negative effects on agriculture and business in some regions (UN Habitat 2014). In turn, these developments have lead to increased reliance on ground water, leading to lower water tables and increased amounts of saltwater intrusions in coastal aquifers (IPCC 2012).

The IPCC's AR5 Working Group II concluded that it was likely that there had been increases in the number of heavy precipitation events over the second half of the twentieth century (Trenberth et al., 2007). Increases in heavy precipitation events have been observed even in places where total precipitation depths have decreased; implying that there has been an increase intensity (IPCC 2008). The changes in precipitation intensity imply changes in the risk of pluvial flooding in some regions. It is likely that the frequency of heavy precipitation or the proportion of total rainfall due to heavy rainfalls will increase in the twenty-first century over many areas of the globe. It is predicted that these heavy rainfalls will contribute to increases in local flooding in at risk catchments or regions (IPCC 2012).

The World Economic Forum's Global Risks Report has placed water crises as the risk with highest potential impact. The increasing exposure of people and economic assets to weather related impacts has been the major cause of long-term increases in economic losses from climate disasters. (World Economic Forum 2015; IPCC 2014; Jha et al. 2012).

In the face of these changes, new infrastructure systems must be built, or existing ones modified. This has been highlighted by numerous sources (Geltner & de Neufville 2012; UN Habitat 2014). Due to poor levels of historic funding and a lack of investment in infrastructure within the Western world it has been estimated that 57 trillion US dollars will be required to meet global infrastructure demand worldwide by 2030, with over two fifths of this amount needed for power and water infrastructures (Dobbs et al. 2013). The design life of an infrastructure system can range from thirty to two hundred years (Hallegatte 2009). These time scales result in a high degree of uncertainty with regard to future conditions under which the infrastructure must perform. It can be said that long-term decisions relating to infrastructure planning are undertaken within a context of deep uncertainty (Hallegatte et al. 2012).

Deep Uncertainty & Predictive Errors

Deep uncertainty can be defined as the situation where "the parties to a decision do not know— or agree on—the best model for relating actions to consequences or the likelihood of future events" (Lempert, 2003 pp.3). Hallegatte, Shah, Brown, *et al.*, (2012) stated that there are three factors present within infrastructure decisions under deep uncertainty: (1) Knightian uncertainty; (Knight 1921) (2) Multiple different but equally valid scenarios of the future exist (3) Decisions must be considered with path dependence in mind.

Under conditions of deep uncertainty, the uncertainty surrounding the future cannot be significantly reduced through intensified data collection (Walker et al. 2013) as the past is of limited use as an indicator of future conditions (Milly et al. 2008). In the context of urban water management multiple sources of uncertainty are associated with climate change, population growth, and per-capita water use. Given the limited confidence in our ability to predict the future state of these systems it is critical that methodologies of planning to account for these uncertainties are utilised, as traditional optimum design is not appropriate in addressing decisions with the characteristics of climate change (Groves & Lempert 2007). McInerney, Lempert & Keller (2012) noted that infrastructure systems are optimised to operate under very specific conditions akin to "dancing on the top of a needle". These systems are fragile to future conditions whereby small deviations between the predicted and actual conditions result in large deteriorations in system performance. Thus, developing systems that operate well under narrow ranges of conditions require high levels of confidence in the future state of the world, a level that is generally speaking not possible to achieve for open systems, as Taleb (2012, pp.215) notes "when you are fragile you need to know a lot".

It could be argued that there is broad agreement from Taleb on the presence of deep uncertainty and its underlying causes. Particularly when historic data is used as the basis for making assumptions, historical record tend to contain a low number of rare events as by their very nature they tend to not appear in past samples, as such, the tails of estimated probability distributions are likely to poorly characterized. Resulting in a poor ability to accurately assess the probabilities and risks associated with extreme events. This has partly been reflected in modelers' poor track record of making accurate long-term predictions for complex systems. The inability to make these predictions stems from what Taleb termed the "extended disorder cluster". These represent various facets of uncertainty delineated by Walker, Harremoës, Rotmans, *et al.* (2003) as epistemic or aleatory uncertainties.

The ability to build robust plans and reliable systems is more developed than the ability to predict events from happening. "Not seeing a tsunami or an economic event coming is excusable, building something fragile to them is not" (Taleb, 2012 pp. 136), with this in mind, it is more effective to evaluate the robustness of strategies, systems, and components than to estimate and design to remote return periods. As shown in the previous section, cities require continual re-invention of their urban water systems in order to manage growing extremes and changing conditions. In order to achieve this cities should instead focus on exposure to failure and the consequences of extreme events occurring (Taleb et al. 2009).

Smart Cities

Proponents argue that the implementation of Smart City technologies would make urban infrastructure and management systems more efficient and cost-effective (Department for Business Innovation & Skills 2013). The "concept of the smart city emerged during the last decade as a fusion of ideas about how information and communications technologies might improve the functioning of cities" (Batty et al. 2012 pp.483). Under the Smart City paradigm, the data collected through sensors is transmitted via a telecommunications network to storage where it is then analysed in order to adjust urban operational processes. Certain data collected from Smart Cities can be particularly useful when used for the purposes of urban climate change adaptation. With regards to adapting urban water systems to climate change these data collection networks would take the relatively simple form of weather data collection apparatuses along with sensors used to quantify system response. A more detailed discussion on the architecture of the data collection system is presented later. For urban adaptation to changing conditions, the data collected by these sensor network allows for the post-mortem identification of how failure occurred and the efficacy of management options, thereby allowing for better informed future adaptation that may include physical or operational changes.

Robustness

What is traditionally thought of robustness has been termed “static robustness” by the Deep Uncertainty community. Static robustness aims to reduce vulnerability for the largest possible range of conditions (Walker, Haasnoot & Kwakkel, 2013; Buurman & Babovic, 2016). This is generally achieved by over-dimensioning elements of infrastructure systems to accommodate unexpectedly large shocks or stresses. While this is practically easy to achieve, it can incur significant costs to build over sized infrastructure. Furthermore ‘when it comes to random events, “Robust” is certainly not good enough. In the long run everything with the most minute vulnerability breaks’ (Taleb, 2012 pp.8). Residual risk remains even for infrastructure systems designed to withstand high return periods. This. methodology is prone to many of the errors highlighted earlier, including incomplete historical knowledge and a limited degree of confidence in the inflow distributions derived from historic data (Milly et al. 2008), extrapolating these data into the future results in even greater uncertainties.

Dynamic robustness addresses some of these issues by attempting to adapt systems over time in order to maintain a required level of reliability in the face of changing circumstances. For example, for a storm of any given return period, sensor networks can be utilised to quantify changing precipitation patterns and then adapt drainage systems accordingly, thus avoiding the need to invest great quantities into these adaptations. While this is preferred over a more passive attitude towards risk management, the aim is to maintain a level of reliability rather than continuously build an increasingly robust system.

Antifragility

Antifragility extends dynamic robustness by providing “a mechanism by which the system regenerates itself continuously by using, rather than suffering from, random events, unpredictable shocks, stressors and volatility” (Taleb, 2012 pp. 8). This is akin to the natural world where “systems subjected to randomness-and unpredictability-build a mechanism beyond the robust to opportunistically reinvent themselves” (Taleb, 2012 pp. 68). Proposals for similar concepts have been made. Beck (2013) argued that antifragility is similar to Holling’s ecological resilience (Holling 1973), while Liao (2012) proposes that periodic flooding creates opportunities for cities to become better fit for increasingly extreme floods. Antifragility is a process of continual adaptation as opposed to an end state. When a system is antifragile perfect knowledge of future conditions are not needed as they would be for a fragile system. For antifragile systems, unexpected shocks offer opportunities for reinvention, resulting in more robust systems.

When antifragile systems experience shocks they “bring more benefits (equivalently, less harm) as their intensity increase up to a point” (Taleb, 2012 pp. 272). This is akin to the body’s response to exercise, where imposed shocks lead to improved physical ability. For the fragile, the cumulative effect of small shocks is smaller than the single effect of an equivalent single large shock. This is exemplified by brittle objects which can withstand small loads but experience catastrophic failure once loading exceeds a threshold value. This is exemplified in Figure 1, system performance must be modified such that *F(x)* delivers the performance that is desired.

Antifragile systems are self-healing. This property differentiates antifragile systems from mechanistic systems which require continuous maintenance. Due to this, antifragile systems overcompensate from shocks whereas mechanistic systems undercompensate. For example, after a shock, the local body in charge of the urban water system would assess its performance, find causes of failure, modify their system and perhaps update their plans appropriately. In doing so, the system becomes better at coping with climate randomness as it they have the property of improving with shocks rather than merely resisting them or quickly recovering from them.

Antifragile systems are conditioned by the frequency and magnitude of the stressors to which they are exposed. They respond more positively to acute shocks than chronic stressors, particularly when these shocks are followed by ample time for the system to recover and reorganize. Critically, antifragile systems are not immune to events of all sizes; they can fail if they are affected by an event of sufficient magnitude. However, events that are below this threshold are treated as opportunities for growth and development. Urban areas can become antifragile when they seek to learn from shocks and the system response. In doing so the experience can be utilised to prepare and compensate for climate shocks. The question remains however: how does one translate the notion of antifragility to the domain of infrastructure planning? The development of antifragility occurs at two levels: the first occurs at the city scale, the second level occurs on an informational level.

Both of the varieties of antifragility require local governance of urban water systems. Within any city there are several potential solutions to water problems. The question of which of these strategies should be utilised is best left to local leaders and organisations who have both local knowledge and direct accountability. This bottom-up leadership should guide the adaptation of urban water systems in such a way so as to result in confidence that the systems would be robust to local climatic conditions. The creation of antifragility rests on feedback on system performance. A sensor network can be utilised to gain an understanding of how water systems operate under stress resulting in simple systems, policies, and regulations to alleviate local water issues.

Antifragility for Individual Cities

A barbell strategy or “bi-modal strategy” (Taleb, 2012 pp.161) is utilised to generate antifragility. The strategy is characterized by having two elements; one element is extremely risk averse, known as “bounded right”. The other is highly risk seeking and benefits from rare events but has limited losses; this is referred to as being bounded left. This results in a dual attitude of being robust to negative events and allows one to capitalize on positive Black Swans, as illustrated in Figure 2, resulting in antifragility.

Bounded Right

There are three factors to be controlled in order to achieve risk averseness: size, concentration, and speed of accumulation of risk (Taleb 2012). The management of these three factors is very similar to the development of static robustness.

The size of the components within an urban water system should be controlled so as to avoid overreliance on any single piece of infrastructure. Additionally, antifragile systems should be composed of layers of redundancy so as to avoid catastrophic failure. Therefore, an antifragile water supply system wouldn't be reliant upon a single source of water and would utilise a diversified water supply system. This would take the form of a set of robust water resource solutions including household collection, reservoirs, and reverse osmosis systems. In doing so, the failure of a single system would not result in an inability to deliver water. This would be similar to the systems employed as part of Singapore's Four National Taps policy (Tortajada 2006). For urban flooding, the magnitude of risk can be controlled through the use of flood rings. These would partition floodwater and provide a barrier between different regions of a flooding city. These would limit damage and a breach within one ring would result in only limited damage in the city, this is similar to the Dutch System of dike rings (van Herk et al. 2014). Risk could also be managed through the use of Sustainable Urban Drainage Systems which offer distributed protection.

High concentrations of risk can result in unacceptable levels of damage, even when only small system failures occur. The purpose of water supply is to deliver sufficient quantities of water such that citizens can have a comfortable existence. As such the concentration of risk is strongly linked to fresh water demand. By limiting the demand for water from it is possible for periods of poor water resource replenishment to pass unobtrusively. For flooding, with regard to the concentration of risk, two distinctions can be made. With government controlled assets and structures it can be ensured that pieces of critical infrastructure such as energy transformers, pumping stations, police stations and hospitals are not concentrated within a small area. This would ensure that flooding would not cause widespread system failure. Controlling the concentration of risk that emerges from the private sector can be more difficult given that certain areas are inherently more attractive places to reside in. The locations of individuals and businesses can be controlled through the planning system but also through the use of mandatory flood insurance with premiums priced according to their flood risk. These premiums can be used to improve and maintain flood defence infrastructure as appropriate.

The speed with which failure occurs is of critical importance. Under favorable conditions optimization occurs, resulting in efficient but more fragile systems, however the avoidance of small mistakes may result in making the large ones more severe. This speed of failure would be established utilising a stress-test methodology, such as the Adaptation Tipping Points approach (Gersonius et al. 2012; Kwadijk et al. 2010; Reeder & Ranger 2011). The problem of widespread failure is compounded if water-energy links are considered.

While it is envisaged that there would be a diversity of solutions within a catchment there would also be a diversity of solutions between catchments. Under conditions of drought some catchments will perform better than others due to differences in meteorological conditions and supply systems. This would necessitate water transfers to alleviate shortage. A catchment that has an excess of water can use its redundancy and utilise this connectivity to sell its water through a water market. This connectivity and responsiveness provides an opportunity for both catchments involved. However, vulnerability occurs when this connectivity does not have responsiveness. Water transfers should be utilised as means to “top-up” failures in supply. Permanent water transfers create tele-connections of risk, where a catchment that receives water is reliant upon the weather elsewhere. In the case of Hong Kong, 80% of water is imported from Mainland China, due to this Hong Kong’s water supply is closely tied to weather conditions outside its own borders (Wang et al. 2016).

Bounded Left

The infrastructure systems described above and known as “bounded right” results in a very robust water supply system. Optionality is the agent of antifragility and differentiates antifragile systems from those which are simply very risk averse. An option allows for the creation of antifragility and while not “risk-seeking” per se it allows one to benefit from the positive side of uncertainty without serious harm from negative events (Makridakis & Taleb 2009). For infrastructure systems, this optionality would take the form of Real Options. Based on financial options, real options give the holder the right but not the obligation to perform a task in the future. These rely on a relatively small increase in capital investment cost to allow for increased operational flexibility. This translates to the ability to limit the effects of negative conditions and take advantage of uncertain ones (de Neufville & Scholtes 2011; Myers 1984; Trigeorgis 1996; Wang & Neufville 2004). The more flexible the option, the greater the benefit. Real Options have been found to increase the value of a project by 30% and have been found to generate positive value for urban supply and drainage systems (Deng et al. 2013; Zhang & Babovic 2012; Zhang & Babovic 2009). Optionality has the added advantage of allowing for a faster construction period due to elements of the project having been effectively completed in advance. Large infrastructure projects require long time periods to be conceived, constructed and to implementatted while smaller increments can be built quickly even if they run in parallel across a wide area. Operational research has found that “it is the size per segment of the project that matters, not the entire project” that are indicative of the total time to completion (Flyvbjerg 2009).

As optionality becomes increasingly ingrained into urban water systems through maintenance or construction of new infrastructure systems the speed with which they can be adapted will increase. Additionally with decisions delegated to the local level the speed of decision-making will increase thus further improving the rate of adaptation

Lastly, many project concepts are more successful in theory, than on a practical basis. It is critical that a wide variety of small scale, experimental projects are utilised to help establish which solutions are most suited for a given catchment. These projects should and deliver positive asymmetries with regards to system knowledge and will help guide climate change adaptation.

Smart Cities, Data & Evolution

A second variety of antifragility occurs at the informational level. This variety of antifragility is evolutionary and grows stronger from one catchment’s struggle to operate a reliable service in the face of a hydrological shock. The lessons learnt regarding the operation and efficacy of infrastructure during times of stress should be shared in order for other catchments to modify their policies accordingly. The diversity between the urban water system is important as it allow for different strategies to be compared, allowing for the adoption and rejection of strategies based upon their performance.

The Smart City allows for the objective measurement of an urban water system's performance. Large data collected by the Smart City should be treated cautiously as they can lead to over-confidence in findings, As such only a modicum of data is needed to guide decisions and test potential strategies, therefore, the data collection apparatus does not need to offer infinitely fine temporal and spatial resolutions. This will reduce the noise present in the data and allow for easier identification of the signal. The data collection system needs to be structured in such a way that urban water managers are aware of the broader climatological trends and the performance of infrastructure within their system. The observation of climatological trends may require significant amounts of time however, some data will be made available immediately which may lead to decisions. For example, if a piece of infrastructure is frequently at or near capacity this would indicate a need to at least begin planning an intervention immediately.

The analysis of this data should result in heuristics that capture the majority of the information content. Of particular importance would be identifying which planning assumptions are incorrect and must be rejected. Given the complex nature of urban water systems, establishing causality will prove to be difficult but may be achieve through tools such as Granger Causality which measures the predictive ability of one time series to forecast another and has been found to be successful in identifying potential heuristics (Eichler 2011).

Local Urban Governance

As noted earlier, the development of an antifragile urban water system should be achieved by dictating managing to the local level. Local governance is best able to balance domain knowledge with local residents' desires and needs, thus resulting in a system architecture suited to local hydrological and social conditions. This allows for the creation of local confidence in urban water systems. By having these systems controlled through local structures, it is relatively easy to maintain direct accountability to citizens. Due to this they cannot indefinitely offload risk onto certain groups without repercussions through democratic processes.

However, it is clear that currently many if not most cities do not have an appropriate local governance structure for antifragility. Globally, there are substantial differences in the powers and responsibilities that cities have in relation to state or national governments. One global survey of cities found that only 56% of cities are the primary leader in controlling their city's utilities (Ricky Burdett et al. 2014). For effective management of an antifragile system, the locus of control of water infrastructure would require these powers to be devolved to either city or metropolitan governments. This may also require the transfer of vast amounts of responsibility and control over the infrastructure necessary to manage a modern water system.

Under systems with private water utilities, once local governmental oversight is established a large degree of co-operation will be required from the utility. The antifragile paradigm in many respects runs counter to the traditional view of optimizing infrastructure procurement. This is as the bi-modal strategy requires the construction of very robust infrastructure and real options , both of which would increase capital costs.

Conclusion

The development of antifragility in urban water systems offers a paradigm through which systems can continually evolve to better face the challenges caused by a changing world. This paradigm would result in water-independent regions which have the ability to trade water and information in order to strengthen the cohort's ability to withstand hydrological stresses.

There are practical difficulties associated with the antifragile model that would need to be addressed for such a system to be applied in practice. The first is that local government will require a high degree of control over their water systems that is not normally available. Further, the nature of antifragility is such that it is not "efficient", antifragility requires infrastructure which is bounded right, resulting in a system more robust and expensive to construct than the current method of 'lean' development. Additionally, infrastructure which is bounded left may be constructed but not utilised for many years or decades which could be perceived as a failure to make efficient use of public finances. Lastly, the antifragile model places a fairly high degree of burden on the local managing organisation requiring a much quicker cycle of continual observation, decision making and acting. However, this model offers significant advantages in dealing with variable hydrological conditions, which are expected to occur in the medium to long-term future.

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