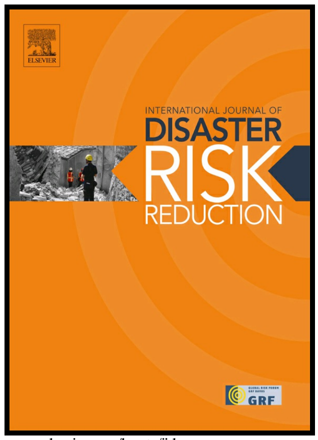

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From engineering to evolutionary, an overarching approach in identifying the resilience of urban design to flood

Mohanad Abdulkareem, Hisham Elkadi, Mohanad Bneane

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From engineering to evolutionary, an overarching approach in identifying the resilience of urban design to flood.

Mohanad Abdulkareem [a]. Prof. Hisham Elkadi [b]

[b] Head of school of Built environment, University of Salford, M5 4WT.UK.

[a] UPRISE, school of Built environment, University of Salford, M5 4WT.UK.

Abstract

Resilient urban design has become an essential theme for cities to withstand the rapidly escalating natural and human-induced disasters, yet cities and their infrastructure are becoming vulnerable and more threatened as the flood protection measures are still following the same line of thinking of flood control structures. There is an urgent need for new approach for resilience steaming from the urban form itself, beyond the focus on construction-based infrastructure like dams, levees and or channelization.
This paper is presenting an introductory sense of urban form resilience building on the resilience definition of maintaining the minimum functionality of a system and how this conception can systemically corresponds with resilience perspectives. The aim is to develop a measurable sense of urban design resilience. Hence, the paper carried out theoretical investigation into two complementary domains; the urban design and resilience thinking. Finding out the urban form most essential commodity and to which one of resilience perspectives it could possibly associate to achieve resilient urban form. The paper is aiming at establishing a common ground where the two domains can possibly congregate. It also suggests possible effective future approaches using the principles of ecological and evolutionary resilience.

Key words: Ecological resilience; evolutionary; urban design; pluvial flood; accessibility.

1. Introduction

"Floods are acts of God, but flood losses are largely an act of man." (Gilbert White, 1945)

Natural disasters including flooding, earthquakes and extreme weather events have escalated in recent years and increasingly capture attention on a global scale. Resilient urban design has become an essential theme for cities to withstand disasters, yet cities and their infrastructure are becoming vulnerable and more threatened; and flood protection measurements are yet to adapt their approach to the principles of resilience found in the natural world. Conventional structures of flood protection are increasingly questioned among academics, decision makers and communities, and new approaches are urgently needed at local and regional scales. In this sense, Hall et al. (1997) affirmed that explicit assessment of risks has in the past tended to be limited to the appraisal of major decisions to invest in flood defence infrastructure.

This paper highlights the potential role of using ecological principles in urban design to mitigate flood consequences. It identifies the minimum acceptable level of functionality from which urban systems can bounce back/forth or forward from a flood disaster to a state of equilibrium. In order to realize this objective, an exploration of the nature of resilience pivotal dimension will be identified. This is going to be envisioned in connection with the characteristics of urban design. The theoretical basis of urban design main commodity will be examined due to realize the essential functionality required during and after flood event.

From epistemological perspective, and in the light of the escalating environmental inevitability, solution for the problem within urban design discipline can be realized into two interrelated urban levels:

1-**Urban Innovation:** responsive change achieved by advancing the technical properties of manmade objects and materials over the ground and the geotechnical aspects of the ground itself to account for a more adaptive performance in times of flooding.

2-**Urban Regeneration:** which relies on the urban design capacities to invest in inherent resilience and develop a flood-responsive physical urban form.

The paper is shedding the light on the second level, identifying the resilient value of urban design in correspondence with the relevant resilience perspective. Although the field of urban design is very well established and clearly addressed, and the resilience line of thinking witnessed a considerable theorizing throughout the last decade, yet, potentials of association between urban design and resilience are awaiting realization.

The author is not claiming to address the full nexus between resilience thinking and urban design, rather an initial effort to specify where the urban design as a discipline systemically meets the resilience thinking and on which resilience perspective. Though, the study offers quantifiable approaches in applying selective ecological-built resilience scenarios.

2. The significance of physical dimension in urban design to flood

This section will cover the importance of the physical aspect of urban design, as it is the main boundary where the final configuration of the urban form formulated, although cultural, social and economic characters of the city are within significant importance, but it is the geometric configuration of the urban form that is going to confront the flood impact in the first place and draw associated consequences.

Town and country planning might be described as the art and science of ordering the use of land, buildings allocation and communicative routes, in the sense in which we are concerned with it, deals primarily with land, and is not economic, social or political planning, though it may greatly assist in the realisation of the aims of these other kinds of planning (Keeble, 1952). In the same perspective, the second national assessment on natural and related technological hazards cites land use planning as the single most promising approach for bringing about sustainable hazard mitigation (Burby *et al*., 2000).

“The idea of town planning was essentially about physical design, and hence involved producing blueprint plans for future urban form" Taylor (2004, p.17). A physical disturbance in the built environment will affect the functioning of human society and economic and social development of the country, due to its strong connection with human activities, and therefore achieves a resilient built environment is of paramount importance for resilient cities (Valdes, Amartunga and Haigh, 2013). Pescaroli and Nones (2016) also referred to the functional vulnerability to address the implications of disrupted physical networks on the urban life in prone and non-prone areas as cascading impact. Likewise, White (2008) confirmed that; resilience approaches should not come late with structural and non-structural solutions; rather, they should be developed systematically within the core of the urban planning process.

Urban planning can play a central role, through its ability to integrate multi-dimensional aspects affecting disaster risk reduction, planning has inherent capacities: to systemically and comprehensively influence the location and design of urban development (Leon 2014, p.251). Before the appearance of mankind on Earth, the purely natural system ruled our planet. Many geophysical events such as earthquakes, volcanic eruptions, land sliding, and/or flooding took place threatening only the prevailing flora and fauna. Millions of years later, the human presence transformed the geophysical events into natural disasters by hazardous exposure (Ayala , 2002). In the same sense, flood as a natural hazard, has been seen as a physical event which makes an impact on human beings and their environment (Alexander, 1993). The flooding system includes the physical process of flooding, the inhabitants of floodplains, their infrastructures and ecosystems, and the people and organizations in the public and private sector that influence or are subject to flooding and its impacts (Hall, Meadowcroft, Sayers & Bramley, 2003).

Hence, the significance of flood as geophysical phenomena is stemming in great sense from its physical mode of occurrence as it is physically influencing the natural and manmade settings. This paper therefore, invest in the role of the urban design-as a physical dimension-in addressing floods, and will offer an alternative view of resilience. Considering urban areas as key for a solution rather than a boundary of a problem, as the previous discussion showed evident benefits associated with exploring the potential role of urban design to achieve resilient response to flood. However, more clarity is required on the key parameters, elements, measurements, or characteristics of the urban form that can potentially promise a resilient state, and also how these parameters, or characteristics influence a city's resilience to flood. Therefore, both theoretical analysis and quantitative methods will be applied in this study to stand on those concerns.

3. The insufficiency of the resistance mode of flood infrastructure

One of the early calls to shift thinking in storm water management from the conventional flood protection infrastructure to more adaptive and creative solutions was made by Malmquist and Bennerstedt's (1997); They stated that; for the moment, we are forced to take temporary measures but the real challenge in storm water management is to find more environmentally sound materials and technologies. In the long-term, it will be necessary to change also our habits and life style. Similarly, calls for a transformation in urban design involves moving beyond a focus on construction-based interventions or simple sequential land-use modes of governance aimed at flood risk 'defence' and/or 'accommodation'. Instead, it entails a holistic reassessment of the relationship between the built and non-built components of urban environments (O'Neill & Scott, 2011). Likewise, Pescaroli and Nones (2016) confirmed that the increased knowledge of globally networked risks and the sensibility of their interdependencies required a shift in the paradigm of knowledge. Ning (2006) also referred to this essential shift in thinking when he asserted that fostering the concept of transferring from flood control to flood management and promoting the harmonious coexistence between man and flood is an important action to carry out scientific development and new water management concepts, and has vital and far-reaching significance in both theory and practice.

In most of the countries that witness extreme events that lead to flooding, flood prone areas are managed by defensive structural measures. According to UNISDR (2009); structural measures are defined as: 'any physical construction to reduce or avoid possible impacts of hazards, or application of engineering techniques to achieve hazard- resistance and resilience in structures or systems'. In the same report, the UNISDR state that it is possible to reduce the probability of a flood with new defences but still increase the overall risk by placing vulnerable receptors behind the defence thereby increasing the overall consequences. Modern flood risk management no longer relies solely upon engineered flood defence structures, such as dikes, channel improvement works and barriers. It also considers a host of other measures that may be used to reduce the severity of flooding (e.g. land use changes in upstream catchments) or reduce the consequence of flooding when it does occur, by reducing either exposure or vulnerability (Hall & Rowsell, 2001). Nevertheless, Pescaroli and Nones (2016) mentioned that the shift in considering non-structural modes of flood protection only arose in the early nineties.

Potential threats associated with dam failure as the worst type of flood event as, when a dam fails, a gigantic quantity of water is suddenly let loose downstream destroying anything in the path (Gustin, 2004). Similarly, in disaster management, Alexander, (2013) referred to the significance of the physical dimension of urban critical infrastructure by viewing it as central elements in a widespread network of risk, because, for the most part, they have physical attributes as well as functional and organisational ones. Concerning Flood mitigation, the theory and measurement of flood management both indicate that flood adaptation should replace flood control in order to build urban resilience to floods (Liao, 2012). Ning (2006) also confirmed this argument by saying that: we understand that exclusive dependence on flood-control works is insufficient and falls short of the objectives of reducing losses. Batica, Gourbesville1, and Hu, (2013) confirmed that the flood risk is not only a threat to the city and its inhabitants, but also one of the essential components of urban structure and the evolution of its urbanisation. Therefore, the attention of this paper is drawn towards an urgent need for new approach for resilience steaming from the urban form itself, beyond the resistance-based flood infrastructure like dams, levees and or channelization.

4. Pluvial flood as an elusive phenomena

Among all types of urban flooding, pluvial flooding (rain related) are the hardest to deal with. This is due to the fact that pluvial flood is different in terms of direction where the source of threat is coming from, their courses of occurrence can take different scenarios in terms of intensity and location, and so in an urban area the threat can happen anywhere according to the circumstances of the precipitation. For the reasons of uncertainties regarding intensity and location of its occurrence, Houston et al, (2011) addressed ‘pluvial’ (rain-related) floods as the invisible hazard, as they are less well known by the general public, and less well understood, their courses of occurrence termed with short intense downpours that cannot be quickly enough managed by the drainage system or infiltrated to the ground.

Pluvial flood can be generated from two types of rainfall events, convective and advective rain falls, the characters of these two types of rainfall in terms of time scale and intensities are remarkably altered. Convective events have a small spatial extension (not more than few tens of km2), also limited duration (few hours) but high rainfall intensities, while advective events results in large region being affected by the rain over a long period of time with relatively smaller rainfall intensities (Niehoff, Fritsch & Bronstert, 2002).

For reasons associated with difficulties in tackling pluvial flood, this paper will try to find new pathways to achieve urban resilience to flood, as prototypical modes of infrastructure defences proven sustain inefficiencies in dealing with this illusive power of nature. The focus will paid to how successfully the physical character of both urban form and adjacent ecology congregates with resilience perspectives in order to achieve resilient response to flood.

5. Defining resilience

This section introduces the concept of resilience and its parameter according to the urban design elements and characteristics that will be measured. The Oxford English Dictionary defines resilience as: ‘the act of rebounding or springing back’. The term resilience is derived from the Latin root 'resi-lire' meaning to spring back (Windle, 2010). However, the 1960s witnessed the emergence of notions of resilience within the field of ecology where multiple meanings of the concept emerged with each rooted in different world views and scientific traditions. By 1973, Holling coined the term resilience for ecosystems as a measure of the ability of these systems to absorb changes and still persist, and to determine the persistence of relationships within an ecosystem; it is widely recognised that Holling was the first to present the term in ecology (Kreimmer, Arnold, & Carlin 2003). Nevertheless, theoretical investigation reveals that the term's early appearance dated back to 1874 when R.H. Thurston, an American engineer and the first Professor of Mechanical Engineering at Stevens Institute of Technology, described the resilience of timber wood in machinery parts concerning a membrane facing physical stress before it breaks apart (Thurston, 1874).

The 2009 report by UNISDR defines resilience as: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.

In urban planning, the study of resilience began in the late 1990s. At that time, discussions on resilience focused on developing strategies to mitigate environmental threats. This was often related to the physical and infrastructure improvements to prevent the occurrence of disturbance (Pei-Wen, 2014, p.27). Meanwhile, resilience in urban design referred to the ability to respond to a contemporary sense of complexity, uncertainty and insecurity and to set up a new approach or priority for adaptation and survival Christopherson, (2010). In contrast, in flood hazard management, the use of resistance was more likely to be used to measure the flood prevention performance of a flood-control infrastructure (Liao, 2012). From the same perspective, Liao stated that, in flood hazard management, resistance means flood prevention by a flood-control infrastructure, while resilience is the rate of return from a flood-impacted state to a normal pre-disaster state.

To conclude, resilience is a concept that is applied in various disciplines and different fields, including geography, engineering, psychology and ecology. One common thread among these disciplines is the ability of materials, individuals, organisations and social-ecological systems, from critical infrastructure to rural communities, to withstand severe conditions and to absorb shock Weichselgartner and Kelman (2015). However, definitions are still being formed within the different disciplines at different rates and thus, this fluidity must be taken into account.

6. Resilience perspectives

Three main perspectives of resilience surfaced when the idea was discussed nearly around the early seventies, C.S.Holling, an ecology scientist firstly discussed the idea of engineering resilience in static engineered systems to build a comparison with the ecological resilience in bio-systems. Evolutionary resilience emerged later discussing the main idea of resilience in more dynamic economic, cultural, social and other human systems. Those systems known as the soft systems compared to engineering and bio-systems, they account in the first place for relational and organizational aspects. The following section will discuss resilience three perspectives, engineering, ecological and evolutionary, addressing the characteristic of each perspective and its association with the urban design.

Holling (1973) defined **engineering resilience** as the ability of a system to return to an equilibrium or steady-state after a disturbance. While, resilience in infrastructure systems defined as the ability to reduce the magnitude and/or duration of disruptive events (Francis & Bekera, 2014). The effectiveness of a resilient infrastructure depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event. In this perspective, the resistance to disturbance and the speed by which the system returns to equilibrium is the measure of resilience, the faster the system bounce back the more resilient it is. It is a fail-safe strategy. Therefore, the emphasis is on return time, efficiency, constancy and predictability, all of which are sought-after qualities for a "fail-safe" engineered design (Davoudi, 2012). Figure 1 explains the idea of engineering resilience measured by the rapidity of the process by which a stressed system restores its original stability.

Engineering resilience exists in nature. The Axolotl salamander1, shown in Figure 2, is a superhero of regeneration and a salient case. It has the ability to replace lost limbs, damaged lungs, and a sliced spinal cord; it can even renew bits of its damaged brain. When the salamander loses a leg, a small bump forms over the injury called a blastema2. Given its lifespan of approximately 12 years, it takes around three weeks for this blastema to transform into a new, fully functioning replacement leg. Figure 2 shows the transformational phases. This ability is a fact of nature, and it is suggested that researchers should learn how to replicate it in human systems (Zielins et al, 2016).Scientists have long credited the capabilities of the Axolotl Salamander, because its cells have the ability to morph into whatever appendage, organ or tissue happens to be needed or due for replacement (Hoover, 2014). The current focus is now on understanding the process so that it hopefully stands for reverse engineering to human therapies (Godwin, 2009). Replicating the logic and mechanism by which this creature can successfully reproduce and replace a damaged organ can be helpful in studying and efficiently applying engineering resilience.

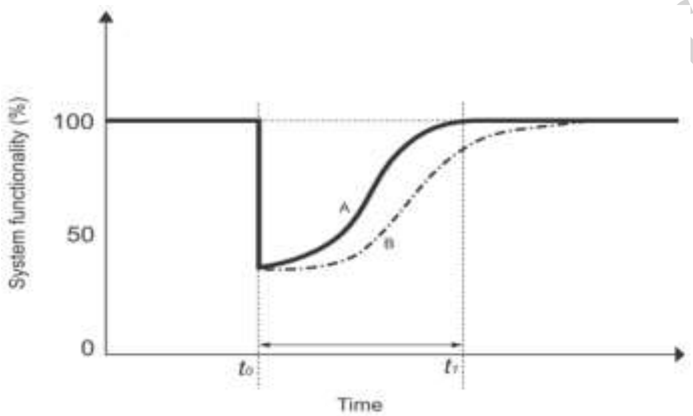

Figure 1: Engineering resilience (Liao, 2012)

The regeneration process of the salamander resembles engineering resilience: the ability to restore an amputated limb to an original state without even a scar highlights the philosophical comparison between resistance and resilience. Resistance is an expression of conventional flood engineering infrastructures, while resilience reflects the crucial role of urban design in facing stressors. The amphibian can still walk while its body's biological mechanism replaces the lost limb. In urban design, resilience resembles maintaining the ability 'to walk', while other partners and systems in the city 'replace the amputated limbs'.

[1] Axolotl Salamander: any of several aquatic salamanders of the North American genus Ambystoma, esp A. mexicanum (Mexican axolotl), in which the larval form (including external gills) is retained throughout life under natural conditions: family Ambystomidae. (dictionary.com).The name "Axolotl" comes from the Aztec language, "Nahuatl". One of the most popular translations of the name connects the Axolotl to the god of deformations and death, Axolotl, while the most commonly accepted translation is "water-dog" (from "atl" for water, and "xolotl", which can also mean dog).(axolotl.org).

[2] A group of cells that gives rise to an organ or part in either normal development or regeneration.(medical-dictionary.com)

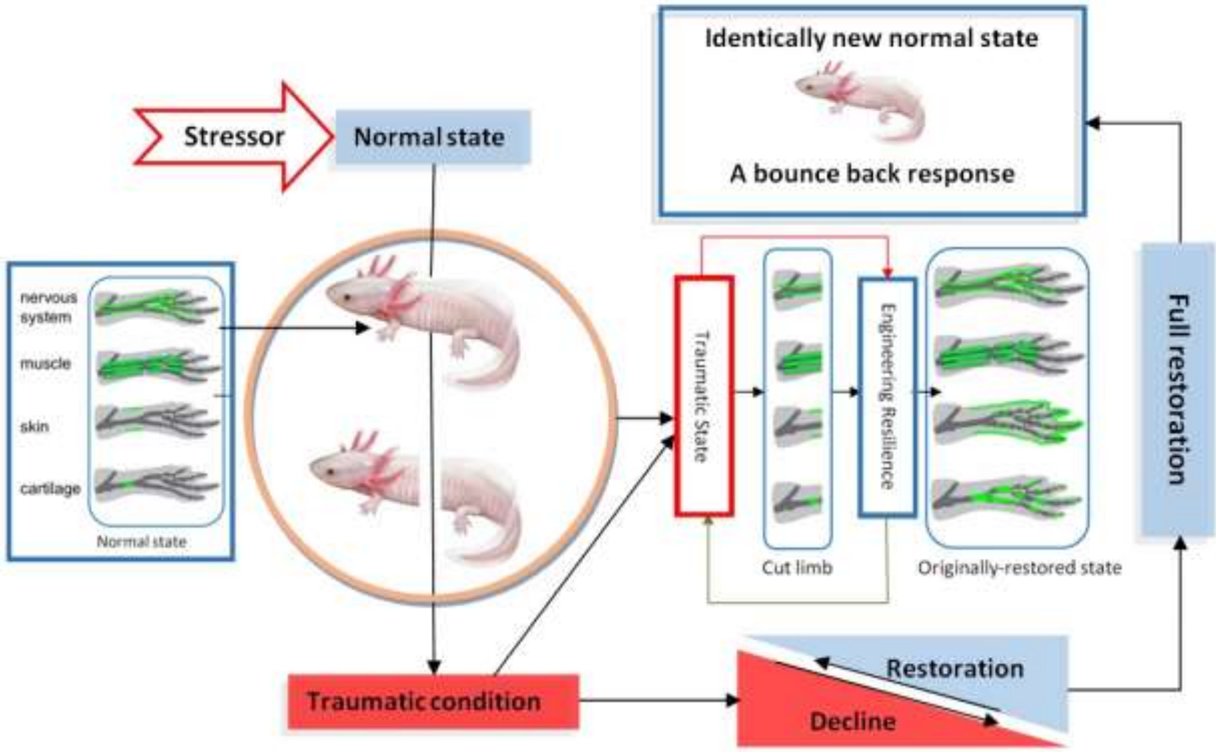

Figure (2) Salamander regeneration process

The regeneration process of the salamander resembles engineering resilience: the ability to restore an amputated limb to an original state without even a scar highlights the philosophical comparison between resistance and resilience. Resistance is an expression of conventional flood engineering infrastructures, while resilience reflects the crucial role of urban design in facing stressors. The amphibian can still walk while its body's biological mechanism replaces the lost limb. In urban design, resilience resembles maintaining the ability 'to walk', while other partners and systems in the city 'replace the amputated limbs'.

Ecological resilience is defined as, 'the magnitude of the disturbance that can be absorbed before the system changes its structure' (Holling, 1996, p.33). Accordingly, ecological resilience is not only defined by the time that the system takes to bounce back after a shock, but also the how much disturbance it can take and still remain within the critical thresholds. In identifying the main difference between ecological and engineering resilience, Davoudi (2012, p.301) stated that ecological resilience rejects the existence of a single, stable equilibrium and instead acknowledges the existence of multi equilibria, and the possibility that systems flip into alternative stability domains. Davoudi also ordered the distinctions between the two perspectives to consider the notion of a stable equilibrium, 'be it a pre-existing state to which a resilient system bounces back (engineering) or a new state to which it bounces forth (ecological) (Davoudi et al, 2013).

"The idea of design for ecological versus engineered resilience in socio-technical systems is an emerging concept that advocates the design of engineered systems based on the ecological principles of diversity, adaptability, interconnectedness, mutual evolution, and flexibility" (Francis, 2014, p.93). Ecological resilience is focused on systems far from any equilibrium steady state, where the system could turn over into another regime of behaviour (Batica, et, al 2013). This conception is facilitated by Jones and Holling's (1975) understanding between the two perspectives (engineering versus ecological), as stated earlier; this is the difference between a safe-to-fail strategy, which resembles the ecological perspective, and the fail-safe strategy, which resembles the engineering perspective. Figure 3 represents the threshold stages upon which systems bounce-forth in ecological resilience.

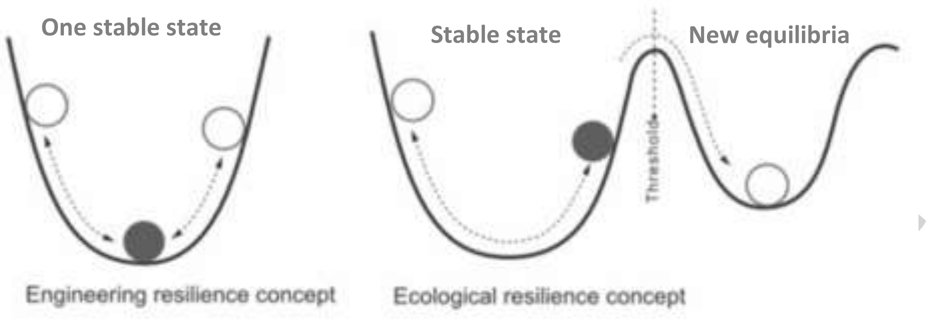

Figure 3: Ecological resilience concept (Liao, 2012)

An example of an ecological resilient-based response can be seen in the type of housing people developed in the Himalayas' seismic-active regions. Sharma (2001, cited in UNHS, 2007) stated that indigenous people living in the Himalayas regions developed a type of vernacular house that was build to survive frequent earthquakes; the Kat-Ki Kunni house, Figure 4. The replacement of stone built houses with a new type of building where wood bonding was arranged in vertical intervals with mud masonry from the outside to give the structure flexibility for earthquake resistance (shown in Figure 5). Even though these were multi story buildings, Kat-Ki Kunni were the last standing structures after the Kangra earthquake hit the Himachal Pradesh region in 1905.

Figure 4: The Kat-Ki Kunni house
materialinks.wordpress.com

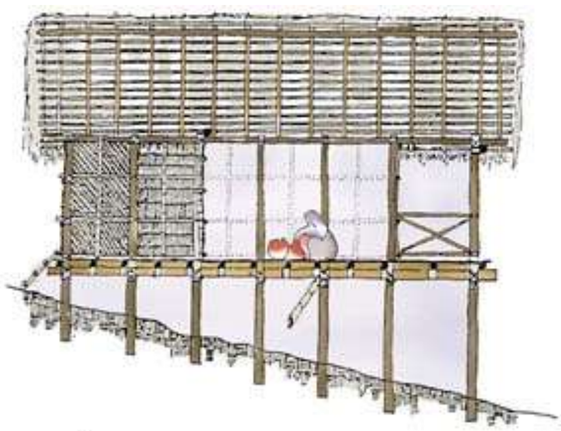

Figure 5: The Kat-Ki Kunni house structure
downtoearth.org

The ecological resilience of the Kat-Ki Kunni manifested in departing from the previous non-efficient stone-based type of building to an entirely new, eco-compliant wooden-based structure. The new type of buildings represented a shift from the old stone building state to the new stable state (addressed earlier as new equilibiria) but within the same ecological regime. This new equilibiria was achieved by adopting ecologically reliant material like wood, which was ecologically abundant, and a physically feasible structure, that used wood bonding in vertical intervals.

The third key perspective is **evolutionary resilience**. Evolutionary resilience challenges the whole idea of equilibrium stating that the system may change over time with or without an external disturbance. Some commentators call this socio-ecological resilience. It is defined as not returning to normality (the pre-disaster state), but rather as the ability of complex socio-ecological systems to change, adapt, and, crucially, transform in response to stress and strains (Davoudi, 2012). Shaw, (2012) argued that rather than seeing resilience as a process of bouncing back, a more radical deployment would view it as a dynamic process in which change and constant re-invention provide for social, economic, and/or environmental strength. Furthermore, Francis (2014) defines socio-economic resilience as the ability of the system to maintain its identity in the face of change and external shocks and disturbances. The components of this system, the relationships among these components, and the ability of these components and relationships to maintain themselves constitute the system identity.

Evolutionary resilience is embedded in the recognition that the seemingly stable state that we see around us in nature or in society can suddenly change and become something radically new, with characteristics that are profoundly different from those of the original (Kinzig, 2006). Meanwhile, Davoudi (2012) mentioned that evolutionary resilience is principally the vehicle for the adaptation and evolution of dynamic natural and social systems. Advances in evolutionary resilience have been made largely in the fields of social and ecological systems. In contrast, in the built environment, the *inertia* of urban form emerges from a combination of undiminished geographic advantages, long-term investment in infrastructure, and place-dependant business networks (Vale & Campanella, 2005.p.346).

calls for a transformation in urban design involves moving beyond a focus on construction-based interventions or simple sequential land-use modes of governance aimed at flood risk ‘defence’ and/or ‘accommodation’. Instead, it entails a holistic reassessment of the relationship between the built and non-built components of urban environments (O’Neill & Scott, 2011). Likewise, Pescaroli and Nones, (2016) called for new assessment methodologies to integrate social, physical and structural drivers, taking as reference, respectively, the community, environment and buildings in defining the sensibility of areas to flood-triggered cascading. In the case of evolutionary resilience, the transformability character, which calls for a departure to a new regime, is a crucial threshold. It is unlike ecological resilience, which is measured by the readiness to tolerate stressors while exhibiting one ecological regime. Instead, evolutionary resilience is a totally new stable state that the system successfully arrives at after the old ecological regime is destructed. According to its dynamic description, evolutionary resilience is more applicable to socio-economic systems, as discussed above. The evolving mechanism to new stable status can follow all the way through to full operationalisation in single or multiple stressing event/events, due to their system's non-static nature. Yet, it is difficult to spot such evolutionary responses in complex socio-economic systems like cities. Therefore, the following example was selected to exemplify the evolutionary resilience of a species that has a dynamic complex life style and survives a deluge by having the ability to undertake such a response.

Figure 5: fire ants' colony in normal and flooding situation. Adapted from inhabitat.com

Fire ants, shown in Figure 5, live in colonies in the soil. If a colony is flooded during rainfall, or other water-logging situations, the ants cling together and form a living raft that floats on the flood water (Adams et al., 2011). The pattern demonstrated by fire ants encompasses a number of mechanisms to survive a flood. The way the colony confronts this stressor, is by having all the valuable assets of the colony in the safest place, namely on the floating living raft. The queen is situated in the middle, maintaining the important identity of the colony and by saving the next generation by reaching the safety of the nearest dry land. Fire ants have the ability to set themselves free from the physical boundaries of their endangered shelter. The whole colony transforms into a transitory phase of a mobile colony to avoid drowning; thus, transformability characterises the resilience survival techniques of the fire ant.

In the case of evolutionary resilience, the transformability character, which assigns a departure to a new regime, is the crucial threshold. It is unlike ecological resilience, which is measured by the readiness to tolerate stressors while exhibiting one ecological regime. Instead, it totally departs for new stable state that the system successfully arrives at after the old ecological regime is destroyed or departed.

7. From engineering fail-safe towards ecological safe-to-fail response

Jones and Holling, (1975) distinguished between the two strategies of fail-safe and safe-to-fail. The goal of a fail-safe policy strives to assure that nothing will go wrong. Systems are designed to be foolproof and strong enough to withstand any eventuality. Efforts are made to radically reduce the probability of failure. Meanwhile, a safe-to-fail strategy acknowledges that failure is inevitable and seeks systems that can easily survive failure where possible. Rather than rely on reducing the occurrence of failure, this policy aims at reducing the cost of that failure. Later on, Holling (1996) identified the characteristics that discriminates the two strategies; a fail-safe strategy that focuses on efficiency, constancy, and predictability, which are all attributes at the core of engineers' desires for fail-safe design. In comparison, the safe-to-fail strategy focuses on persistence, change, and unpredictability; all of these attributes were embraced by biologists with an evolutionary perspective and by those who search for safe-to-fail designs. Contrary to the engineering resilience perception, Francis and Bekera (2014, p.100) stated that ‘efforts in design should be allocated to increase emphasis on “safe-to-fail” rather than “fail-safe” provisions’.

8. The essential commodity of urban form throughout natural stressor events

With the abundance of resilience definitions discussed earlier in general, and in describing different dimensions or systems within the complexity of the city context, there is still a common thread that came across in all resilience perceptions. That common understanding was about maintaining the minimum required level of functionality until full restoration is restored. The ultimate goal of resilience is the continuity of normal system function. Normal system function is to be defined according to the fundamental objectives obtained in system identification (Francis & Bekera, 2014). Although definitions of resilience differ, they imply that resilient cities can absorb shocks while still maintaining function (Chang, et al, 2014). Correspondingly, urban resilience will be addressed in this paper with a focus on urban form essential commodity t be provided throughout times of natural stressors.

Marcus Vitruvius identified three essential components of any architecture, which are commodity, firmness and delight. According to Vitruvius, the three components are not problems that can be solved in isolation from each other, but rather, architecture that must be considered simultaneously from the three perspectives (Daas, 2014; Jones, 2003). Building on the argument of the three essential components of architecture, the remainder of this section will try to chase the main commodity in the urban form through times of natural stress. This is to help steer efforts to achieve the minimum required level of functionality in the urban context, and thus achieve a resilience response.

Establishing cities’ resilient response required specific design for roads, utilities, and other infrastructure systems to continue functioning under extreme hazard conditions. Urban resilience to flood is about successful management and not about preventing flooding or even minimising flood losses. Instead, urban flood management is about maximising and maintaining the performance of a city as a whole (Zevenbergen, 2011). Likewise, the measurability of city resilience is related to the functionality of an infrastructure system after a disaster (Tierney & Bruneau, 2007). “Urban systems need to have in advance defined ‘conditions’ in order to have the proper level of functioning” (Batica, et, al, 2013, p.2). The assumption of resilience in urban design related to the essential function of the urban context throughout traumatic situations. Lynch (1981) identified five performance dimensions of urban design; Table 1 show cases these dimensions:

No.	Performance dimensions	Description
1	Vitality	The degree to which the form of places supports the functions, biological requirements and capabilities of human beings.
2	Sense	The degree to which places can be clearly perceived and structured in time and space by users.
3	Fit	The degree to which the form and capacity of space matches the patterns of behaviors that people engage in or want to engage in.
4	Access	The ability to reach other persons, activities, resources, services, information or places including the quality and diversity of elements that can be reached.
5	Control	The degree to which those who use, work or reside in place can create and manage access to spaces and activities.

Table 1: The urban form performance dimensions (Lynch, 1981)

The performance dimensions developed by Lynch covered aspects related to the perception of space, its aesthetic dimensions, and to human behaviour, while Access constitutes the essential commodity that can link together urban physical components of buildings, streets and blocks and the non-physical aspects of people's activities. Tarbatt (2012) also set out ten principles of urban design mostly based on socio-economic, convenience, and aesthetic factors, nevertheless, he addressed the first of these principles as; (more convenient access to facilities).

Access can maintain the flow of goods and services throughout the city during harsh times; when an urban landscape is understood as a system that performs functions, connectivity is often the critical parameter (Ahern, 2011). Smith & Ward (1998) mentioned that the consequences of flooding include the direct damage caused by the flood and the indirect disruption to society, infrastructure and the economy. Taylor (2004) also identified the indirect losses of floods as the cost of goods that will not be produced and services that will not be provided during the event and in the aftermath. Cities are resilient if they absorb shocks, maintain their output of goods and services, and continue to provide their inhabitants with a good quality of life according to the standard of time (Grosvenor, 2015). Similarly, Vale and Campanella (2005) confirmed that the simplest way to crash a network is to block or sever a crucial link.

Building on discussion above, and the insights gained from Tarbatt and Lynch's principles, in which both where were related to the perception of the space, its aesthetic dimension, and to human behaviour, access can constitute the chief commodity that links the urban components physical constituents and other non-physical activities. Moreover, the lack of connectivity is often a prime cause of malfunction or the failure of particular functions; thus, connectivity is arguably a primary generator of the sustainable urban form. Urban design, therefore organises, activates and links the ecological processes of cities encompassing the socio-economic networks, and as far as the fundamental objectives of the urban design is concerned, it is crucial to safely distribute these activates by properly allocating them through the city layout and effectively linking them by maintaining proper access. Accordingly, accessibility is the essential commodity of an urban form. Achieving a minimum required level of this commodity by flood responsive urban design will maintain the connectedness between the affected parts of the city, and correspondingly, is built for a resilience response.

9. Linking two theoretical domains, urban design and resilience perspectives

Building on the concept of engineering resilience, the main characteristics concern; firstly, regaining the same system stability in a timely efficient manner, secondly, a predominant emphasis on the system's functionality through its system efficiency, thirdly, the fact that engineering resilience promotes the desired system robustness, and finally, by looking at the first system state. This is a bounce-back labelled perspective.

Meanwhile, according to the nature of the bio-systems from which it emerged, ecological resilience calls for system multi-stability before the system shift into a new regime; it also considers system functionality. Ecological resilience relies on maintaining the existence of a system's function while undergoing external stresses, looking at the quality of the new system state. It is likely that such an approach addresses the contemporary urban form of resilience, where urban design helps to progressively absorb the flood impact to uphold new critical stability. It is this new stability in which urban design maintains a minimum required level of functionality, a safe-to-fail strategy with a bounce-forth perspective.

Transformability is the principal value that distinguishes evolutionary resilience from engineering and ecological resilience (Davoudi, et al., 2013). Evolutionary resilience considers the various levels of a system's response as a process for future desired trajectories. This goes all the way through an effective system change, looking mainly at the process of the system under stress, which has arrived at an entirely new stable state. Evolutionary resilience best fits social, economic and/or political systems. Although it is not unachievable in the urban form, it takes longer due to the lengthy process of cumulating experiences. This is also very much owing to the inertia of physical structures. Urban form can yield the benefits of the long process of its contemporary responses, reaching maturity and viability for evolutionary reconstruction. This achievement marks the culmination of a long-term process, a restructure strategy with a bounce-forward perspective.

Systemic inconsistency between the dynamic character of evolutionary resilience and the inertia of physical development in the urban context (Vale & Campanella, 2005), actually mark the inflexible physical constructions that shape our cities. The static nature of these long-term constructions customarily hindered the developmental natured policies and programs. Cheshire (2006) referred to the conflict between the dynamics of policies and programs, and the rigid nature with which the city structure is addressed. Cheshire stated that cities have so far appeared to be not just complex but rather robust systems. Thus, policy has had to be clearly demonstrable but often very unexpected and adverse effects. This seems to be mainly because of the inertia of cities. Cities have much more inertia than super-tankers and policy takes a long time to demonstrate any significant effect at all. One obvious reason is the durability of the built environment. Hall and Pennning-Rowsell, (2011) realised the shortcomings of stationary character by relying solely on the engineered solutions in flood management. They argued that modern flood risk management no longer relies solely upon engineered flood defence structures, such as dykes, channel improvement works and barriers. It also considers other measures that may be used to reduce the severity of flooding, such as land use changes in upstream catchments or to reduce the consequence of flooding by reducing either exposure or vulnerability. Therefore, the increasing recognition of nonstationary means of flood risk management is considered in order to face the ways in which flood risk may change in future.

Infrastructure is a critical foundation shaping the manifestation of cities within their ecological and social contexts. Infrastructure operates at the nexus of engineering systems, the natural environment, and socioeconomic systems (Allen, 2016). This paper addresses the notion of resilience within the physical dimension of both the urban form and the natural environment. Thus, the engineering domain is the base line on which the notion of resilience will be addressed, but it will not be the final station on which concluding assumptions will be drawn. The streamlining of resilience will count mainly for the perspectives of engineering and ecology due to their applicability and cohesion with research objectives. Table 2 exhibits how resilience is considered in the research by overlapping the characteristics of three perspectives of the term.

Characteristics	**Resilience perspectives**		
	Engineering	**Ecological**	**Evolutionary**
Domain	Human structures	Bio-physical	Socio-economic
Objective	Single stability	Multi-equilibria	New regime
Philosophy	Bounce-back	Bounce-forth	Bounce-forward
System function	Efficiency	Existence of function	Efficiency in new structure
Looking at	State	Quality	Process
Stability	Previous state	Within system Before shift	Transformability
Activity	Static	Bounded-dynamic Within-system dynamics	In momentum

Table 2: Characteristic of three resilience perspectives

As seen in Table 2, the characteristics of ecological resilience link two opposite stances of engineering and evolutionary resilience. The characteristics of the ecological sense intermediate the distance where the two far ends of the engineering and evolutionary stances can theoretically associate. An overarching approach represented in a balanced state between the rigidity and inertia of the engineering perspective and the dynamics of the evolutionary perspective can be found in ecological perspective; it encompasses the virtues of both these perspectives.

Ecological resilience mediates the distance between engineering and evolutionary resilience. Its virtues mainly manifest in the system departure towards a new stable state before it breaks apart, seeking a within-system new stable state. Ecological resilience also facilitates pathways to overcome the inertia and stationary of manmade structures by relying on the reliability of ecological solutions. The inertia of urban structures makes them difficult to examine through the holistic dynamic perspective of evolutionary resilience, especially over a short time span where the flood phenomena is taking place. Therefore, this paper is going to examine the resilience of urban design to pluvial floods in Muscat city from the perspective of ecological resilience. Table 3 outlines the cohesion between the ecological resilience characteristics and the urban design parameters.

Ecological resilience	Reflections on the physical urban context
Bio-physical	Generated morphology incorporates natural topology & urban morphology as one hydrological unit
Multi-equilibria	
Bounce-forth	Cumulative experience from ongoing events to place urban physical fixes
Existence of function	Minimum functionality (accessibility)
Quality	Providing Minimum required service
Within system Before shift	System altered internally within the same structure to meet future resilience response
Bounded-dynamic Within-system dynamics	(Restructured/Reorganized/Redistribute) within system new characteristics

Table 3: Reflection of ecological resilience in urban design

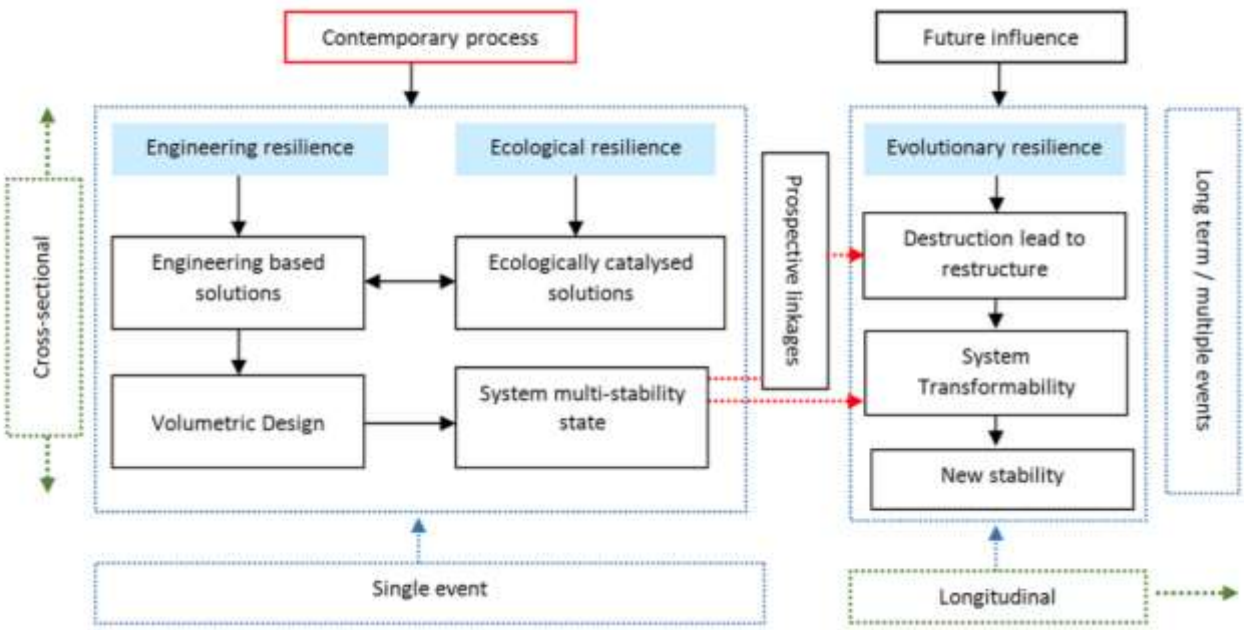

Figure 6: The process of contemporary and long term system's resilient response

The contemporary process in Figure 6 theoretically resembles the system's first resilient response to maintain essential functionality when undergoing external stressors by bouncing back/forth to previous systems or new stabilities. Correspondingly, with the system experiencing multiple stressors over time, the accumulation of experienced responses will initiate a system transformation from its old settings. Building on previous responses, and in due course, system ultimately bounces forward to entirely new stability. Figure 6 illustrates the relationship between urban design and resilience three perspectives against time factor, where frequent stresses from multiple events erode a system's structure, magnifying the overall maintenance cost, and hurdling the process of political decision making. This will ultimately shape the evolutionary response of the system over future courses.

10. Socio-economic limitations in adopting resilience surrogates

Courses of ecological and evolutionary resilience can vary in general logic dependant on time scale. This depends on a single or several extreme events. Figure 7 illustrates the ultimate achievable resilience response within ecological paradigm and the zone of departure from which the whole process leaps forward to a new regime preside over evolutionary paradigm. In another way, the ecological scenario could - under circumstances of increased mitigation cost - depart towards a new critical state that facilitates a shift to stability in a totally new paradigm.

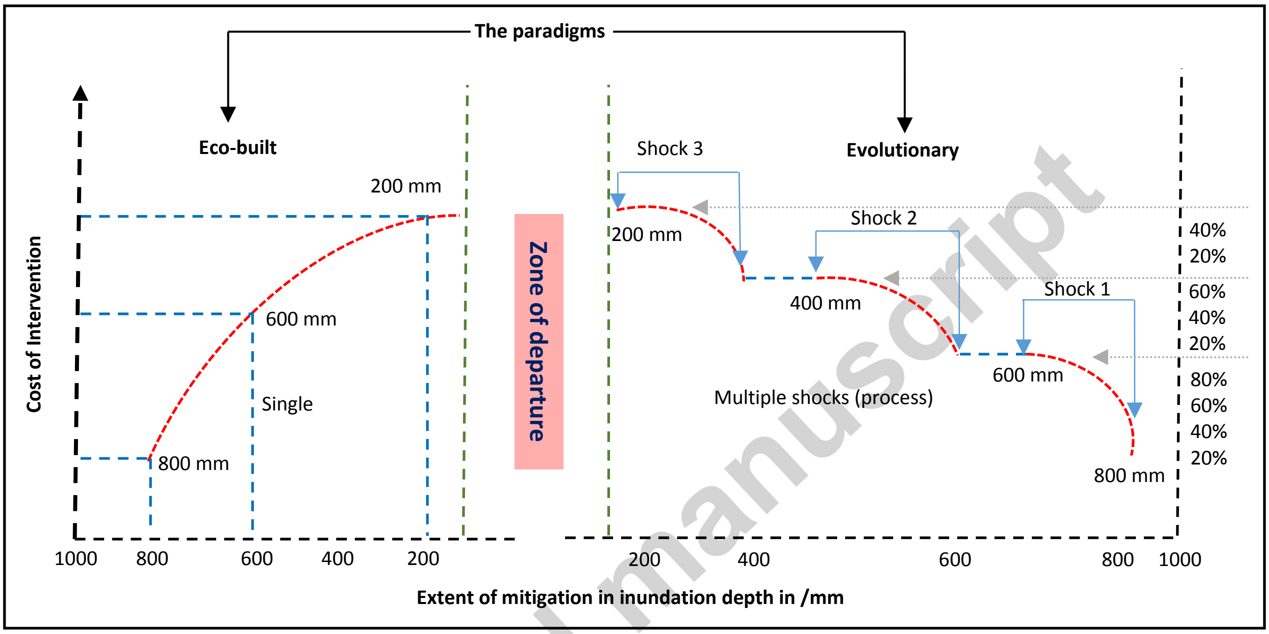

Figure 7: Threshold between two interrelated paradigms

This paper sets a call to depart from the conventional thinking of the urban infrastructure engineering resistance towards a new understanding of urban design ecological resilience. This is to efficiently cope with natural threats that are increasingly witnessed in terms of frequency, intensity and magnitude and to cope with the insufficiency of the flood infrastructures. Nevertheless, in existing prone areas, socio-economic challenges might emerge throughout the process of implementing ecological resilience scenarios.

In a case study performed in AlKuwair area, a flood prone area in Muscat city in 2016, the aim was to test the viability of ecological measures to mitigate flood consequences and maintain accessibility in the urban context in flooding times. The prone area is highly specialised and clearly clustered in terms of land use. Moving from the mountains at the upstream side all the way down to the sea coast line, there are three apparent types of land uses (residential, mixed-commercial, and administrative-governmental) dominating the area. They also outline four adjacent corridors lying perpendicularly on the main topographic gradient, Figure 8.

The development of residential district created early in the 1980's upstream and served by main traffic route. Recurrently, the area was developing towards the seaside; a commercial and mixed used corridor adjacent to the main traffic route was created, and was later dominated by the state ministry amenities to form another corridor, known later as the ministry district. The final urban expansion at the downstream side occupied with embassies amenities forming embassies district.

Figure 8: Urban corridors in Alkuwair catchment Google earth

An overarching approach of ecological resilience was developed to mitigate the flood problems in the area. Mitigation scenarios built upon the physical characteristics of both natural settings and the urban form. Suggested solutions were built mainly upon ecologically oriented parameters. The nexus between the physical dimensions of the urban form and the adjacent ecology was the main core of the developed scenarios.

10.1 Existing prone situation

The full flood magnitude of an event that occurred in 2007 was simulated; Figure 9; this was done before any intervention scenarios. The result of this simulation will build the comparison background for the mitigation gained from scenarios in terms of flood wave depth, direction and coverage area. Although depth and coverage area were the most important readings in the case of this study, the travel velocity of the flood wave was also monitored in HEC RAS through the event from the initial conditions to the end of event. No significant runoff velocity was found to be merit recording.

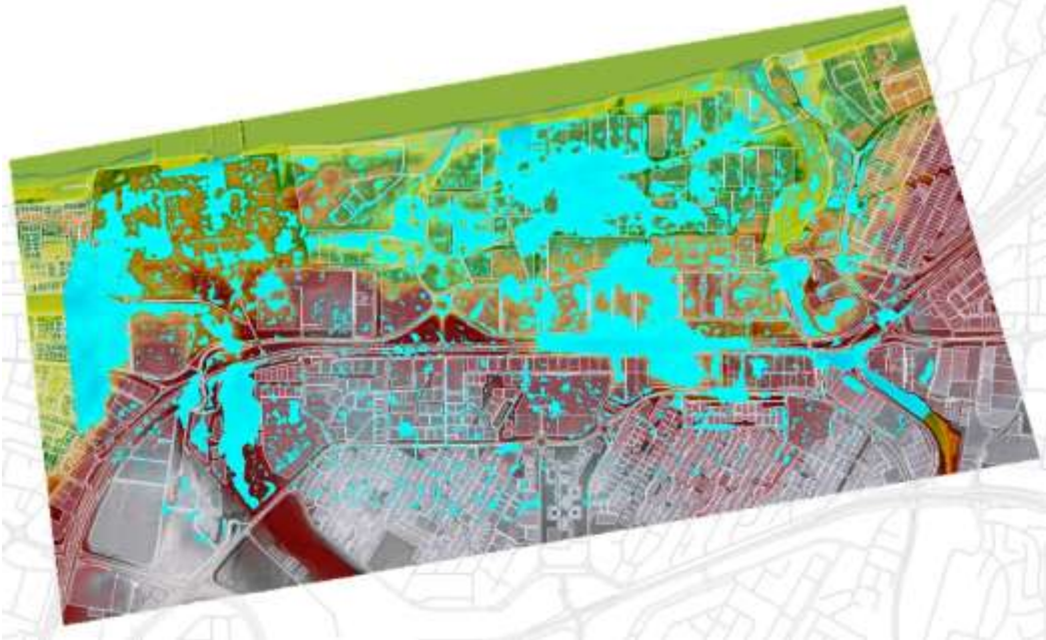

Figure 9: Flood magnitude end-of-event

Results

A profile line was assigned along the affected corridor, shown in Figure 9. This profile line depicted the peak of the event. A combined model of rainfall data and natural stream flow was built in HEC RAS platform. The module simulated an unsteady flow resulting from 16.5 hours of convective rainfall in the study area. The extent of the flood wave depth and coverage across the event period was indicated. The profile line shows the levels to which runoff depth and coverage were arriving. The area between 1.4 km and 2.3 km, in Figure 10, was heavily susceptible to inundation. A maximum depth of around 1.6 metres was recorded as a peak flood depth at some point on this part of the main street corridor.

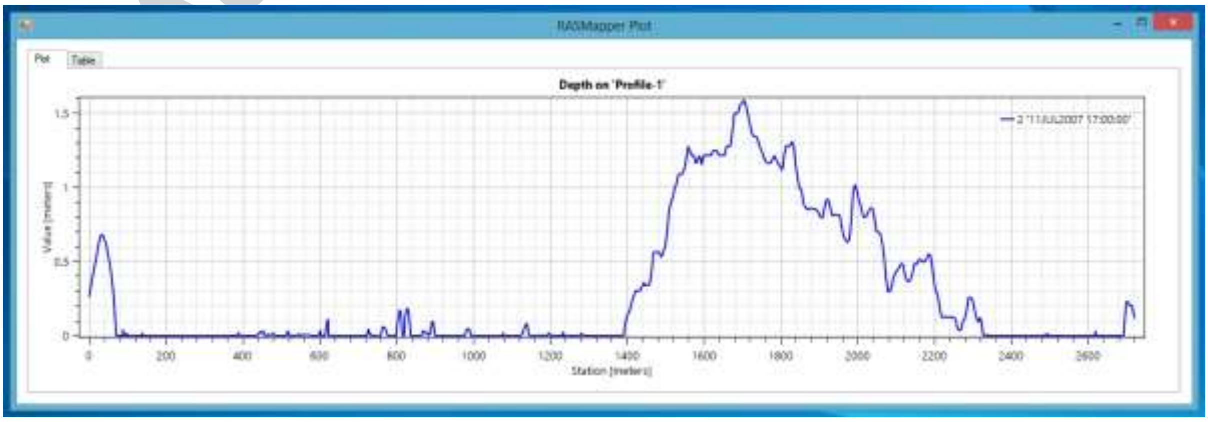

Figure 10: Existing flood situation profile line along the prone corridor

10.2 Scenario one: major stream restoration

The topography of the area was analysed in Arc GIS to trace the natural streams running in the area from up-to-downstream destinations. It was noticed that one major natural stream was eliminated 500 meters before its final connection with the sea. An urban expansion of roads and buildings had interrupted the stream course and completely wiping it out. At the end of the natural stream where it meets the sea, a desalination plant of potable water was established, Figure 11.

Figure 11: scenario-1 major stream extension to the sea

Despite the financial cost associated with the urban alterations to restore that natural stream, a strategic concern was on the top of the scene. This concern was associated with the safety of the desalination facility. Nevertheless, the study went on in building the simulation of the mitigation scenario restoring the path of the natural stream in Arc GIS and then allows the alterations to flood simulation in HEC RAS 5.0.3. Rain fall and natural stream flow data of an extreme event in the form of tropical cyclone that took place in 2007 was fed to simulation software. Simulation for the existing situation was established to be as the base line to where the viability of the mitigation scenarios will be compared.

Despite of the considerable reduction in surface runoff noticed from an initial flood simulation following the restoration of the natural stream by correcting its path all the way to the sea cost downstream, decision maker was reluctant to adopt this scenario due to the close proximity with a strategic desalination facility mentioned earlier.

10.3 Scenario two: Watershed connectedness through land use redundancy

The second Mitigation scenarios developed from four influential variables from three different morphological levels; urban morphology, ecology and nexus between the two mentioned dimensions. Those variables, along with their reflection in the area of study, are displayed in Table 4.

Scenario two variables and reflections		
Variables	**Variable orientation**	**Variable manifestation**
▪ Natural stream restoration ▪ Watershed connectedness	Ecology	▪ Natural stream course was restored. This was done in the virtual environment of Arc GIS giving interpolated geometric characteristics for this feature according to its starting and ending point. ▪ The restored natural stream was originally connecting the two major streams running across the study area. Having them connected as they were in their original context will meet the variable set to this scenario.
Land use redundancy	Urban morphology	Green area that covered the vanished natural stream was set to be part of natural stream network and flood process. In drying times it can be used as a luxury walking path by providing proper pedestrian pathways.
Gradient oriented route design	Nexus between built and ecological	The dual carriage way adjacent to the restored stream is already designed with cross sectional gradient towards the green area. This slope was causing a problem of surface runoff accumulation. With the restoration of the stream, surface runoff will steadily flow into the stream reducing the previous inundation depth to maintain traffic flow.

Table 4: Influential variables

Building up this scenario was based on the potentials of ecological setting and urban form reliability for physical alterations. The demolition of a previously existing natural stream under increasing urbanism has depressingly impacted the hydraulic performance of the area with respect to surface runoff. The restoration scenario was to bring this feature close to its previous setting and establish connectedness to the watershed. The cross section of the existing main street was already designed to have a gentle slope towards the natural stream, as it was naturally running parallel to the main street linking two bigger streams that ended at the sea downstream. Figure 12 outlines the area boundary’s initial conditions with the restoration of the natural stream before the event. Figure 13 exhibits the peak event of the flood wave demonstrated in the HEC RAS flood simulation platform.

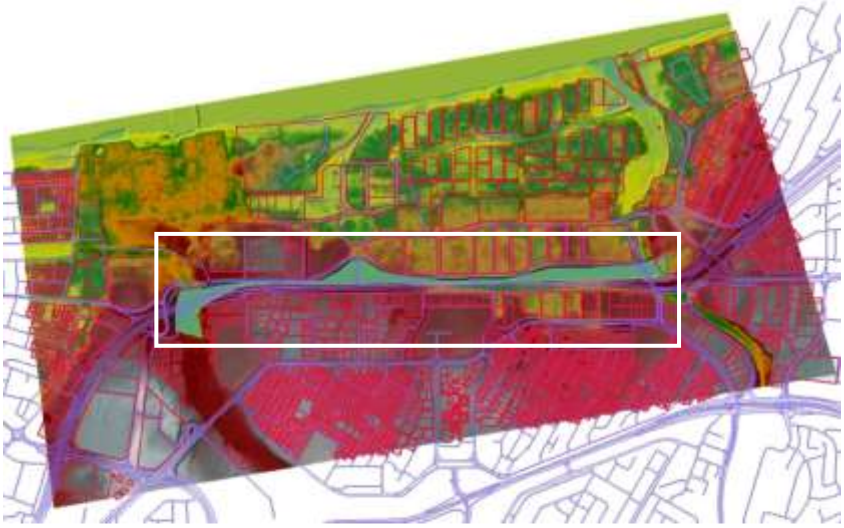

Figure 12: CS-2 Scenario-1 showcasing the restored natural stream

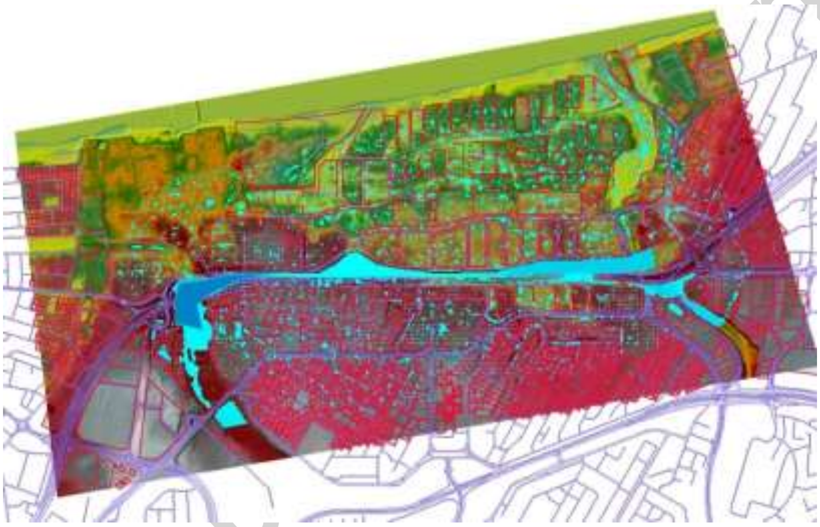

Figure 13: CS-2 Scenario-1 flood wave peak in HEC RAS

The crafting of the scenario was initiated by feeding the alterations on DEM layer that incorporates the restoration of the natural stream into the simulation platform. After that a flood simulation phase was facilitated by the HEC-RAS platform in order to clarify the extent to which the ecological-oriented changes have influenced a resilient response.

Results

Using the capabilities of the HEC RAS platform, shown in Figure 14, a profile line was created along the prone area. The profile line facilitates tracing the impact extent along its alignment and in different simulation times. Figure 15 shows the profile line and how it was designed to run along the affected area which was inundated with a (1.65) meter surface runoff in the existing situation. The mitigation scenario shows how the depth and coverage of the surface runoff has significantly ameliorated across the whole prone area alignment. A noticeable reduction of surface runoff took place, from stations 0 to 2,3 km. The levels of surface runoff depths fluctuated between 0.01 meter to 0.1 meter at almost the whole alignment, except for the area on the road corridor between stations 1.8 km and 2.05 km, where a significant inundation of almost 0.68 meters was left after the end of event. This is a considerable reduction in flood consequence. Comparing to the existing situation that suffered from surface runoff of (1.65) meter.

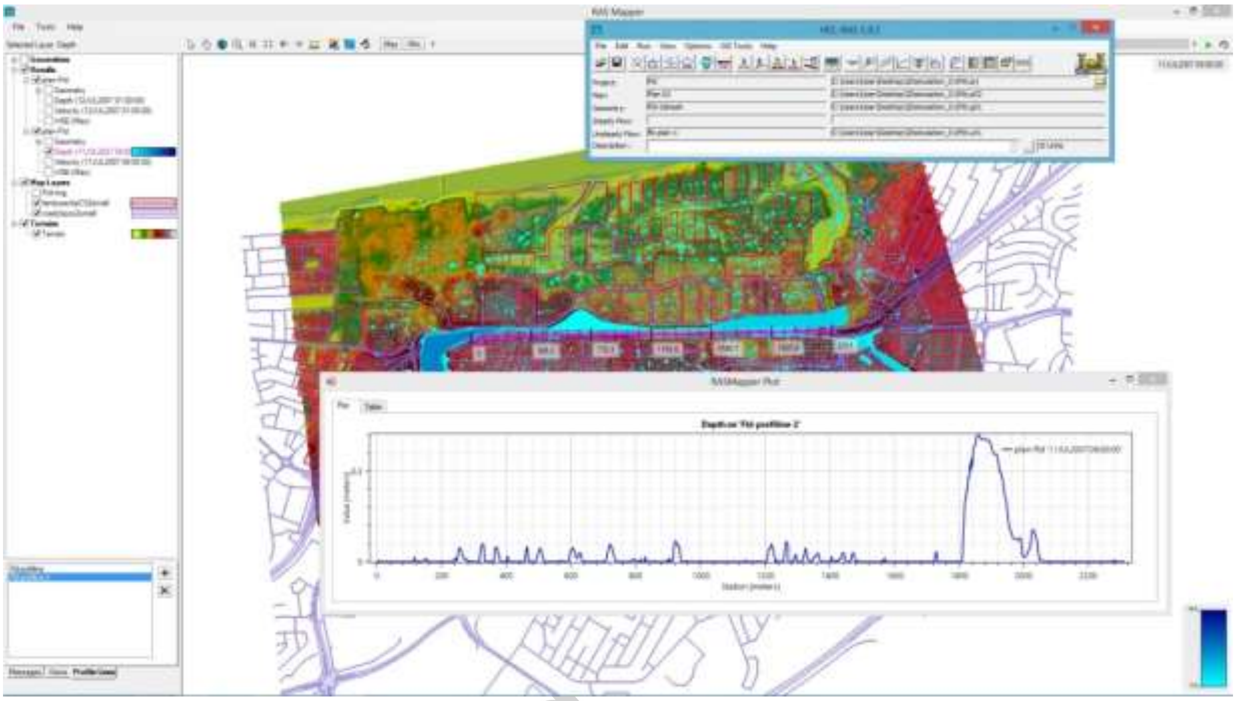

Figure 14: HEC RAS 5.0.3 platform interfaces

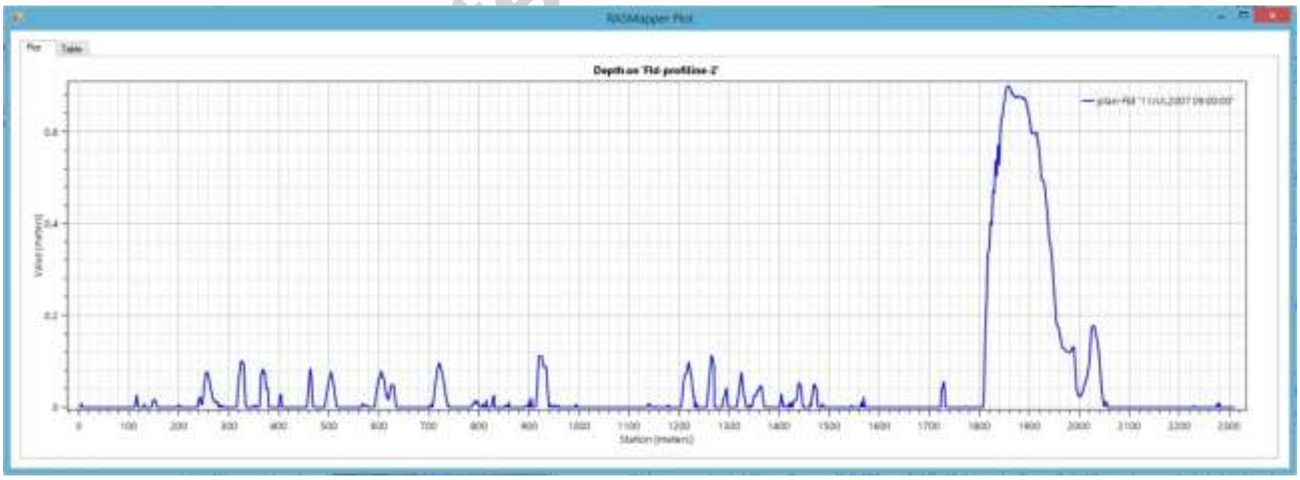

Figure 15: Profile line along the prone corridor

10.4 Challenges associated with scenarios implementation

The two adopted scenarios where examined for flood mitigation. Aside from technically sound resilient response achieved, there were some socio-economic and strategic challenges associated with the implementation of these scenarios. Those challenges and concerns jugged the overall viability of the adopted solutions. Challenges and concerns vary from financial to implementation convenience. Nevertheless, public might reject scenarios of flood mitigation over the evacuation of recreational facilities. The comparison in table 5 showcases the challenges associates with considering each of the adopted mitigation scenarios.

Evaluation of adopted physical intervention scenarios		
challenges	**Scenario one**	**Scenario two**
Cost	Relatively low cost excavations of almost (500) meters in length and stream banks protection structures	Restoring a natural stream course of 1.2 km relatively deeper excavations and relatively costly right and left of bank protection and slop generation structure
Implementation reliability	Clear land from the connection point to the downstream at the sea cost	Busy area with adjacent main street and service street on both side of the restored natural feature site traffic disturbance is expected and traffic rout management through the implementation phase is a real challenge due to the busy adjacent roads
Associated negative impact	Jeopardizing the safety of strategic desalination plant in a less likely case of runoff surcharge	The scenario built principally on land use redundancy where the restored natural feature will remove an existing green strip very popular for the area residents to practice so outdoor sports and walking. Nevertheless, the restored stream would have a recreational significance.

Table 5: challenges associated with the implementation of the two scenarios

11. Conclusions

This paper sheds light on the resilience value and its trajectories in urban design, moving from the descriptive approach on one side of the resilience continuum to the far end whereas more normative sense applied in order to identify the measurability of the term. This is accompanied with the general concern of turning resilience conception it into amorphous idea as there are so many definitions and descriptions for the term in various fields. A critical leap is required from the generality of the descriptive approach in addressing resilience to a more normative sense. Resilience need to be addressed clearly and individually in the designated system of interest.

The role of resilient ecological-urban design to flood is very much linked to the vital commodity of accessibility outlined in this paper. In the urban design discipline, access was found to be the critical commodity for city survivor. That’s because it is associated with flood consequences, identified earlier as; indirect losses and secondary impact, where the indirect losses are the cost of goods that will not be produced and services that will not be provided during and aftermath. Since important good and services in a time of crisis require access to be produced and provided, vital access between goods-services' provider and potential vulnerable consumers will be of relevance. Connectivity and access can be maintained by physical interventions for people to access safety destination and for the surface runoff to gently flow towards natural downstream without disturbing the urban context with inundation.

The rethinking of urban design as an important tool to maintain resilient status is one of the important goals of this paper. A cross examination was made across three resilience perspectives and setting inferences from the natural world correspondingly with identifying the essential commodity of urban design required to maintain minimum system's functionality. Comparisons between resilience perspectives, and the way they engage with urban design characteristics, yields different level of interdependencies. Moving from the static approach of engineering resilience, to a more systemically flexible ecological resilience; and ending with the absolute dynamic regime shift-based evolutionary resilience. The level to which urban design transforms from the rigid approach of infrastructure resistance to the three resilience perspectives is very much relating to the dynamics of each perspective. This is can be apprehended by understanding the systemic conflict between urban form inertia or rigidity and any transformational change. The more dynamic the resilience perspective, the more time the urban form requires achieving.

The in-depth analysis for resilience perspectives with the special attention to the ecological approach yielded some beneficial insights for developing ecologically compliant urban design with flood. The prone area investigated within two ecologically-built scenarios witnessed significant flood mitigation varies in extent and impact ton the adjacent urban and ecological settings. Despite the response achieved, there were critical socio-economic aspects that govern the process of taking those scenarios forward into implementation. Successful resilience surrogates have to consider challenges associated with contextualised socio-economic key factors and limitations.

12. Recommendation and Future perspectives

The city is a manifestation of a multiple complex adapted systems. The fact that resilience concept is still in motion, and its endeavour to address city's complex adapted systems will make an outstanding challenge on the way of conceptualising, measuring and implementing resilience.

The main objective that this paper was chasing when addressing the physical dimension of urban design was to stand on its effective commodity-of connectedness arrived at earlier in this paper- and its potential role in demonstrating resilience to flood. Accordingly, This paper recommends-on the way of configuring resilience-that each speciality, discipline, or active individual, to close down to each single field, discipline and system they belong to, and start to intensively investigate their system's components, behaviour and crucial technical thresholds. This is to facilitate introducing resilience measures by eliminating complexity occurred in addressing city's complex adapted systems as whole.

In future perspectives, the paper also suggests further investigation into the physical dimension of urban ecology, represented by topography and surface landscape. This is of significance in achieving ecologically-built urban resilience. The reason behind this necessity is the physical nature of flood phenomena itself. Considered as site-specific phenomena, flood characteristics of water accumulation, runoff courses and velocity are also related to the landscape physics associated with the location of its occurrence. This geo-morphological aspect may efficiently liaise with urban morphology to perfectly address an ecologically-resilient urban design approach to floods.

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