An Approach to Resilient Strategic Planning in the Face of Climate Change: A Case Study of Oman

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Abstract

An Approach to Resilient and Intelligent Developmental Planning in the Face of Climate Change: A Case Study of Oman

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This research makes a significant contribution to strategic planning by introducing an approach that integrates science into the planning practices and policy-making of Oman to enable more informed and resilient development. Oman, like many of its neighbors in the *Arabian Sea* region, is quite vulnerable to the potential impacts of climate change including: increased temperatures, erratic precipitation, desertification of much of its land mass, coastal flooding brought on by sea level rise (SLR), and increasing frequency of hazardous storms events. Throughout history, Oman has been subjected to various storms and cyclonic events that have resulted in both flash wadi flooding and high-tidal storm surge. Records show that major storms and cyclonic events have not only caused catastrophic damage to infrastructure and loss of agricultural lands and livestock, they have often resulted in loss of human life.

These events have been frequent and climate change projections indicate that they are on the increase. Northern Oman has documented evidence of major storms and cyclonic events as far back as 1890, and increasing in periodicity today (ie. 1971, 1977, 1987, 1995, 1997, 1999, 2003, 2007, 2010, 2015, 2016, and 2017). Dhofar, located in southern Oman and the geographic study region for this research, has experienced major storms and cyclonic events on a regular basis (ie. 1948, 1959, 1963, 1966, 1983, 1996, 2002, 2004, 2011, and 2015). In order to mitigate and reduce the damage caused by these events, Oman, at an early stage of economic and industrial development, must modify its approach to strategic planning and policy-making. In fact the motivation behind this research is to promote resilient planning within the strategic-development planning process already taking place in Oman by providing a better understanding of how integrating science into the process can result in a better vision for the future, and more resilient infrastructure and development in general.

This dissertation produces the first visualization of the inundation caused by the 2002 storm at Dhofar. It integrates a high-resolution earth surface model with a dynamic three-dimensional flood model based on the 2002 historic Dhofar extreme storm event that resulted in unprecedented damage. This novel modeling method allows researchers to analyze the realistic flow of water across the landscape during an extreme storm event. In addition, increments of sea level rise are modeled to predict future inundation levels based on predicted climate change. New GIS based technologies support the modeling and quantifying of impacts on infrastructure at a very high resolution at not only local scales but across vast regions.

This research demonstrates the application of a process that can help Oman move toward sustainable development and develop the creation of a resilient infrastructure to support the local population, in addition to the tourist industry that is quickly becoming a vital economic driver. It offers a glimpse into a future in which this knowledge and approach could be informative for the development of Oman and other Gulf countries. This is achieved by: 1) providing an overview of the principles of sustainable development and the implementation of those principles within the Omani context, 2) modeling the 2002 storm-surge event in association with various SLR scenarios along the coast of Dhofar, 3) quantifying coastal tourism projects that show vulnerabilities for the 2002 storm-surge event with different SLR projections, and 4) modeling the impacts of flash wadi flooding in 2002 and investigating the effects of this flooding on urbanization and infrastructure.

Producing accurate measurements regarding the depth and extent of sea level rise and wadi flooding inundation in areas where infrastructure and urban areas are threatened is critical to sound decision-making. Analyzing the impacts of flooding on current infrastructure, economic projects, and urban areas are first steps in implementing resilient and intelligent planning in Oman.

DEDICATION

This work is dedicated to my beloved daughter, Layan, and to my husband, Ahmed.

Dear daughter Layan, thank you for your patience and for accompanying me during this journey. Thank you for tolerating the long hours of my being away from you. As much as I regret being apart from you and missing your wonderful growth, I hope I will be your role model in future. We started this journey together, and now I am finishing and there you are, cheering me on. There are no words in the world that can express my gratitude and thankfulness for you, but I promise I will be there for you when you are doing your Ph.D.

Dear husband Ahmed, I owe you my loving thanks. Thank you for keeping, supporting, encouraging, and advising me throughout all these years. Ahmed, you are my hero. Thank you for your patience and for tolerating being apart from me and from Layan. I would never have been able to do it without your love and help.

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CHAPTER 1

1.1 Introduction

Climate change impacts have been increasing since the 20th century and continue to accelerate. Even though many countries are focusing on reducing greenhouse gas (GHG) emissions, the impacts of climate change on infrastructure and cities has not yet been mitigated, due to adaptations to climate change not being widely implemented in planning and development. For example, the impacts of climate change on Asia's urban areas, infrastructure, and populations are inevitable, and concern should be paramount given that these large cities contain the majority of population and the greatest regions of development (Revi et al., 2014; Tyler & Moench, 2012). According to Tyler and Moench (2012) the necessity of increasing investment in infrastructure capacity and raising competencies is facing climate change impacts on urban areas and their infrastructure. Land degradation in the Arab Region is continuing at an accelerated rate due to failures in devising and implementing resource management policies and because of the use of inappropriate technologies (Abahussain et al., 2002). Because the climate is changing, it is essential to integrate science when planning infrastructure and development, to achieve efficiency and resilience. This research studies a site located in Dhofar, in the southern part of Oman, where a lack of infrastructure resilience was demonstrated following a substantial storm in 2002. The term *resilience*[1] has been defined as the ability of a system to withstand external forces that are outside the norm, such as storm events, while maintaining its functionality during an extreme event (Chang, 2014); or as the system's ability to regain functionality rapidly after an event (McDaniels et al., 2008).

When modern development in Oman began, the county adopted the concept of sustainable development (SD) in its strategic development planning. Oman believes that applying SD principles are the pathway to a sustainable future. Yet despite the professed popularity of SD concepts, neither conventional development planning, nor environmental planning demonstrates the integration of environmental concepts (Slocombe, 1993). A lack of emphasis on creating resilient cities and infrastructure that are capable of withstanding expected climactic events, is evident throughout Oman.

[1]The term resilience has been defined as the ability of a system to withstand external forces that are outside the norm, such as storm events, while maintaining its functionality during an extreme event (Chang, 2014); or as the system's ability to regain functionality rapidly after an event (McDaniels et al., 2008).

Oman's professed enthusiasm for applying SD principles to strategic developmental planning is perhaps grounded in a desire to diversify the economy. Science has influenced policy for some time, as is apparent in Oman's national survey projects that are used to inform sustainable economic development, such as Integrated Coastal Zone (ICZ) development for the entire country. In 2005 a National Tourism Development Plan was formulated to integrate tourism as an aspect of sustainable socioeconomic development. The integration of science into the realms of natural, physical, and social policy has been effective in achieving informed policy and regulations (Holmes & Clark, 2008). It is clear that the government and policy makers saw the significance of integrating science in achieving the country's target goals, in that science provided a deepened understanding of, and solutions to, both current issues and those that are expected to be encountered in the future. However, in Oman, most of these science-driven policies are directed toward achieving sustainable economic development, with little emphasis being placed on using science as a tool for building resilient infrastructure and cities that are capable of serving future generations cities that are resilient in the face of the consequences of climate change such as frequent flash wadi flooding and sea level rise (SLR).

Natural disasters serve as an alarm, delivering good lessons for policy makers and planners to plan proactively for climate change and to encourage the building of resilient infrastructure. Even though rain in excess of 50 mm per day is rare in Oman, when it does take place, the consequences are severe, and include flash flooding, human and infrastructural devastation, and land and environmental degradation (Kwarteng, Dorvlo, & Vijaya Kumar, 2009). That being said, Oman is a country with a history of various cyclonic and storm events that have resulted in tremendous infrastructural damage, disruption of human life, and loss of crops and animals. For example, cyclonic storms took place in 1963 in Dhofar, in 1977 in Masirah, in 2002 in Dhofar, and in 2007, 2010, and 2015 in Muscat. Oman's mitigation strategy emphasized identifying risks and responding through defensive measures in a reactive manner rather than implementing proactive planning. The logic here followed that it is easier to mitigate the impacts of climate change than to adapt the entire system to make it less vulnerable (Parry, 2007). The reactive approach takes action to adopt in response to an existing impact or stimulus, whereas the proactive approach is triggers changes made for the long-term, in expectation of climate change or readiness for non-anticipated events (Berrang-Ford, Ford, & Paterson, 2011). Reactive strategies temporarily reduce rather than eliminate the risk in potentially hazardous areas (Klein, Nicholls, & Thomalla, 2003). For example, after the 2002 storm events in Dhofar, construction of dams were used as a mitigation strategy to preclude future events. This approach has given the country the perception that the flooding problems have been solved and has recently stimulated the development of many new coastal infrastructure projects.

Frequent exposure to flash flooding of wadi, often the result of cyclones or short-term extreme weather events, serves to illustrate Oman's inability to mitigate such events. Measuring exposure due to projected future Sea Level Rise (SLR) resulting from climate change, reveals vulnerabilities of Oman's population, cities, and infrastructure. These flood events also demonstrate the urgency of the need for Oman to adapt to the consequences of climate change. Only through acceptance of and preparation for the coming changes can Oman create resilient infrastructure. Oman's adoption of the reactive approach in facing any unpredicted challenges indicates that the country needs to strengthen the relationships among sciences, planning, and policy. To integrate science more fully into new strategies for planning development and building infrastructure, beyond strictly planning for economic development.

The current developmental planning approaches in Oman are still incapable of handling the uncertainty of natural hazards resulting from climate change. The potential magnitude of the damage and destruction to the built area, cities, and infrastructure is not an acceptable risk for Oman to take, especially in the currently unstable economy and with oil prices fluctuating.

Oman's current and future infrastructure and developmental planning are highly vulnerable given the country's current developmental pathway. Since the inception of environmental planning, people have been challenged to ascertain the causes and effects of environmental problems. This has led to a change in the natural order and process, in which it was assumed that nature would be resilient and would acclimate to the results of human interference. Once several crises occurred, it became apparent that each crisis could not realistically be viewed in isolation from a broader context. To solve environmental problems we must cautiously adapt to anticipated futures (Briassoulis, 1989). The concept of creating a balance between long-term and short-term, proactive and reactive, adaptation options is discussed by Lioubimtseva and Henebry (2009). Oman's ability to adjust to the unseen impacts of climate change by maintaining stability between long-term and short-term adaption actions, is a first step toward designing resilient infrastructure and sustainable cities. Relying on a reactive approach will result in adverse environmental changes in the longer term and likely increased infrastructure vulnerabilities. This could hinder Oman's strategic developmental planning progress, and cost Oman an enormous amount as the country is forced to fix the aftermath of impactful events. Planning to adapt for climate change impacts, on the other hand, would contribute to the country's well-being by reducing the risks and financial costs associated with global climate change.

There is a need to protect cities and infrastructure from climate change consequences. Discussion has already begun among researchers regarding the need to think beyond the modification of physical structures. Work must be undertaken to improve planning strategies, governance processes, and built structures to be ready to adapt to the impact of climate change on cities and infrastructure (Birkmann, Garschagen, Kraas, & Quang, 2010). This means it is time for Oman to change its adaptation direction from being reactive to being proactive. Planning for reactive adaptations takes place when there is no government intervention, whereas proactive adaption planning results when the government intervenes (Berrang-Ford et al., 2011). Oman is unique here as, government intervene at the reactive approach level. Since Oman's government is already involved, effective and early may be possible. This research will hopefully motivate Oman to take a more proactive approach in adapting for future climatic changes. A shift in approach should serve to reduce the likelihood of sea level rise and of flooding resulting from natural hazards, moving Oman toward developing longer term resilient cities and infrastructure.

1.2 Problem Statement

Natural hazards cause significant loss of life and setbacks to economic and social development in many countries. Weather, water, and climate disasters contribute annually to 90% of the total number of disasters, 70% of the two million casualties, and 75% of economic loss (Golnaraghi, 2012). The human and environmental damage resulting from Cyclone Gonu in 2007 and from a

Cyclonic Storm ARB 01 in 2002, showed Oman's vulnerability to climate change and natural hazards. This lead to the recognition for the need for precautions and for the integration of science within Oman's strategic developmental plans. The vulnerability of the Omani coastal zone, for instance, is also related to the area's socioeconomic significance. Sixty-seven percent of the Omani population resides along the coast; population growth, infrastructure development, and economic activity, for example the fisheries and tourism industries, are also clustered in the coastal area (Al-Jufaili et al., 1999; Al-Shaqsi, 2010). The growth and expansion of coastal cities means that people, the built environment, and the ecosystem are vulnerable to natural disasters that may take place. Specifically, there is a need to assess Oman's planning practices. According to Belqacem (2010), planning in Oman is based on the assumption of a constant, arid climate and normal weather conditions; such planning has previously been adequate due to the country's geographic location, which meant that natural disasters were rare. As a result, Oman's urban planners rarely take into account the natural disasters that might occur as a result of climate change.

Charabi and Al-Hatrushi (2010) stated that "literature and scientific knowledge concerning the climate of Oman are limited, incomplete and scattered" (p. 472). Yet, the literature demonstrates awareness of the influence of climate change in Oman in terms of frequent and intense cyclones (Al-Maskari, 2010; Al-Shaqsi, 2010; Bailey, 1988; Dibajnia, Soltanpour, Nairn, & Allahyar, 2010; Fritz, Blount, Albusaidi, & Al-Harthy, 2010; Membery, 2001). However, few studies have been conducted in an effort to understand the consequences of climate change, including potential sea level rise inundation and wadi flash flooding, and the potential impacts on existing and future coastal development and infrastructure. This research aims to encourage and demonstrate how Oman can integrate science, as the underlying process, into urban infrastructure, and developmental planning. This research demonstrates a proactive approach to measuring and quantifying future climate change impacts that lead to minimizing human loss, property loss, and the disturbance or destruction of both private and public coastal infrastructure. Such an approach will hopefully become an integral process within Oman's developmental planning.

Moreover, this study answers the following question: Given Oman's current environmental challenges and its geographic location, how can science be integrated as part of the underlying process of creating policy within Oman's planning practices. In addition, the results of this research map and encourage the adoption of resilient building practices within the country's infrastructure.

1.3 Research Contributions

This research downscales models and maps at a very fine spatial scale the impacts of extreme storm events in Oman's future. Downscaled sea level rise (SLR) estimates, based on future climate change predictions from the Intergovernmental Panel on Climate Change (IPCC), are used to estimate storm surges to the year 2100. We specifically map and model Dhofar's vulnerability to SLR and wadi flash flooding using real-time data from a 2002 storm event to calibrate our model. We employ our scientific SLR and storm surge estimates to analyze and evaluate the resilience of the coastal infrastructure of Dhofar. We question whether current policies, plans, and designs are sustainable under conditions of climate change, specifically SLR, storm surge and wadi flash flooding. This research demonstrates an approach to enhancing planning and design by integrating science into the process. As a result, Oman can better locate future infrastructure development in a way that will achieve resiliency.

This research integrates high-resolution surface modeling with high-resolution 3 dimensional, dynamic hydrology modeling and applies it as a regional scale to assist planning, design and policy issues affected by extreme storm events and SLR. In addition, this research introduces high resolution flood modeling within the wadi where extreme storm events can quickly turn a watershed into a flash flood. These landscape models are built, processed and eventually visualized within a GIS environment at a very high spatial resolution, not common in planning. The contribution here allows not only for regional decision-making but also for the localized quantification of impacts of storms to infrastructure at the building level. This resolution produces spatial products that directly impact landscape design decisions at the sub-parcel level.

This research provides a process and direction for Oman's planning with regards to adapting to climate change and encouraging resilient infrastructure for the future. Only with accurate data and the integration of science into Oman's strategic development planning can successful policies for the protection and safe transformation of the country's infrastructure be realized.

This generalization of the approach taken here can benefit other countries facing similar challenges. Other Gulf States are good candidates for this as they share similar social, economic, political, and environmental situations with Oman.

1.4 Research Outline

This dissertation consists of four independent research chapters. Chapter 2 presents a review of the literature addressing resilient infrastructure as an aspect of sustainable development (SD) in Oman. Included is a review of sustainable development principles, the significance of integrating resilient infrastructure to align with sustainable development principles, Oman's attempts to achieve SD, and discussion of the piece of SD that is lacking in Oman—resilient infrastructure. The chapter concludes with recommendations for the Omani government about how to integrate resilience into their infrastructure with their strategic developmental planning rather than being focused on sustainability only in terms of the economy.

Chapter 3 of the thesis covers a case study of modeling the SLR and the storm surge of the 2002 cyclone along Dhofar's coast. A 3 dimensional hydrodynamic model (3Di) simulation software tool is used. The hydrodynamic modeling is based on 60-minute interval water level data for a 72-hour, extreme storm event, coupled with 0.5 meter, 1.0 meter, and 1.41 meter SLR for different inundation scenarios. This chapter offers a visual representation of SLR and storm surge inundation resulting from a 2002 cyclone. In addition, the storm's impact on buildings and roads in Dhofar's Governance is documented here.

Chapters 4 covers the impacts of projected SLR scenarios and storm surge on some of the tourist beach resorts along Dhofar's costal area and proposes that science and calculating resilience, can be incorporated into coastal tourism development plans in Oman.

Chapter 5 includes simulations of the 2002 flash wadi flood for the Zayk and Ghadow watersheds in Dhofar in association with SLR projection. The simulations quantify the effect of the 2002 wadi flash flooding on urban and agricultural lands; the simulations use a 3Di hydrodynamic model and provided visual representation of flash flooding and its consequences on the wadi every hour.

Finally, Chapter 6 provides the conclusions of the study and recommendations for future research.

CHAPTER 2

2.1 Introduction

Since sustainable development (SD) theory was developed in 1987 by the World Commission on Environment and Development, it has become a popular idea among the international community and policy makers. The emergence of this theory has been helpful in addressing various global issues in relation to the economy, the environment, and society. Therefore, the term *sustainable development* has been used widely in sustainability planning; however, discerning the best way to implement sustainability in planning is subjective and is confusing for decision makers.

The term sustainable development is defined in different ways. The most commonly cited definition was offered by the United Nation's World Commission on Environment and Development (WCED) in *Our Common Future*, also known as the Brundtland Report, that describes sustainable development as the "ability to make development sustainable to ensure that it meets the needs of the present generations without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 15). This definition was embraced by many countries, including Oman, as is evidenced by their initiating sustainable development in their policies.

Generally, the term *sustainability* is used in planning to indicate sustainable development in various realms; however, the term is interpreted subjectively. As Quaddus and Siddique (2001) noted, sustainable development relies on the interpretation and the understanding of planners or policymakers. For example, in Italy, planners had focused on natural resources analysis by adopting the ultimate environmental threshold (UET) as a sustainable planning process to achieve sustainable land use (Senes & Toccolini, 1998). Policy makers and planners are anticipated to be able to draw a balance among the economy, quality of life, protection of the environment, and preservation of natural resources for future generations. But the reality is that making decisions in relation to sustainable development is challenging due to external factors beyond their control, such as extreme natural hazards.

Although the definition of sustainable development indicates consciousness of the natural environment, the economy, and society, it does not lay out how to approach a balance among these three elements of SD. According to Santillo (2007), to achieve sustainable development, a simultaneous linkage among the economy, the environment, and social well-being is required. Therefore, many countries are facing challenges in creating a balance among the three elements of SD since it is influenced by the country's own interests. Applying SD elements alone is not enough to achieve SD; awareness of infrastructure resilience is crucial if SD goals are to be achieved.

The term *resilience* has been defined as the ability of a system to withstand external forces that are outside the norm, such as storm events, while maintaining its functionality during an extreme event (Chang, 2014); or as the system's ability to regain functionality rapidly after an event (McDaniels et al., 2008). Holling (1996) described resilience from two perspectives: that of engineering resilience, and that of ecological resilience. These two perspectives are deviating from one another because engineering resilience is based on long-term infrastructural efficiency, constancy, and predictability, whereas ecological resilience is built on persistence, change, and unpredictability. Even though the resilience of infrastructure and of ecology appear to contradict one another, in real life they do coexist within one system; so achieving a mutual relationship between these two will provide safe connection between the natural and built environment, and people.

The idea of creating resilient infrastructure has emerged in response to natural hazards associated with climate change impacts on infrastructure. Scholars have begun to implement proactive planning to move toward resilient infrastructure; for example, Biging, Radke, and Lee (2012) conducted a study to investigate the impacts of predicted sea level rise (SLR) and extreme storm events on the transportation infrastructure in the San Francisco Bay region, and they recommended to the government of California that it stop maintaining vulnerable infrastructure transportation and instead build new roads that will not be vulnerable to SLR in the next 100 years. This example clearly indicates that adopting resilience infrastructure theory can help save money in the long run and reduce the disruption of daily life.

The world has witnessed increasing natural hazard events that cause a crisis. In 2001, a universal survey was conducted that showed that 700 natural disasters took place. These disasters were combined with huge losses, resulting in 25,000 deaths, $36 billion in economic losses, and $11.5 billion in insured losses (Godschalk, 2003). Many countries face economic losses related to natural hazards as a result of the vulnerability of their infrastructure, which is evidence of the lack of inclusion of resilient infrastructure awareness in their sustainable development policy. This paper discusses how Oman's sustainable development strategy is missing the component of resilient infrastructure.

Currently in Oman, whenever there are major or minor natural hazards, the infrastructure is often severely impacted and requires expensive repair and maintenance. This action is in conflict with the definition of sustainability and infrastructure resiliency. In the case of Oman, implementing the three elements of sustainable development is challenging because it has an oil-based economy along with challenging physical topography. Most of Oman's national development, including its infrastructure, is reliant on unsustainable oil revenue, and any crisis in oil prices has a significant impact on strategic developmental plans. Even though Oman is using oil revenue to build its infrastructure, the country's inability—or unwillingness—to build resilient infrastructure is what threatens sustainable development in Oman.

Much like the rest of the world, Oman has witnessed various natural hazards events such as cyclones Gonu in 2007, Phet in 2010, and Ashoba in 2015. These cyclones affected the infrastructure and daily life across the country and required a long time for recovery and return to normal life. As a result, these events cost the country a great deal of money: $4 billion in 2007 and $1 billion in 2010, and the 2002 extreme event cost about $25 million dollars, just to maintain the basic infrastructure (AlShaqsi, 2010). These severe impacts demonstrate the significance of Oman's missing resiliency in its infrastructure development: Long-term functionality after an event is not present.

Since the sustainable development portion of Oman's strategic development planning mainly focused on diversification of the economy and sustainable socioeconomic development, this paper argues that this strategy led the country to underestimate the need to incorporate resilient infrastructure within the national development strategy planning. *It also argues that any new developmental project in Oman has inherited the similar goals of focusing on sustainable socioeconomic development.*

This paper focuses on understanding resilient infrastructure as an aspect of sustainable development in Oman, and it is organized as follows. The second section reviews the literature on resilient infrastructure and its importance to sustainable development. The third section discusses the application of sustainable development to Oman. The fourth section provides an overview of sustainable development in Oman and its lack of resilient infrastructure. The fifth section goes over the urgent need for resilience in Oman. Finally, section six presents the conclusion of the paper.

2.2 Resilient Infrastructure and Its Importance to Sustainable Development

To understand the contribution of resilient infrastructure to sustainable development, we need first to review elements of sustainable development such as the theory's application within social and environmental contexts.

2.2.1 Sustainable Development Interpretations and Applications

Sustainable Development is mostly concerned with both environmental and socioeconomic issues. SD had been understood as comprising entities—the environment, the economy, and society—that were both separate and connected, with a balanced intersection among them (see Figure 1). Sustainable development debates usually prioritize either the environment or the economy. According to Neumayer (2003), most often the economy takes priority in policies, and the environment and society are treated as separate elements that will benefit from a strong economy. For example, Agenda 21 agreements at the Rio Conference included issues having to do with social and economic development, strengthening participation, and means of implementation (Grubb, 1993). As a result, sustainable development is embraced by big business, governments, social reformers, and environmental activists.

This study agrees with Giddings, Hopwood, and O'Brien (2002), who suggested that the interpretation and implementation of sustainable development is subjective and that the three elements of sustainable development are not properly connected and are treated differently at various levels. Within the SD concept, the environment and society are focused on social equity and environmental justice (Hopwood, Mellor, & O'Brien, 2005). Garcia-Ruiz et al. (1996) showed at Central Spanish Pyrenees that sustainable development is achieved by focusing on environmental issues within land use planning. Bilgen, Keleş, Kaygusuz, Sarı, and Kaygusuz (2008) cited the use of renewable energy to reduce environmental pollution as a sign of sustainable development in Turkey. Within developed countries, environmentalists advocated for the preservation of wild animals and wilderness as a sustainable development requirement (Howarth & Norgaard, 1992). These studies show how varied interpretations can be of SD from an environmental perspective.

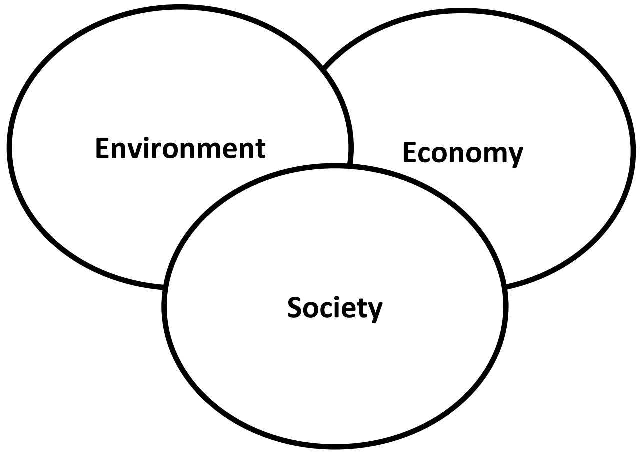

Figure 1. Three elements of sustainable development.

2.2.2 Social and Economic Interpretations in Sustainable Development

Sustainable development was interpolated from a social perspective through a participatory planning approach. Participatory planning means the involvement of the citizen in the decision-making process. The value of participatory planning within recent legislation has been recognized worldwide. Integrating participatory planning into the decision-making process is considered an aspect of sustainable development (Hopwood et al., 2005; Tippett, Handley, & Ravetz, 2007). This because participatory planning has the ability to promote environmental awareness and environmental justice as discussed in sustainable development concepts. The participatory planning is based on a bottom-up mechanism that starts with the public and locals and moves to the top policy makers in both the public and the private sectors (Sabatier, 1986). This dynamic process is described as an interaction between the governmental institution and citizens at an early stage of any decision making that is different from the conventional policy approach (Woltjer, 2002).

Participatory planning was applied in many countries on a community scale and showed great success. For example, the decision makers of Denmark faced challenges in developing the rural landscapes. They adopted a participatory planning approach, which played a crucial role in improving communication between the interested parties and resulted in successful planning for the area (Tress & Tress, 2003). Loring (2007), in his study about establishing wind energy in England, Wales, and Denmark, showed that the integration of the participatory planning process within the project made the project more publicly accepted and successful. However, although there is a huge benefit from using participatory planning on a community scale, participatory planning becomes more challenging on a larger scale because of the time needed and possible conflicts between various authorities, the public, and political interests. For example, the Dutch infrastructure planning showed the benefit of using participatory planning to provide public support. However, on a larger project, participatory planning is not highly desirable because of the challenge of having to homogenize interests and knowledge (Woltjer, 2002).

Countries like the UK considered the increase in GDP as an indicator of sustainable development because British urban policy has concentrated on economic and physical regeneration (Giddings et al., 2002). Attention must be paid to creating resilient built environments and infrastructure, and to the role and contribution of resilient infrastructure in sustainable development. Such attention is warranted because the goal of economy prosperity and sustainable socioeconomic development is to create an infrastructure that will serve these conditions. If the infrastructure is not resilient, a sustainable socioeconomic status cannot be achieved due to the instability of the context. We argue sustainable development cannot be achieved without resilient infrastructure, and without resilient infrastructure, sustainable socioeconomic conditions cannot be achieved.

2.2.3 Significance of Resilient Infrastructure to Sustainable Development

Resilient infrastructure is an aspect of sustainable development. The impact of climate change on infrastructure is no longer only a local matter for certain regions, but has become a global issue that is subject to external variables. No nation in the world is immune to catastrophic natural events. However, the destruction of infrastructure caused by these events can be reduced to lessen economic loss and minimize the effects on daily life. The physical infrastructure is a representation of a modern society that functions to serve people. Having a sustainable and resilient infrastructure is crucial as countries develop.

Resilience is an "ability to bounce back or to overcome adversity" (McCubbin, 2001, p. 3). Specifically, resilience in regard to infrastructure focuses on three elements: performance of a system under stress; consequences of this stress on the system and return to normality; and scale and affordability of required response (Hansen & Neale, 2014; Lokuge & Setunge, 2013; McDaniels et al., 2008). Whenever an extreme event takes place, it goes in parallel with economic loss and devastation of everyday life. The world has already experienced various extreme natural hazards events that caused severe economic losses, such as the 2009 floods in Jeddah, Saudi Arabia; Hurricane Katrina in the southeastern portion of the United States in 2005; Hurricane Sandy in 2012, in New York, U.S.A; and flooding in the UK and Ireland from extreme storms in 2012 and 2015. All these extreme events alerted us to the need for resilient infrastructure because they caused huge disruption to critical infrastructure that cost millions to billions of dollars to repair. In the case of floods in the summer of 2007 in the UK, the damage cost about $3.5 billion; the flood disaster in 2009 in Australia that caused infrastructure damage cost $6.8 billion; and natural events in the USA in 2012 cost about $400 million in damages (Bissell, 2010; Lokuge & Setunge, 2013; Sullivan & Uccellini, 2013).

Infrastructure is the interface between humans and the environment (Chambers et al., 2008). A city has resilient infrastructure when it is able to respond, recover, and adapt fast to a major storm, and is able to reduce the risk of significant damage from future storm events (Hurricane Sandy Rebuilding Task Force, 2013). In other words, resilience is reflected by being able to predict prior to an event; being able to resist, absorb, and adapt to it; and being able to recover rapidly. On the other hand, sustainability requires the capability to ensure long-term viability in social, economic, and environmental contexts, which requires consideration of the consequences associated with climate change (Hurricane Sandy Rebuilding Task Force, 2013). Infrastructural resilience is measured in terms of its ability to maintain its functionality and ability to return to normality after an event (McDaniels et al., 2008). Thus, a proactive approach is a requirement of resilient infrastructure because failure in infrastructure represents its inability to adapt to changes in the real world (Madni & Jackson, 2009). Therefore, resilient infrastructure contributes positively toward the principle of sustainable development.

The developed countries incorporated the concept of resilient infrastructure and got fruitful results. For instance, Australia understood the importance of resilient infrastructure, specifically in terms of transportation, for promoting community resilience to reduce impacts on daily life through strengthening rural roads and bridges (Lokuge & Setunge, 2013). Approaches such as this have the potential to minimize social destruction and allow for rapid recovery after an extreme event. In 2011, the UK took a step toward creating a resilient infrastructure by publishing a national infrastructure plan that indicated the need for decision makers to integrate resilience at all stages of the project life cycle, and to allocate funding at the early stages of planning and conceptual design (Hansen & Neale, 2014). We concur with scholars who suggested the need for designing infrastructure is proactive, reactive, and adaptive to get resiliency into our infrastructure (Cormie et al., 2012; da Silva, Kernaghan, & Luque, 2012; Hansen & Neale, 2014; McDaniels et al., 2008).

Bosher (2008) suggested that in countries like Bangladesh and in slum areas in India, the lack of choice contributes to being not resilient socially and with respect to infrastructure. In the oil producing countries in the Gulf, environmental constraints also contribute to the notion of lack of choice. For example, in Saudi Arabia, the 2009 flooding in Jeddah caused about $3 billion in infrastructural damage. The government lacked choice because of the area's topography: Urban settlements were distributed without regard for any natural risk that might occur, resulting in post-event disadvantages for citizens and the infrastructure (Al Saud, 2010). The flood disaster in Jeddah proves the country is not prepared to deal with natural disasters. The country responded by improving its preparedness for and abilities to respond to natural and manmade disasters (Abosuliman, Kumar, Alam, & Rasjidin, 2013; Momani & Fadil, 2010). This indicated a reactive approach, and one that still failed to promote proactive planning and a response that would move the country toward developing resiliency and a sustainable infrastructure.

The case of Oman is similar to that of Saudi Arabia in that the allocation of some residential, infrastructural, and economic developments are within the wadi watershed and along the coastal area due to Oman's topographical challenges: 82% of Oman is desert, 15% is mountainous, and 3% is coastal (AlSuheili, 2015; Al-Qurashi, 2014). For example, some of the tourist and infrastructure project allocations rely on using the natural asset of its location and. At the same time, Oman is approaching sustainable development through sustainable social and economic conditions. However, these projects lack the principle of resilient infrastructure. Resilient infrastructure should be a requirement in these projects since their resilience is what will help Oman move toward a sustainable socio-economic status.

Bosher et al. (2007) stated that damage from flooding is greater than from any other natural disaster. For that reason, resilience must be integrated within the planning and design processes and not added after an event. This idea complements McHarg's (1971) idea of being in harmony with nature, which, as he explains in his book *Design with Nature,* helps to mitigate impacts from natural disasters. A collaborative effort among city planners, engineers, architects, developers, and decision makers can help to increase knowledge and awareness of resilient infrastructure planning and design (Burby, Deyle, Godschalk, & Olshansky, 2000; Godschalk, 2003). Being proactive and adaptive in planning is the path to resilient infrastructure. According to one study, an increase in expenditure now can reduce long-term costs, and long-term planning will be rewarded by long-term gains (Cormie et al., 2012). The infrastructure we develop now, if it is resilient, has the potential to provide flexibility, to add security, and to be adaptable to uncertainties of future scenarios related to climate change. We agree with Chambers et al.'s (2008) suggestion of uniting resilient infrastructure through "good engineering" with sustainable development principles to contribute toward resilient and adaptable cities that are able to mitigate the impact of climate change.

2.3 Oman's Application to Sustainable Development

Before 1970, Oman lacked basic infrastructure. After 1970, development in Oman moved at a slow rate even though modern development started in 1970 when His Majesty Sultan Qaboos came to power (Tear & Forester, 1992). This is due to the fact that during the 1970s we saw a combination of minimal financial resources and various political problems and civil war. However, upon the end of the civil war, the country started to look for ways to improve development, and to diversify the economy by integrating and using natural resources. The main challenge at that time was the lack of planning and direction in Oman, which are considered among the first obstacles for the new government (Allen, 1987). Nevertheless, the new government led by His Majesty Sultan Qaboos coupled with the introduction of oil to the national economy in 1967, contributed to rapid development in Oman.

Oman is still undergoing major infrastructural developments as the country continues to build (see Figure 2) across its regions and governance is seen in the strategic development plans. However, the new development is taking the same process and path as older development. The new structures are not resilient; they are based on old survey maps created since 1980s through ICZMP (Salm, 1989); and they are located within areas that are vulnerable areas to SLR and flash wadi flooding. Omani people are noticeably sensitive about their land and natural resources. They did not allow construction on fertile land (Al Gharibi, 2014). For that reason, people are actually building among the rock surfaces and keep the lowlands for their oasis and farms; as is the case of Manah (Bandyopadhyay, 2010). If these practices are continuing and implemented now, Oman will be the most resilient country with citizens able to understand their topography, watershed, and environment, and actually apply McHarg's ideas regarding combining design with nature.

To further national development, Oman's government implemented a 5-year strategic development framework. Almost all of the strategic development planning is required to integrate economic factors (Allen, 1987). For that reason, Oman underwent a significant increase in development and building of infrastructure; the transportation sector achieved the highest development across the country. For example, Oman allocated about US$78 billion for the development of roads, ports, and airport infrastructure, as had been outlined in the Oman's eight strategic development plan (BI-ME, 2013; Palmieri, 2012). Much like the rest of the world, Oman has embraced the concept of sustainable development and continues to put effort toward it.

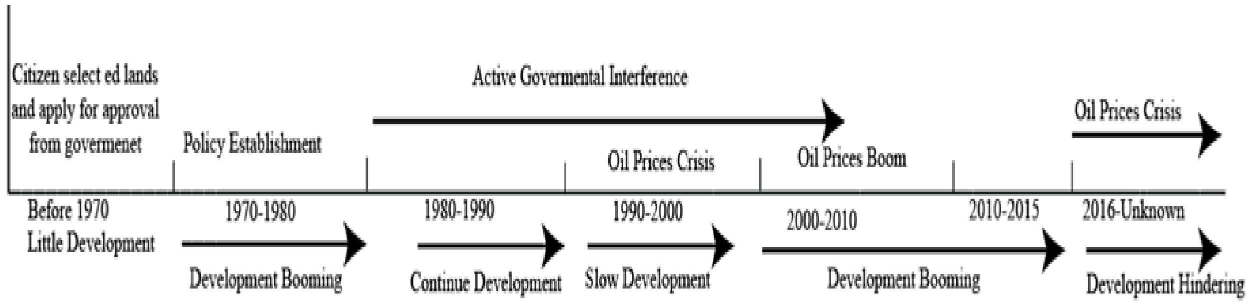

Figure 2. Oman's development timeline. Author: Amna Alruheili, 2016.

2.3.1 Sustainable Development in Oman's Environmental Context

Oman developed a national strategy for environmental conservation that focused on environmental preservation and the conservation of natural resources ("Oman," 2002). For instance, The Ministry of Environment and Climate Affairs (MECA) conducted research that focused on preserving and conserving the habitat and wildlife of various ecosystems in Oman. As a result, 14 nature reserves across the various regions of Oman were established to promote nature and ecosystem conservation. Examples include the Arabian Oryx (Wusta Region), Dimanyiat Islands Reserve (Muscat), and a turtle reserve (Sharqiyah Region) (MECA, 2015). In addition, conservation of native plants was promoted at nurseries, for example the ones in the Oman Botanic garden (Musact), As Saleel Natural Park (Sharqiyah Region), Qairoon Hairiti in Dhofar, and Jebel Samhan Nature Reserve, and in the lagoons (khuwrs) at Dhofar Governorate that protect mangrove trees and vast numbers of birds and fish (Abdel Malek, 2015). This effort reflects the government's emphasis on integrating sustainable development with the environment and its natural resources.

Likewise, Al-Jufaili et al. (1999) in their study discussed the role of the Oman Coral Reef Management Plan: to provide scientific benefits for understanding the marine biology in the Oman waters and to reduce human impacts on coral reefs. Petroleum Development in Oman also contributed to environmental protection in Oman by conducting Environmental Impact Assessments (EIA) to avoid harm to people and the environment (Petroleum Development Oman, 2014). It clear that Oman put forth numerous efforts to preserve nature and conserve wild habitat to align with sustainable development principles from an environmental perspective.

It seems that Oman implements sustainable development in a way that integrates environmental concerns by focusing on ecological and habitat protection. However, sustainable development is not just about preserving and conserving habitat.

2.3.2 Sustainable Development in Oman's Social Context

Oman also incorporated the concept of sustainable development from a social perspective. Developmental policy and decision making in Oman is a marriage between centralized (top-down) and decentralized (bottom-up) approaches. The top-down approach starts from a policy decision maker, the government, and focuses on the objectives to be achieved over time (Sabatier, 1986). Since oil exportation increased in 1970, the government of Oman has moved toward centralization to accelerate the country's shift toward modernity (Allen, 1987). The new government consists of a Council of Ministers and Majlis Oman, which consists of Majlis AlDawla and Majlis Al Shura (Consultative Council) ("Greater Powers for Majlis Oman," 2016; Rabi, 2002). The Ministers' Council is the supreme executive authority for the Administrative Board of the State, as stated by Royal Decree (26/75). It approves the general policy of planning in the Sultanate and supervises and follows the performance of all governmental units and ministries in terms of applying their responsibilities and the correlations among them. The policy is formulated after negotiations between the Sultan and the individual ministers (Metz, 1993).

Before negations take place, policy can be created in one of two ways: 1) Majlis Oman may propose or draft laws and refer them to the Government (Sultan) for review, and then the Government shall return the same to the Majlis; or 2) a policy can be created based on draft laws referred by the Council of Ministers to Majlis Al Shura (Almoharby, 2010). After different ministries agree upon a policy, the legislations are declared in the form of Royal Decrees. Any major projects in the country are declared and approved by Royal Decree (Al Gharibi, 2014).

Researchers have suggested implementing participatory planning as one aspect of sustainable development. Al Shueili (2015) and Al Hadhrami (2006) recommended doing so in Oman. However, policy and strategic planning in Oman demonstrates a sense of the participatory planning process already, as it is based on a bottom-up approach that reflects the essence of participatory planning. Even though we affirm Al Shueili's (2015) and Al Hadhrami's (2006) and Rodriguez's (2015) findings about the need to strengthen the participatory planning aspects and move toward sustainability in Oman, we argue that the centralization and decentralization planning is not the main challenge regarding sustainable development. The country shows some aspects of these practices within its planning process at various scales. However, the focus in Oman on modernization and sustainable socioeconomic development has created a government that perceived sustainable development through the lenses of sustainable socioeconomic development and economic diversification.

2.3.3 Sustainable Development in the Context of Oman's Economy

Oman fell into a similar trap of applying sustainable development through the lens of a sustainable economy (see Figure 3). "Economic Vision Oman 2020" stressed creating sustainable development by diversifying the economy and by strengthening other sources of income especially agriculture and tourism. This is implemented to satisfy the demands of a growing population and development. "Economic Vision Oman 2020" leads the government's efforts to eliminate its dependence on oil for its revenue. In regard to the urban level, Oman National Spatial Strategy (ONSS) was established to promote a long-term strategy that attempts to achieve sustainability in socioeconomic contexts to enhance quality of life (AlGharibi, 2014). This strategy shows the Omani interpretation of sustainable development and how it focuses on diversification of the economy as a piece of sustainable development.

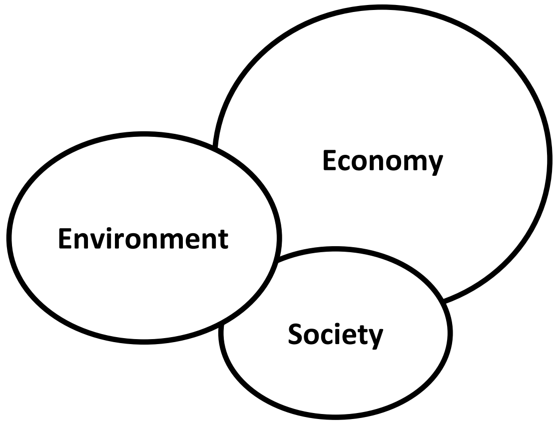

Figure 3. Oman's implementation of the three elements of sustainable development.

As the government continually focused on improving life and infrastructure for the Omani people, strategic developmental planning was shaped to respond to those issues. The various strategic development plans in Oman showed a significant trend toward socioeconomic development planning, with minimal focus on resilient, sustainable infrastructure development. For example, the first development plan between 1976 and 1980 focused entirely on economic and infrastructure development and had no focus on environmental or climate change issues. The second development plan, of 1981–1985, offered the first discussion of regional planning and of integrating natural resources into development as a way to diversify the economy (MNE, 2008). It is obvious from the two strategic plans that sustainable development concepts are perceived as sustaining an advantageous socioeconomic status through diversifying the economy and that no attention is being paid to resilient infrastructure requirements.

The third development plan, developed between 1986 and 1990, also focused on socioeconomic elements. It was not until the seventh strategic plan, of 2006–2010, that the government focused on incorporating environmental criteria into development policies (MNE, 2008). Al Shueili (2015) noted the existence of a gap between strategic development plans and implementation in Oman. Despite this gap, the recent strategic development plan of 2016–2020 and the 2040 plan still show minimal adaptation to the impacts of climate change in the country's infrastructure and developmental projects. Indeed, there are no signs of infrastructure resiliency in the newly developed projects, such the new tourist projects and roads in Salalah, and in other regions as well.

2.4 The Piece of SD That Is Lacking in Oman: Resilient Infrastructure

The era of oil discovery moved Oman toward vulnerability in the context of climate change and its impacts on the country's development, infrastructure, and urban areas. People's day-to-day life had changed to a stationary lifestyle that required the establishment of infrastructure to serve people where they settled. The problem with the acceptance of the settled pattern is that the chosen locations are prone to natural hazards. As these locations are further developed and expanded, it became clear that these areas were not well planned, being neither resilient to natural hazardous events nor having sufficient infrastructure to face the future impacts of the consequences of climate change. The necessity of integrating science, or of conducting out site analysis in a proper way, is neglected in the early planning stages.

As mentioned earlier, Oman is applying the three principles of sustainable development—the economy, the environment, and society—at different magnitudes, and the diversification of the economy is dominant. However, Oman's sustainable development strategy faces various critiques. For instance, Al Shueili (2015) stated in his Muscat study that in Oman, the path toward sustainable planning policy is still not clear within the SD context. Even though Oman is applying the principles of SD, it is not enough to claim that Oman is under the umbrella of sustainable development. Resilient infrastructure is not included in the country's strategic development, and the country's infrastructures are not resilient in response to the effects of climate change.

Researchers struggle to come up with a generalized definition of sustainable development. Since the definition has not included focus on the built environment, almost all sustainable development efforts have neglected this aspect. Infrastructure is not being taken into consideration as the county further develops. Resilient infrastructure has not been linked to sustainable development, a choice that ends up costing the county more from an economic and an environmental perspective. Continuing efforts to create a sustainable economy will always be wasted if they are directed toward fixing non-resilient infrastructure after a natural hazard is exacerbated by climate change.

The role of resilient infrastructure is to reduce vulnerabilities and damage resulting from SLR or flash wadi flooding. Oman's focus is on meeting sustainable socioeconomic goals, which means that Oman is not ready for the repercussions of climate change as they applied to infrastructural development. Oman does not take care to create resilient infrastructure while implementing their strategic developmental plans. Actions that the country takes in response to natural hazard impacts, particularly the 2002 storm in Dhofar, includes building sea walls, building dams, and re-channelizing wadis (AlHakmani, n.d.). The country's long-term master plan shows no evidence of Oman's ability to guide urban and infrastructure development toward resilience. Moreover, AlGharibi (2014) suggests that the fragmentation of planning policy among multiple authorities creates fragmentation of land use and planning that hinders the application of sustainable development practices. Since the Supreme Council for Planning (SCP) is the core for both infrastructure and urban planning, fragmentation should not be an issue, because the fragmentation of agencies can be perceived as a chance for SCP to be informed by representatives of various regions. But it seems what is missing is SCP's ability to move its focus away from Oman's main strategic sustainable development aim: creating sustainable socioeconomic conditions ("Supreme Council for Planning Meets," 2015).

The Supreme Council of Planning, is considered the engine of strategic development in Oman and relies on the Ministry of Regional Municipalities and Water Resources to issue the required policy for wadi-flooded areas (Ministry of Regional Municipalities and Water Resources, 2016, "Specialties"). According to Belqacem (2010), the planning practice in Oman is based on the assumption of a constant arid climate and normal weather conditions. As a result, Oman's urban planners rarely take into account the natural disasters that might occur due to climate change, and they underestimate the effects of climate change on the country's infrastructure. Charabi and Al-

Hatrushi (2010) stated that “literature and scientific knowledge concerning the climate of Oman are limited, incomplete and scattered” (p. 472). Yet, new research has contributed to knowledge and awareness about the influence of climate change in Oman in terms of frequent and intense cyclones (Al-Maskari, 2010; Al-Shaqsi, 2010; Bailey, 1988; Dibajnia et al., 2010; Fritz, Blount, Al-busaidi, & Al-Harthy, 2010; Membery, 2001), but no measure toward resilient infrastructure has been implemented.

In short, Oman’s sustainable development plan lacks an emphasis on resilience. According to Choguill (1996), a connection between infrastructure and sustainability has rarely been made. However, Klein et al. (2003) and Carpenter, Walker, Anderies, and Abel (2001) stated that resilience contributes to sustainability by providing attributes that complement those of infrastructure. Sustainability discourse focuses on impacts on the economy, society, the environment, and the infrastructure is allocated over its entire service life. Whereas resilience focuses on the impacts of infrastructure failure during an extreme event, which at the same time creates destruction to society, the environment, and the economy. As Bocchini et al. (2013) noted, the joining of resilience with sustainability offers an inclusive assessment of the quality of the infrastructure, and both these concepts measure the consequences of decisions associated with the infrastructure.

Over the past 10 years, Oman has been exposed to more than three cyclones, costing the country a substantial amount of money to repair damaged infrastructure and to support affected families. The classic example of Gonu in 2007 cost the country about $4.2 billion dollars; Phet 2010 cost about $1 billion dollars; and the 2002 extreme event cost about $25 million dollars. The country reacted defensively by building more artificial defenses such as sea walls and dams. No change within the physical planning strategy had been resolved; the new development taking place was based on the old survey projects, that had no focus on the impact of climate change in Oman. An example is the recent construction of new tourism resorts along Salalah coast that now are threatened by SLR.

2.4.1 The Urgent Need for Resilience in Oman

Unfortunately, the ability of Oman to establish and maintain its infrastructure is largely dependent on income from oil resources. Oil provides about 82% of the general budget of the country. Therefore, any damage to the infrastructure in Oman will be costly. Although Oman has included the concept of sustainability in its development plan, the reality is that oil resources contribute significantly to the country’s infrastructural development; this means that any fluctuation in oil prices and/or productions and prices could have serious implications for the country’s developmental plan (Al-Badi, Malik, & Gastli, 2009; Allen, 1987). Since the early stages of its development journey, Oman has tried to become less dependent upon oil revenues; but the path is challenging and was not taken seriously in the early planning stages.

Instability in oil prices has an effect on the country’s development plans and on its citizens (“Plan Council Reviews Steps,” 2015). Recently Oman reduced oil subsidies, increased the corporation tax, and reduced government spending on development to cope with the oil price crisis (Bouyamourn, 2015; Al Mukrashi, 2015; ONA, 2015). Oman continually looks for ways to diversify the national economy, as doing so is one of the main objectives within its development plan; however, the country has not achieved this goal. An emphasis on diversifying the economy and finding sustainable socioeconomic development has kept the country mainly focused on sustainable socioeconomic goals that have taken priority over the need for resilient infrastructure ("Oman Development Plan," 2001).

In addition, Oman underestimated issues related to the effects of climate change on current development planning and to the need to focus on creating infrastructure resiliency. Thomas Kuhn (1996) suggested that a shift in paradigm occurs in theories and methods when the dominant paradigms are unable to formulate consistent solutions to scientific problems (as cited in Ndubisi, 2002). In the case of Oman, integrating modeling of different sea level inundation scenarios and flash wadi flooding, for example, will create a paradigm shift. The integration of science with the current regional planning and strategic planning will help the country build both resilient infrastructure and sustainable development. Creating resilient infrastructure is a step toward Oman reaching its sustainable planning goals.

Because we are living in an era of uncertain futures, and with higher exposures to extreme natural hazard events due to climate change, it is important to think seriously about resilient infrastructure (Cormie et al., 2012; Bissell, 2010; Bosher, 2008; Godschalk, 2003; Fenner & Ainger, 2014). Nonresilient infrastructure is vulnerable and usually requires reactive action after an event. These reactive responses are usually slow, costly, inefficient, and ineffective (Hansen & Neale, 2014). Oman needs to embrace resiliency in its infrastructure. It is clear that nonfunctional infrastructure affects all measures of sustainable development, because it creates disturbances in society and in the environment. To achieve sustainable development goals, it is essential to avoid the destruction of everyday life, and doing so requires the presence of functional infrastructure at all times.

Furthermore, the continuous pressure of population growth and migration to urban cities has put the country in a mindset of moving toward what they call a sustainable economy to meet the needs of a growing population. The resources that are now used to create infrastructure show no resilience for the future generation: They are vulnerable at 0.2m or even 0.5m of sea level rise and to flash wadi flooding in lowland areas. A study conducted in Oman, shows that Oman is highly vulnerable to SLR given that 400 km2 of total land area potentially will be inundated in the 0.2m scenario at a national scale. The study also indicated that the governor of both Al-Batinah and Muscat will be vulnerable under all SLR scenarios. The governorate of Muscat, the capital of Oman, is the most densely populated area, and SLR are projected to claim between 5 km^2 and 23 km^2 of valuable public/private property. This corresponds to between 10% and 16% of residential, commercial, and government land (Al-Buloshi, Al-Hatrushi, & Charabi, 2014).

Even though Oman is an arid country, its location exposes the country to frequent cyclones; and its geography of steep mountains, impermeable rocks that cover the wadi watershed, and narrow wadi ravines make the flash wadi flooding significant (Al-Qurashi, 2014). Integrating science into Omani national developmental planning and incorporating the various scenarios of 100 years of storm and extreme events must be the beginning of creating resilient and sustainable infrastructure for Oman's future. Lee (2001) stated that integrating science within a system produces unexpected outcomes that at the same time help the researcher to recognize the non-anticipated change within the system. For that reason, integrating science into strategic planning in Oman is key in moving toward sustainability and resilience within an Omani strategic plan where the country will be able to predict climate change impacts.

2.5 Conclusion

We concede that Oman, like the many countries worldwide, has gone down the sustainable development path, we argue that Oman needs to consider resilient infrastructure as part of its sustainable development strategy to avoid infrastructural and economic losses.

It is clear that Oman is applying the three principles of sustainable development regarding the economy, the environment, and society at different magnitudes. Even though Oman is applying these principles, resilience in infrastructure they are not included in the country's strategic development plans, where the country showed vulnerability and no resilience in its infrastructure during the last decade's extreme events and cyclones.

The strongest focus of Oman's policy is on achieving sustainable development by diversifying the economy. Oman's "Vision 2020" represented the Omani hope of diversifying its economy as a means of SD. This vision encouraged the country to invest in various sectors without paying attention to the need to have these elements of infrastructure be resilient. One explanation for this is Oman's lack of resilience in infrastructure. Such resilience is not included in the definition of sustainable development as it was stated in 1987. For that reason, varying interpretations and applications of SD exist. The approach that Oman adopted toward sustainable development may fit the definition of SD; however, SD is not just about preserving or conserving habitat and diversifying the economy. The resilience in infrastructure is not just about being able to fortify or being able to detect impacts of natural hazards and storms early on. Infrastructure resistance, coupled with rapid recovery is what ensures the sustainability and resilience of infrastructure.

Being proactive in planning and being prepared for consequences of climate change with a resilient infrastructure is a progressive move toward sustainable development. Since strategic development planning in Oman has little to no emphasis on climate change and its impacts, the country has and will continue to suffer huge economic losses from natural disasters.

The government and the decision makers have the responsibility to promote proactive planning to provide resilient infrastructure for future generations. Developing resilient and sustainable infrastructure is not an easy task, but it is possible to successfully undertake. Since Oman is not yet infrastructurally mature, we consider it fortunate as it still has time to learn from Western experiences. Being scientifically sound in planning and implementing infrastructure resilience plans is what will protect Oman from wasting money or hindering the country's developmental plans during fluctuations in oil prices. Planning wisely by considering the various environmental, physical, and social challenges associated with climate change will help Oman move toward proactive planning and to ensure resiliency for the infrastructure, the people, and the environment.

The latest reports from Ministry of Environment and Climate Affairs (2013) on the environment and climate change, predict that Oman will experience cyclones more frequently over the next several decades. Money is always required to fix infrastructure damage resulting from natural disasters brought about by climate change. Although Oman is working hard to build a sustainable economy, if it does not have a sustainable plan, resilient infrastructure and policy, it is likely a sustainable economy cannot be achieved.

CHAPTER 3

3.1 Introduction

One of the challenging aspects of climate change is sea level rise (SLR). Global acceleration in sea level rise has been taking place since the 20th century and continues to accelerate at an increasing rate (Church & White, 2006; Church et al., 2008). New research continues to show that during the early 21st century, the global sea level rise rate has increased more than ever before (Church & White, 2011; International Panel on Climate Change [IPCC], 2013). The AR5 report from IPCC projects a significant increase in sea level rise over the next century. The new SLR projections anticipate an increase of 0.26–0.55 meters (10–22 inches) by 2100 under a low emissions scenario and of 0.52–0.98 meters (20–39 inches) under the high emissions scenario (IPCC, 2013). Furthermore, various studies show uncertainty in predicting the future of sea level rise given that most experts estimate a larger sea level rise by AD 2100 than the IPCC AR5 (Horton, Rahmstorf, Engelhart, & Kemp, 2014; Rahmstorf, Foster, & Cazenave, 2012). Due to these studies indicating sea level is currently rising faster since the early 1990s, it is key that countries prepare their coastal infrastructure and other construction to be resilient.

New studies show that SLR is likely to increase by 1.2m or 2.0m by 2100 (Parris et al., 2012), which is significant for lowland areas. The causes of SLR are known to include such factors as an increase in ocean temperature, the melting of land ice, and changes in water storage (Cazenave & Llovel, 2010; Church et al., 2008; Nicholls & Cazenave, 2010; Pfeffer, Harper, & O'Neel, 2008; Rahmstorf, 2007). According to Rignot et al. (2011), in Greenland, ice-sheet melting is considered as the dominant contributor to SLR, since by 2006 ice melting contributed to 1.3±0.4 mm/yr of SLR. In addition, the variability of El-Nino Oscillation also has the potential to contribute to SLR over time (Church & White, 2006). The rising seas increase the risk of coastal flooding, storm surge inundation, coastal erosion, shoreline retreat, and wetland loss. The existing cities and infrastructure that lie along the coasts are already vulnerable to damage from storm surges and SLR. The potential for more frequent storms due to climate change increases the chances of frequent inundation and the resultant damage to infrastructure.

It is clear that SLR poses a threat to our environment, our economy, and our people. Our response to SLR and its consequences must be effective, given the implications of climate change. Sea level rise causes a variety damage to coastal zones, such as land loss through inundation and erosion; infrastructure damage due to flooding during storm surges and rainstorms; and ecosystems destruction due to saltwater intrusion into aquifers, estuaries, and wetlands (Nicholls & Cazenave, 2010). In addition, underestimating SLR can result in weak preparation for SLR and its effects that can have enormous financial implications (Pfeffer et al., 2008). For example, raising California Central Valley levees by a mere 0.15 meters will cost more than $1 billion (Mount & Twiss, 2005) in damages. It is essential, given the projections for 2100, that SLR be addressed in a serious way that includes long-term planning and infrastructural resilience.

Climate change in Oman is evidenced by higher temperatures, frequent extreme storms, and rainfall events. According to Al Wardy, Al Rawas, and Charabi (2016), between 2041 and 2060, a trend of an increased temperature of 2–5°C will take place in Oman, and between 2061 and 2080 the temperature is likely to rise by about 1.5–5.5°C. Al Wardy et al.’s study also projected a wetter climate over Dhofar’s region during the period of 2061–2080. Another study by Al Hatrushi and Charabi (2016) anticipated a significant increase of warm nights in the southern part of Oman. The projection of SLR in Oman, Muscat, is that at a 4°C temperature increase, SLR is projected at a median of 0.64 m (low emission estimate: 0.44 m; high emission estimate: 1.04 m). With a 1.5°C temperature increase, median sea level rises of 0.34 m, 0.35 m, and 0.39 m are projected for Tunis, Tangier, and Muscat, respectively (Snoj, 2015). We adopt Bromirski et al.’s (2012) global SLR projection of 1.41m by 2100 as a conservative metric.

Within the Omani context, extremes rainfall events/storms are usually associated with wadi flash flooding and storm surge. The damages from natural hazards are challenging and expensive. Golnaraghi (2012) estimates that natural hazards cause significant loss of life, in addition to setbacks in economic and social development in many countries. Ninety percent of disasters were related to weather, water, and climate; 70% of the events resulted in two million casualties; and 75% caused economic loss. According to Dasgupta, Laplante, Murray, and Wheeler (2009), Oman is placed within the top 10 countries that are likely to experience a 50% increased exposure to intensified storm surge events along their coastal areas. The increase in extreme storms or cyclone frequency for the coast of Oman was also predicted in a Ministry of Environment and Climate Affairs (MECA) report in 2013 and in Al Habsi, Gunawardhana, and Al Rawas’s study in 2015. Charabi, Al Wardy, and Al Rawas (2016) demonstrated that more than 50% of the rainfall will be associated with extreme events. In other words, catastrophic damages are what will be left after such events. Frequent natural hazards are already seen in Oman, for instance, the cyclonic storm ARB 01 in 2002, cyclone Gonu in 2007, Phet in 2010, cyclonic storm Keila in 2011, and Ashobaa in 2015. These events resulted in infrastructural damage that cost about $50million, $5billion, and $1billion, respectively, and the costs of infrastructural damage for cyclonic storms Keila and Ashobaa have not yet been released. Charabi et al. (2016) stated that by 2050 there will be an increase in the extreme rainfall events for return periods (49–52%), and change will be even more prominent by 2100 because the return period of these events will be between 81% and 101%. These figures shed light on Oman’s high vulnerability to flooding and its consequences for current and future development and infrastructure. A path toward resilient infrastructure is what Oman needs to engage in to mitigate for the future challenges of climate change.

Despite the effects of SLR in the coming decades, the consequences of storm surge are even more critical at a lower magnitude for lowland areas. According to Tebaldi, Strauss, and Zervas (2012), any increases in SLR by even a small amount creates huge impacts in low-lying coastal areas’ infrastructure and development, and these impacts are magnified when combined with storm surges. Therefore, the coastal zones are highly vulnerable to sea level rise when joined with storm surge. For instance, 20% of the world’s population lives within 30km of the coastal zone, and approximately 40% live within 100km of the coast. By 2100, 600 million people are expected to dwell on the coastal floodplain below the 100-year flood level (Nicholls & Small, 2002; Small & Nicholls, 2003). In other words, large numbers of people and infrastructure in low-lying lands will be vulnerable with the estimated SLR of 2100 and preparation for resiliency is needed.

focusing in on Asia and Africa, most countries in the South, the Southeast, East Asia, and Middle East/North Africa face serious consequences from SLR due to having densely populated cities and a growing infrastructure (Dasgupta, Laplante, Meisner, et al., 2009). At the same time, the Middle East and North Africa's coastal populations are predicted to have the largest percentage of exposure to storm surge devastations: 56.2% (Dasgupta, Laplante, Murray, & Wheeler, 2009). In Singapore, major developed lands on the low-lying islands will be inundated at 0.86m, a truth that led the country to construct a sea wall to protect their coastal areas (Ng & Mendelsohn, 2005). The socioeconomic infrastructure of Morocco's Mediterranean coast is vulnerable at 2m of SLR because 24% of the total area is subject to inundation (Snoussi, Ouchani, & Niazi, 2008). Furthermore, Snoj (2015) stated that Qatar is projected to lose 2.7% of its total land area at 1m SLR. Egypt is projected to lose about 13.1% of its agricultural and about 5.52% of its urban area. Libya is projected to lose 5.39% of its urban areas, the United Arab Emirates 4.8% of its urban areas, and Tunisia 4.5% of its urban areas. Another study, conducted by the World Bank in 2012, showed that the Middle East and North African regions are vulnerable at 1m of SLR because about 99% of their coastal wetlands at one meter elevations or less will be affected. It is worthwhile to mention the consequences of SLR in the Middle East goes beyond land loss; it also creates tension over the availability of fresh water sources due to the increased salinization of fresh water resulting from SLR. Oman, like other countries such as Bahrain, Qatar, UAE, Saudi Arabia, Kuwait, and Yemen is water-stressed country and would struggle to supply and maintain a fresh water supply given the salt intrusion from SLR (David, 2014).

Oman has undergone rapid modernization that transformed the country from being 11% urban in 1970 to 79% urban by 2005, and it is projected to be 86% urban by 2030 (Peterson, 2004). In Oman, sixty-seven percent of the Omani population inhabit the coastal areas. In addition to the population, the economy has also been booming along the coast. For example, new industries and tourism are located within the coastal area (Al-Jufaili et al., 1999). The coastal zone is an important space in terms of its social, economic, and ecological value given that there is a need to initiate reliable national-to-global scale readiness to deal with the potential consequences of SLR (Vafeidis et al., 2008). The growth and the expansion of coastal cities in Oman indicates the vulnerability of social, built environments and of ecosystems to any natural disasters or SLR that may occur in the future (Belqacem, 2010). Quantifying land impacted or lost and infrastructure damaged at various SLR scenarios is important to motivate Oman to take adaptive action toward a resilient future in the context of coastal development and city expansion.

The geographical location of Oman exposes the country to various natural hazards, especially on the eastern tip of the Arabian Peninsula (Warren & Miller, 2007). Tropical cyclones yield flash flooding along the wadis (Al-Shaqsi, 2014; Al Rawas, Hewawasam, Alwardy, & Charabi, 2016). The steep mountains and the impermeability of wadi watersheds, coupled with the narrow wadi ravines, contribute to severe flooding in Oman during hazardous natural events (Al-Qurashi, 2014). The most sensitive area in Oman is the plain that overlooks the Omani Sea. This plain is only 3% of the country's total land area, yet it is the most densely populated area in the country with rapid growth and industrialization that creates a challenge for emergency management during the cyclone events. The mountain ranges occupy almost 15% of the total land area of Oman, and the watersheds of this region endure an increased risk of wadi flooding. The remaining 82% of the land area of Oman is mainly dry river beds and deserts (Al-Shaqsi, 2014). Thus, looking at the extent of the flooding during the 2002 storm surge event in Dhofar in the context of SLR is significant and provides valuable information for planners and decision-makers.

The impact of SLR will be felt most intensely through extreme events. The water level associated with storm surge is significant because it exposes coastal development and communities to water intrusion at increasingly unusual tidal heights (Tebaldi et al., 2012). These events encourage us to change our responses and to adapt in anticipation of frequent extreme events. Consequences from climate change and storm surge require that designers, planners, and policymakers promote the development of resilient infrastructure and cities for the future (Hunter, 2012). For that reason, a delineation of 100-year floodplains or extreme events should influence coastal policy and development toward resilient communities and infrastructure.

This study delineates and maps the flood damage to infrastructure and cities along Dhofar's coast from extreme storm surge in 2002. The 2002 storm was the first storm to hit Oman that resulted in $50 million worth of infrastructural damage since the onset of development in the country. Extensive flooding inundated the coastal area and led to the necessity to reconstruct roads and rebuild residential areas. The goal of this research is to model and measure the extent of the damage from the 2002 storm, and the risk of future damage given a rise in sea-level resulting from climate change.

This research also presents a model of SLR using 3Di flooding software[2] to Dhofar's governance in Oman and models the extent of the inundation resulting from the 2002 storm, and the storm surge processes, to quantify and estimate the coastal and inland vulnerability to SLR. In addition, the study maps and quantifies the impact of multiple SLR scenarios during extreme storm surge events of 2002 in Dhofar in association with 0.5, 1.0, and 1.41 m of SLR. The model simulation is based on 60-minute interval water level data for a 72-hour, extreme storm event, coupled with 0.5 meter, 1.0 meter, and 1.41 meter SLR for different inundation scenarios. The results of 3Di modeling includes a series of inundated areas at 1-hour-interval time steps that demonstrate the extent of spatial inundation and water depth at every hour of the 2002 event. The modeling effort is both 3 dimensional and dynamic through time.

3.2 Study Site

The Dhofar Governance is located in the southern part of Oman. Its coastal plain is divided into three geomorphological areas: the mountainous area, which forms the catchment for the southward and northward flowing streams; the intermediate zone area, located at the mountain's foot; and the plain, which is a belt of tertiary limestone that extends to Rub AlKhali Basin (Forster & Magnan, n.d.).

[2]Stelling, G. S. (2012). Quadtree flood simulations with sub-grid digital elevation models. Proceedings of the ICE-Water Management, 165(10), 567-580. doi:10.1680/wama.12.00018

Generally, the climate in Oman is characterized by arid and semi-arid climates. The country is exposed to two different climatic systems: one is a cyclonic system, moving from the north during winter, and the second is the monsoon, moving from the southwest in summer. The climate is known to be uncertain due to the variation in frequency of these two systems. Wadis usually have water after rainstorm events. The density of wadi flooding is strongly related to the annual rainfall duration and frequency in the long term (Nouh, 2006).

The coastal zone management plan of Dhofar that was created in 1988 and is used as the basis for current and future development projects in the area. In 1988, the Ministry of Commerce and Industry conducted an ecological survey of Dhofar’s coastal zone through IUN-World Conservation Union. The goal of that study was to develop a management plan for different land uses along Dhofar’s coastal area. The survey revealed that the coast of Dhofar is exposed to seasonal wave action ranging from moderate to heavy. Ecological concerns were noted as a result of road construction that created a significant threat for the lagoon area and in terms of beach encroachment resulting from oil spills and solid waste (Salm & Jensen, 1989). It is worth mentioning that the issues related to climate change were not within the scope of the survey at that time. For that reason, some of the developments that are taking place in the Dhofar area are vulnerable to effects of climate change such as SLR, which has an enormous impact on the infrastructure.

3.3 History of Natural Hazards in Dhofar

Throughout the history of Dhofar Governance, the city of Salalah was at particular risk for exposure to cyclonic and extreme events, which registered at various levels of the magnitude table (Table 1). Salalah’s exposure to cyclonic storms resulted in extensive disruption of the life and infrastructure of the city (Al-Hakamani, 2002). According to Forster and Magnan (n.d.), the governance’s location had exposed the Salalah plain to frequent and severe weather events at six-year intervals. Even though the city had experienced eight natural hazards before the extreme storm events of 2002, that storm created a wake-up call for the government. This was partly because the development in Oman had started by the onset of 1970s and any earlier damage from storms was minimal from the perspective of infrastructure. The 2002 storm was the first storm to result in high infrastructural damage that Oman had on record since development had begun. According to Al-Hakmani (2002), the 2002 storm in Salalah was considered a severe storm within Oman, especially in the context of the significant infrastructural damage it inflicted, which cost about $50 million. Yet, the 2002 event was not close to the 100-year magnitude. Looking at the amount of rainfall during 12 hours, a storm event in 1963 or 1966 was higher in magnitude and had a higher potential for greater infrastructural damage. The density of wadi flooding is strongly related to the annual rainfall depth and frequency (Nouh, 2006). The morphology of Oman makes it conducive for severe flooding either from the sea or from flash wadi flooding which often leads to serious damage.

The consequences of flooding for urban areas, infrastructure, and everyday life are significant because damage from flooding creates direct and indirect monetary loss (Schmitt, Thomas, & Ettrich, 2004; Mark et al., 2004). For that reason, the creation of long-term sustainable development and resilient infrastructure is extremely important for the coastal area of Oman. Modeling and integrating impacts of natural hazards into the land-use planning contributes to resilient cities (Burby et al., 2000). Taking action by constructing dams for the new development, as is suggested by Salalah's master plan created after 2002 (Al-Hakamni, 2002), or enhancing and constructing more sea walls, as was done in Singapore (Ng & Mendelsohn, 2005), is not an adequate solution toward resiliency and adaptation regarding climate change threats, however, they could help to mitigate impacts.

Table 1
Cyclonic Storms in Salalah Plain

Month	Year	Total Rainfall in mm	Max. Rainfall per 12 hrs in mm
23-26 October	1948	156.8	33.0
23-26 May	1959	117.2	81.8
26-29 May	1963	236.1	134.0
12-13 November	1966	202.3	178.1
14-18 June	1977	122.7	70.3
4 April	1983	Not Available	127.0
11-13 May	1996	98.0	Not Available
9-12 May	2002	191.8	145.6
20 May	2003	Not Available	Not Available
29-30 September	2004	116.2	116.2
3 November	2011	700	200 (Noos Mountain)

Source: Alruheili, 2016.

Creating resilient infrastructure and cities by incorporating extreme event flooding risk at high resolution in the planning of development is important, as was shown by Biging et al. (2012) and Radke etal. (2017) study. Their high-resolution data set helped to better predict the impacts of SLR and extreme storm events on the transportation infrastructure of the San Francisco Bay region.

3.4 Method of Inquiry

This study used a 3 dimensional hydrodynamic model, 3Di, developed by TU-Delft, Netherlands, to simulate the inundation extent of Salalah's 2002 extreme storm event using 0.5, 1.0, and 1.41meter increments of SLR. 3Di combines four numerical methods to conduct the simulations: the sub-grid method; bottom friction, that is based on roughness depth; a finite volume staggered grid; and quad-tree techniques (Stelling, 2012; Dahm et al., 2014).

The 3Di model inputs include time-series water-level data and digital elevation surface data. The model simulates an entire tidal cycle and calculates, in a series of time steps, the flow direction, velocity, and water depth as a flood event progresses. From each time step, the inundation frequency and average inundation depth are obtained (Figure 1). In addition, by combining the output from each time step, the model provides visual communication for potential risk areas, making the model a valuable tool for planning and mitigation actions. To run a 3Di simulation, a digital elevation model DEM, bathymetry, initial water boundaries, and water levels are required as input for the software.

3.4.1 Digital Elevation Model (DEM)

The DEM is used to represent bare-ground elevations. A Lidar-based digital elevation model (DEM) is an ideal input for flood modeling in 3Di as it can work with a Lidar-based DEM at 1meter resolution (Dahm et al., 2014). However, in Oman this type of data has not been gathered.

For the Dhofar case study we use the most recent and highest resolution data, a 5m DEM that exists for Oman. A 5m DEM was created for the "Nationwide Orthophoto Coverage and Data Management System" project in 2013. The 5m DEM was obtained from Oman's National Survey Authority (NSA).

We delineate and include objects such as buildings when creating the 5m DEM because they have the potential to play a significant role in diverting the path of water. Their inclusion provides more realistic inundation and water movement paths during an event. Since Lidar data does not exist in Oman, the elevations of objects on the ground, such as building height, is assumed. Finally, the assumed building height, combined with the DEM and bathymetry, data an elevation surface model that best represents the environment to be inundated by the 3Di hydrodynamic model.

3.4.2 Bathymetry

Bathymetry for the coast of Salalah was obtained from National Oceanic and Atmospheric Administration (NOAA) dataset. The bathymetry grids resolution is ~950m with ~ 10m vertical accuracy (Amante & Eakins, 2009). We resample the bathymetry to $5m^2$ and then combine it with the DEM grids to produce a final $5m^2$ horizontal resolution raster for input to the 3Di model.

3.4.3 Water Level

The possibility that a 100-year storm took place in Dhofar Governance during 1966 is high, as the governance witnessed about 178.1 mm of rainfall in 12 hours, during which huge wadi flooding and losses took place (Al Barwani, 2010). However, no historical records are available to provide information about storm surge height. In Oman, tidal data started to be collected in 1998 through Oman's National Hydrographic Office (ONHO). In 2002, the Governance, Salalah city, had been hit by an extreme storm event in which the city received about 145.6 mm in 12 hours (MRMWR, 2015). The 2002 extreme events were considered one of the most catastrophic incidents that had hit Salalah and resulted in enormous damage to the city.

One aspect of the damage during the 2002 extreme event was to the infrastructure that cost the country about $50 million (Al-Shaqsi, 2014). Due to the absence of historical tidal data records, this research uses storm surge records from May 9–11 of the 2002 event to simulate storm surge. Storm surge from this event was reported to be 3.2m at Marbat and 3.12m at Port of Salalah. The tidal data of these two stations is obtained from ONHO and the data spatially referenced to the WGS1984 vertical datum. Bromirski and Flick (2008) studied the impacts of tidal and storm surge within the San Francisco Bay-Delta region and used hourly water level a data from the 1998 storm to predict storm surge impacts on the delta's levee failure. Storm surge has a significant impact on coastal zones and their ecosystems, and the damage they cause is huge due to high tides.

The model 3Di has the capability to incorporate the dynamic tidal and storm surge processes—to dynamically simulate the movement of changing water volumes over land surfaces over time. For Salalah's coast, the inundation simulation includes storm surge during the 2002 storm event that is based on time-series water level data measured at the two existing tidal gauges in association with different SLR scenarios. A recent study by MECA in 2013 had conducted a simulation of SLR for the entire coast of Oman, but that study did not incorporate storm surge or tidal process. The MECA study used a static bathtub model at 40m spatial resolution. Moreover, no study to date has modeled the coast of Dhofar during the 2002 storm event.

More than 35 tiles are created along the coast of Dhofar Governance each tile is assigned water level data recorded from the ONHO Tide Gauging Stations during the 2002 extreme storm event that affected the Governance coast.

Initial water boundaries and water level data for each tile. Water boundaries are created to simulate virtual waves in 3Di to provide initial water level data; in this case study, the hourly water level is used. The coast of Dhofar is delineated by tiles, and the input of water level data is provided for each tile. Each tile has its own initial boundary generated along the tile's boundary sections that are in the ocean (the bathymetry side of the surface model). As only two stations exist along Dhofar's coast, virtual stations are created at the mid-point of the initial ocean boundary for each tile.

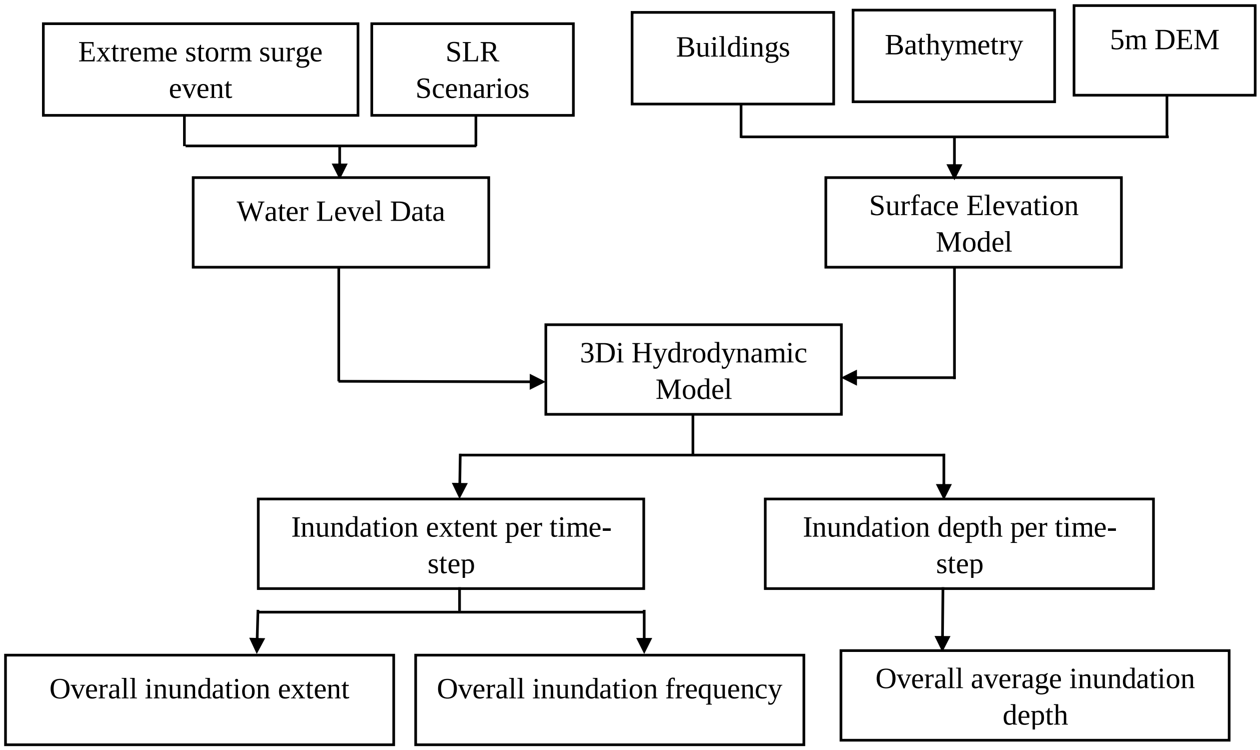

Figure 4. Flow chart of the modeling approach (Alruheili, 2016).

3.5 3Di Modeling of Dhofar's Coast

3Di is used to simulate the entire tidal cycle during the 2002 storm event. 3Di calculates the flow direction, velocity, and water depth at 0.0, 0.5, 1.0, and 1.41-meter SLR, respectively. One-hour interval time steps are defined for 3Di output water-level surfaces. The output from each SLR inundation scenario includes a series of inundated areas that allowes the researcher to investigate the extent of spatial inundation and the water depth every hour. In addition, results from the time steps are combined to calculate inundation frequency and average inundation depth for the entire 2002 storm event.

The accuracy of the 3Di 5 m^2 resolution simulation model is verified by comparing and validating the simulated water level prediction with the actual measured water levels at Port of Salalah, and Marbat tidal gauges during the 2002 storm event. The coefficient of determination (R2) is our indicator of accuracy, where a value close to 1 indicates a more accurate simulation. From Figure 5 the 3Di 5 m2 resolution simulation proves to be quite accurate with the lowest R2 (0.8623) at Port of Salalah[3]. The collection of validation locations is small because only two gauging stations have complete data records for 2002 storm event. Therefore, we use the virtual stations[4] along with Port of Salalah and Marbat stations to calibrate 3Di along the coast of Dhofar.

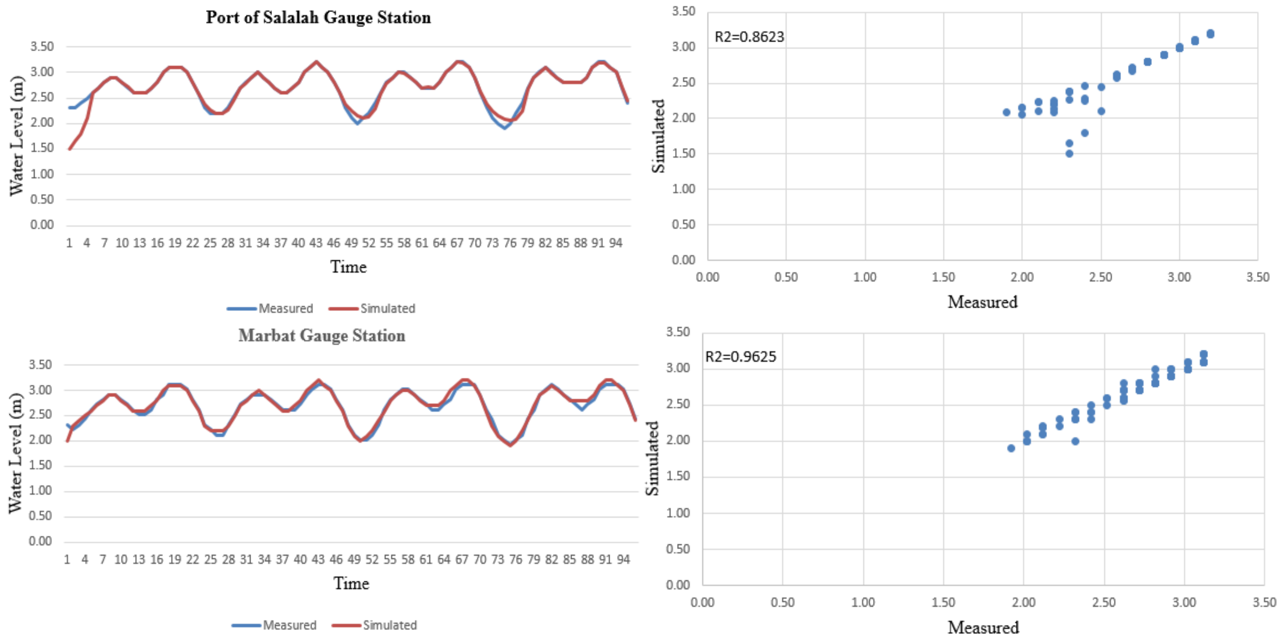

Figure 5: 3Di 5 m^2 resolution measured and simulated water level comparison at Port of Salalah, and Marbat

3.5.1 Consequences of Flooding

The national report of MECA in 2013 stated that Dhofar's coastal areas are under no risk at <2m of SLR and that up to 40 $km^2$of total land will be inundated at that level (see Figure 6). Moreover, the report stated that the inundated area features open land that is not under any agricultural, industrial, residential, or other use (MECA, 2013, p. 58). However, this current research disputes the MECA claim and shows an impact of SLR on infrastructure and residential areas at <1m of SLR.

[3]Radke et al (2017)

[4]Virtual Station is a pseudo station that record simulated water levels and calculate the mean water level used to calibrate 3Di model

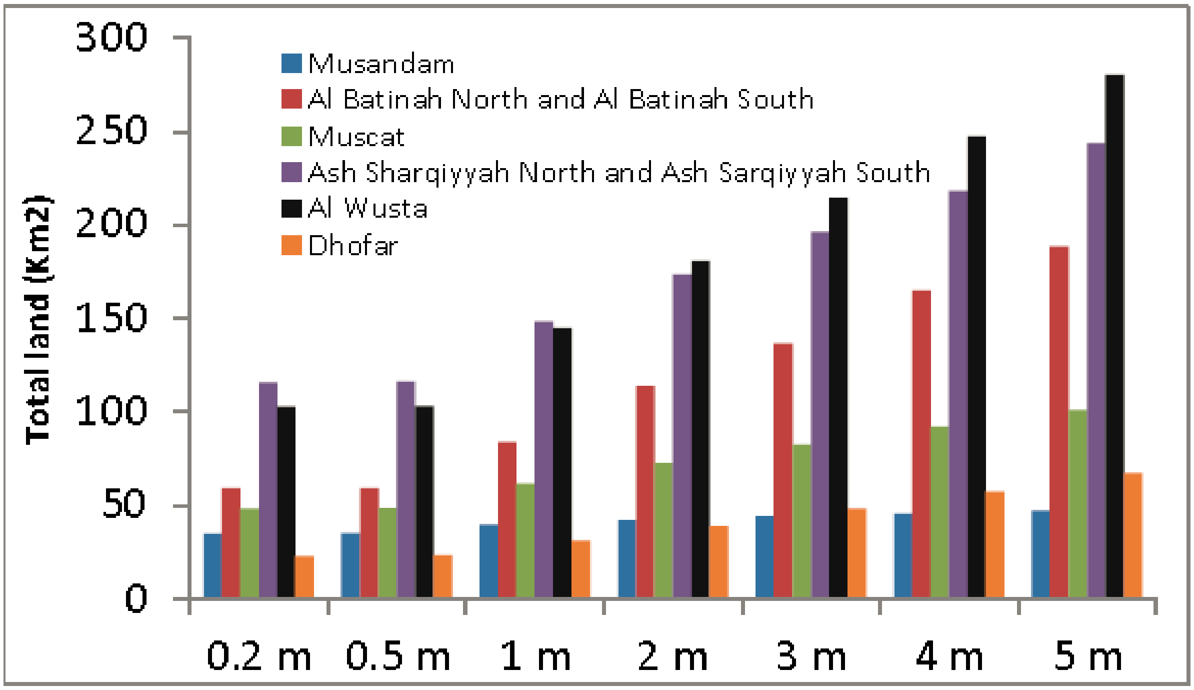

Figure 6. Total inundated land area, by Governorate (obtained from MECA 2013 report).

3.6 Results

The results of this research show the need for resilient planning and infrastructure in Dhofar's Governance as a path toward a sustainable and resilient developmental future. This research provides the most realistic predictions of inundation to date as the simulations are based on a real extreme storm event of 2002. The 3Di model is able to provide a representation of the entire storm surge at relatively high spatial resolutions and including all buildings that influence and channelize the water movement. SLR simulations at 0.0, 0.5, 1.0, and 1.41 m scenarios provide the most realistic inundation measures, today and projecting forward in time, for the destruction of a 2002 extreme storm event for Dhofar's coastal area.

The output of the 3Di inundation extents are intersected with the buildings and roads for Dhofar's governance, allowing the study to quantify the risk to infrastructure associated with the inundation. This study recommends that policy-makers and planners adopt design mitigation strategies to prevent future economic loss and to promote resiliency in future developmental projects.

3.6.1 Dhofar's Coast Inundation Output

The coast of Dhofar features low-lying areas and steep slopes. This research shows coastal inundation to South Dahariz and Taqa, where the landscape is low-lying; more inundation takes place here than on the rest of the coast, where infrastructure is more significantly affected. Dhofar's coastal infrastructure at Taqa and South Dahariz is significantly affected by SLR because the Governance's built area and infrastructure are located within the inundation area (see Figure 7). Overall, Dhofar's coast shows that with 0m SLR, the inundated area is **10.01** km^2. For

0.5 m SLR, the inundated area increases to **15.41** km^2; with 1.0 m SLR, this number increases to **22.27** km^2; and finally, a 1.41 m SLR will result in **30.03** km^2 being inundated.

It also worth mentioning that Marbat and the port area are affected as well. Figure 8 includes a zoomed-in illustration of the change in inundation over the four SLR scenarios at 0.0 m, 0.5 m. 1.0 m, and 1.41m for South Dahariz and Taqa. This research shows inundation took place at South Dahariz and Taqa on the first day of the storm, even with no sea level rise (SLR_0); this is because they are lowland areas that are sensitive to high tides.

Since 3Di is a dynamic model, showing the dynamic results of inundation output is informative for the governance and for emergency responders in Oman. The output of 3Di shows the water flood paths to the infrastructure and buildings during the 2002 extreme storm event. The input of 3Di for this research uses the $PWL_{1.41} = SLR_{1.41}$ + hourly storm surge of extreme storm event of 2002 simulation (see Figure 8).

The model 3Di helps in visualizing the impacts of SLR and 2002 storm surge and shows its dynamic process. The South Dahariz coastal area is an example for mapping inundation extent and depth during the 2002 extreme storm event at various hours for a 96-hour period for the 1.41m SLR scenario. In Figure 8, a large portion of South Dahariz and Taqa are inundated during the first 18 hours. The water accumulates over the inundated areas very fast, leading to deeper water levels and further damage to the built area. The advantage of 3Di lies in its ability to look at time-series output for any area along Dhofar's coast at an hourly interval. This research is also able to map the inundation of the entire 2002 storm event, which had not been done before.

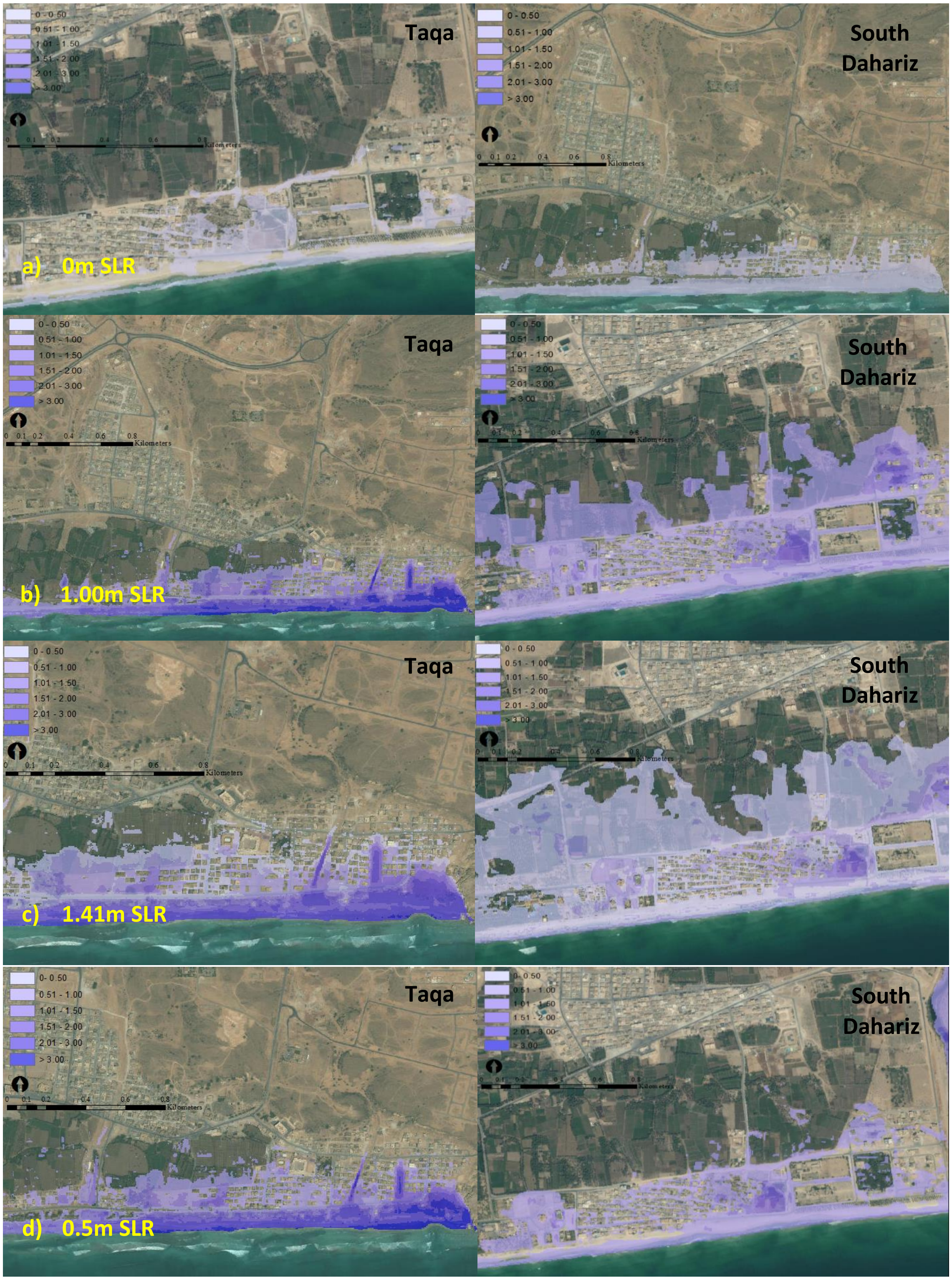

Figure 7. Taqa and South Dahariz inundation through PWLx = SLRx + Extreme Water Event of May 9-12, 2002 (where x = 0.0, 0.5, 1.0, and 1.41m). (basemap ArcGIS, 2017)

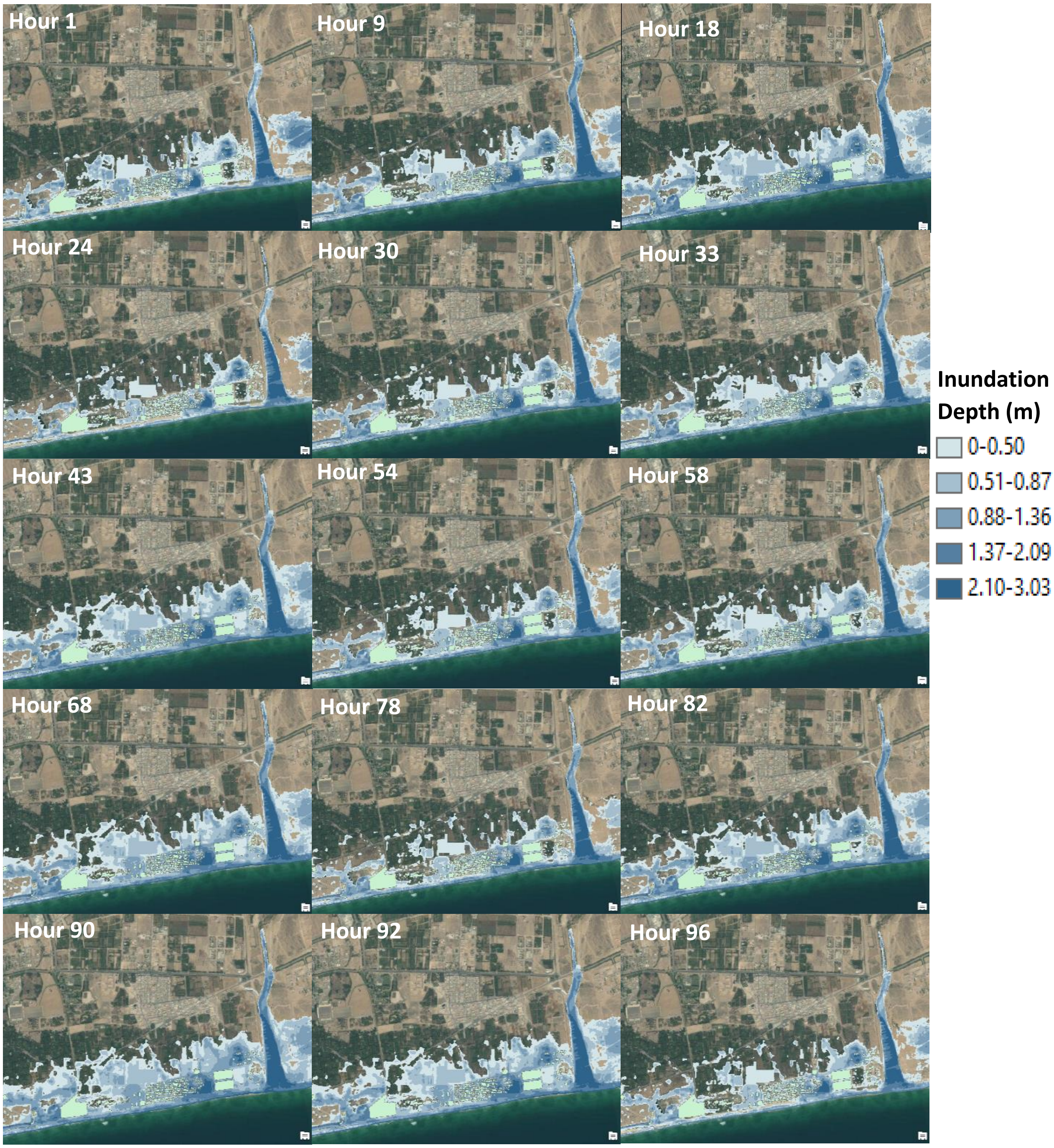

Figure 8. Time-series inundation of extreme storm event associated with 1.41m SLR in South Dahariz city ($PWL_{1.41} = SLR_{1.41}$ + extreme storm event of 2002). (basemap ArcGIS, 2017)

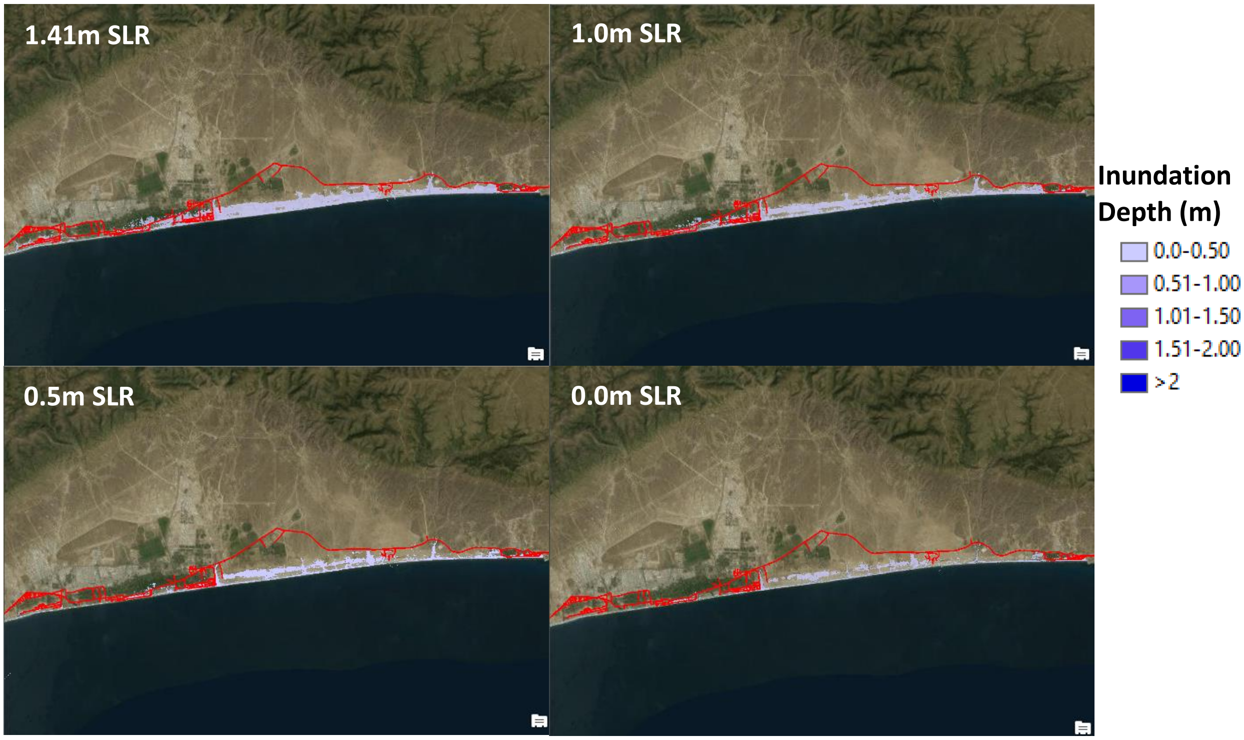

Figure 9. Maps of impact on Dhofar's roads by SLR of 1.41m to 0.0m inundation coupled with 2002 extreme storm event. (basemap ArcGIS, 2017)

3.7 Dhofar's Governance Buildings and Roads Inundation Output

Oman is continually improving its infrastructure to achieve modernity and to meet its national developmental plans. A considerable amount of Oman's income is spent toward road construction such as a $344 million project for major road construction across the country; $150 million for 758km Nizwa-Thumrait road project and so on (Broomhall, 2010). Nerveless, the 8th Five-Year Development Plan for 2011-2015 showed Oman plans to spend around US$14.8 billion on transportation infrastructure such as roads maintenance, ports and airports ("Roads a Priority," 2013). During 2014, the Governance of Dhofar constructed about 866km roads (NCSI, 2014). Since large amount of Oman's revenue is used for roads and infrastructure the resiliency of these newly developed are extremely important.

Because Oman's economy is based on oil, fluctuations in oil prices heavily affect Oman's developmental plans; the country is loath to stop constructing new infrastructure in order to fix damages after a storm. This research shows the vulnerability of some roads in Dhofar during the 2002 event, thereby shedding light on the need for some revision to current infrastructural developmental practices. Figure 9 provides a look at the extent of the inundation over the four SLR scenarios in combination with the 2002 extreme storm event. At SLR 1.41 we see coastal roads are extensively inundated.

Table 2 shows the inundation simulation for coastal roads and buildings in Dhofar for the 2002 extreme storm event. At 0.0m with no sea level rise, only 39km of roads and 897 buildings are inundated. However, by SLR1.41, approximately 101.6km and 1560 buildings are inundated.

Table 2
Results of Inundation to Dhofar's Roads Over Four SLR Scenarios at 0.0, 0.5, 1.0, and 1.41m

SLR Value	Total km of roads inundated in Dhofar's Governance	Total number of buildings inundated in Dhofar's Governance
1.41 m + 2002 storm	101.6	1560
1.0 m + 2002 storm	92.2	1347
0.5 m + 2002 storm	51.5	1197
0.0 m + 2002 storm	39	897

Table 3 summarizes the inundation of coastal roads in Dhofar by offering the amount of roads inundated by depth, or Peak Water Level (PWL) of exposure. The results are classified to clarify the patterns of depth across the SLR scenarios. During the 2002 extreme storm event at no sea level rise, about 39km of inundated coastal roads experience a PWL between 0 and 1 meters. With a simulated SLR of 1.0, about 81.506km of inundated roads experience a PWL of between 0 and 1 of meter, and about 10.662km of roads are exposed to SLR inundation of between 1 and 2 meters. However, with a simulated $SLR_{1.41}$, about 89.045km of roads are inundated to PWLs of between 0 and 1 meter, and about 11.514km of roads are exposed to SLR inundation of between 1 and 2 meters.

Table 3
Length in Kilometers of Coastal Roads Inundation in Dhofar by PWLx = SLRx + 2002 Extreme Storm Event (Where x = 0.0, 0.5, 1.0, and 1.41 m)

Water Depth	1.41SLR_Roads	1.00mSLR_Roads	0.5mSLR_Roads	0.0mSLR_Roads
0-1m	89.045km	81.506km	51.5km	39km
1-2m	11.514km	10.662km	0	0

This research produces a first visual of the inundation caused by the 2002 storm at Dhofar with a high-resolution GIS-based model used in the analysis of various SLR scenarios to help in assessing the risk and vulnerability of current and future infrastructural developments in the region.

That said, it seems that modeling the impacts of the 2002 storm surge using various SLR scenarios does not provide a complete picture of the magnitude of the storm impacts that resulted from wadi flash flooding. The results of this study could not show the extent of infrastructural damage resulting from the 2002 storm; the damage was underestimated because wadi flooding occurred in conjunction with storm surge during the event.

3.8 Accuracy Assessments

A site in San Diego, California, shown in Figure 10, is chosen to compare the impact of DEM resolution in 3Di inundation outputs at 1m and 5m resolutions respectively. The site was selected because it has topographic and climatic conditions similar to those in Oman. Lidar data for the California site is obtained from a 2009–2011 Coastal Conservancy LiDAR Project. Both 1m DEM and 5m DEM models are created from the Lidar data set using ArcGIS. Bathymetry data was obtained at 200m^2 resolution from the California Department of Fish and Wildlife (2007). Data from a 2005 “near 100-year” storm event is used for actual water-level data in association with 1.41m SLR.

Figure 10. San Diego selected site. (basemap ArcGIS, 2017)

Based on the water-level data prepared, models with two different DEM grids, including 1x1m and 5x5m, have been built that simulate the selected 2005 storm event. Results show that the maximum flood extents given by the two models demonstrate similar flood-extent maps, as shown in Figure 10.

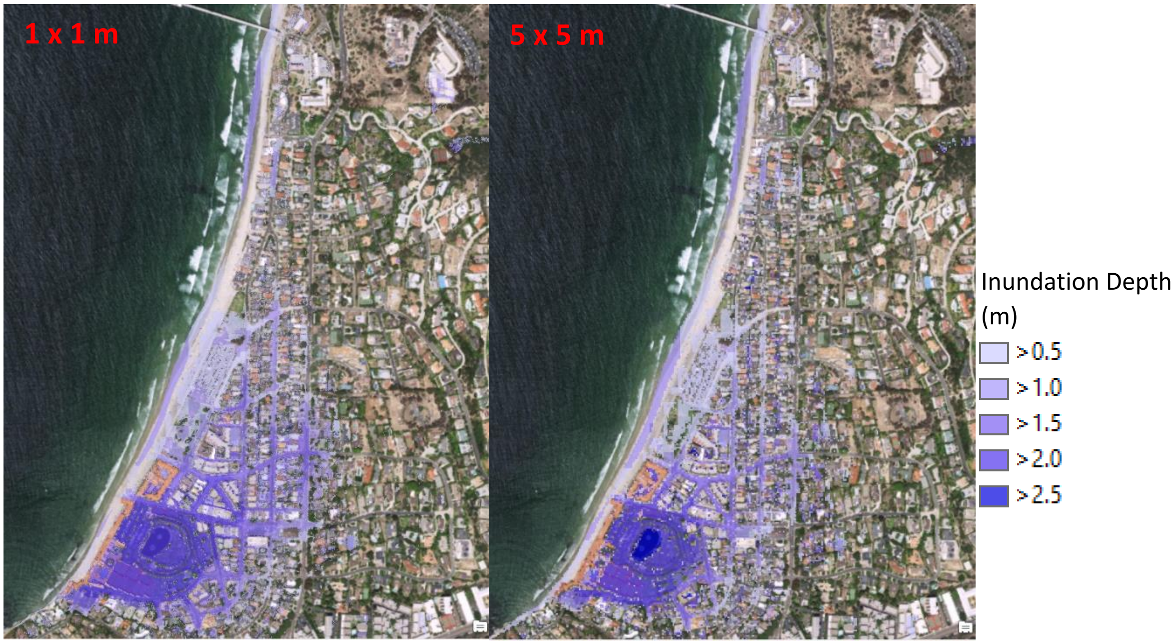

Figure 11. San Diego flood inundation extent at 1m and 5m DEM resolution. (basemap ArcGIS, 2017)

However, the inundation extent between $1m^2$ resolution and $5m^2$ resolution differ significantly in the output of the models. Table 4 shows that at $1m^2$ DEM resolution the inundation extent is covered by 304,802 square meters at a water depth greater than 0.5m, while for the $5m^2$ DEM grid, the inundation extent (for the same 0.5m depth) is 275,250 square meters. The inundation extent, for most water depths, decreases with increased grid size. The coarser DEM grids give a smaller inundation extent and thereby lead researchers to underestimate the inundation impacts from SLR.

Table 4
Inundated area in square meters Evaluated Based on Maximum Flood Extents

Water Depth (m)	Inundated area in m^2	
	1 x 1 m	5 x 5 m
> 0.5	304,802	275,250
> 1.0	155,294	150,100
> 1.5	657,25	53,950
> 2.0	67,447	58,150
> 2.5	90	6,500

3.9 Limitations

One of the main limitations of this research is the flow of water between pixels within the output. This is likely due to the inability of 3Di to detect change within a very low-elevation surface like Dhofar's, even with very fine grid and time-step instruments such as DEM at 1m spatial resolution. A Lidar-based DEM could overcome this problem. This study could be improved if water data were available at 15-minute intervals instead of 1-hour intervals, as was the case with data from Dhofar's coast.

3.10 Conclusion

This research is helpful in developing a better forecast for infrastructural impacts from SLR and storm surge than the study conducted by MECA in 2013 because it incorporates improved, dynamic and higher dimensional sea level rise modeling and the storm surge tidal process.

This study can help the governance of Dhofar to create more realistic mitigation plans and infrastructure management strategies. The ability to map the extent of the inundation area is improved by using the 3Di hydrodynamic model, which simulates the entire tidal cycle. 3Di also is able to model a very large region at a very high spatial resolution due to its sophisticated quadtree-based data compression technology. This produces a better and a higher-resolution surface model of Dhofar's coast. This research includes objects such as buildings that might help in channelizing and accelerating water movements produced by a storm surge. In addition, this research incorporates real data from gauging stations of the 2002 event instead of modeling based on theoretical 100-year storm events. This approach allows the research to produce more realistic predictions and to be able to calibrate 3 dimensional hydrodynamic model.

It is clear that the morphology of Oman is challenging and serves to create severe flooding, either from the sea or from wadi flash flooding that causes serious damage. For that reason, taking steps toward creating local resilience within Dhofar's infrastructure is a step toward national resilience. Vale and Campanella (2005) stated that local resilience is an indication of national resilience, which signifies the resilience of the government as a whole. If Oman is to be ready for the new future, the new resiliency must be present in each unit of urban fabric and government. Adopting resilient thinking and practices will provide a different understanding of the situation around us and allow us to cope with the uncertain future (Walker & Salt, 2012). Integrating science into planning will help us to achieve the meaning of infrastructural resilience as it is defined: "the capacity of system to respond to change or disturbance without changing its basic state and to recover in a short time" (NAIC, 2009, p8).

CHAPTER 4

4.1 Introduction

Since development has accelerated, environmental problems and degradation have become obvious, stimulating the establishment of the World Commission on Environment and Development (WCED) in 1983. WCED created a definition of sustainable development (SD): "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43). The goal of SD is to minimize environmental degradation arising from developmental activities. Because the concept of SD is ambiguous, it has been implemented in subjective ways, creating a challenge in terms of developing an effective, unbiased process (Lele, 1991).

The term *sustainable development* usually refers to the ability of the system to maintain productivity in the face of major disturbances, such as erosion and flooding, that result in system collapse and productivity decreases that mean the system is not considered sustainable (Redclift, 2002). Coastal tourism is considered sustainable when it is able to withstand risks associated with natural hazards, such as cyclones, hurricanes, and storms, without collapsing (Hall, 2001). However, sustainability within the environmental context focuses on sustaining resources through maintaining and prolonging the resources' productivity and their integrity (Dixon & Fallon, 1989). Therefore, the term *sustainable development* is used to indicate either ecologically sustainable or environmentally sound development (Tolba, 1987). Moreover, the definition of development usually is tied to economic growth (Lafferty, 2002; Redclift, 2002). This indicates that SD is connected to reducing environmental and resources destruction resulting from development and has less focus on preserving the built environment. This means that the term *sustainability* originally developed in a biological/physical context and now is applied in a socioeconomic context. Dixon and Fallon (1989) stated that the term *sustainability* has been used as a bridge between development and the environment to justify proposed actions.

For instance, the concept of sustainability was linked to renewable resources, such as fisheries or forests that were adopted by the environmental movement (Brown, Hansen, Liverman, & Merideth, 1987). Sustainability as a concept continues to broaden and evolve as people encounter the challenges of regulating these renewable resources. As a result, sustainability has progressed from being purely physical for a single resource, to a physical concept for a group of resources (ecosystem), to a social-physical-economic concept (Dixon & Fallon, 1989). Now the term has been expanding further, heading toward social-physical-economic-ethic-equity, ever since its appearance in the realm of sustaining forestry (Wiersum, 1995). The ambiguity present in trying to define sustainability has created vagueness regarding what the word means, resulting in varying interpretations and applications of the term.

4.2 Sustainable Tourism

The World Tourism Organization (WTO, 2001) defined sustainable tourism development as development that meets the needs of current tourists and host regions while protecting and enhancing opportunities for future generations. Enhancing opportunities for future generations requires preserving the country's cultural integrity, ecological processes, and biological diversity, in addition to maintaining resources while fulfilling the economic, social, and aesthetic needs of the area's host regions and of tourists. Approaches to sustainable tourism described by Hunter (1997) included *tourism imperative*, *product led tourism*, *environmental-led tourism*, *and neotenous tourism*. These tools were proposed as pathways toward protecting the environment and nature that would help Oman to achieve sustainable tourism.

In the developing world, sustainable tourism has become an increasingly popular field of research since the late 1980s due to the popularization of the SD concept as an environmental management approach (Hunter, 1997; Sharpley, 2000). As a result, sustainable tourism is used as a tool to set principles, policy prescriptions, and management methods for destination tourist areas (Lane, 1994). However, the concept of sustainable tourism is tourism-centric, which means that it fails to provide policies that address concerns about SD and tourism sustainability (Wall, 1993). This is because sustainable tourism is perceived as having the ability to create balance between the demands of tourism and of a sustainable environmental system, or a balance between the environment and economic development (Hardy, Beeton, & Pearson, 2002; Hunter, 1997; Müller, 1994). But figuring out exactly how to achieve this balance is challenging, as was mentioned earlier, because of the lack of clarity regarding what SD means. The question is whether it is possible to have tourism development that has the capability to preserve the absolute natural resources or could serve as a mitigating factor regarding impacts resulting from climate change for future generations. Because we are living in a system and an ecosystem, any interaction with a single element within the system and ecosystem will evoke a reaction in another. As Lanfant and Graburn (1992) stated, the commodification of nature and other aspects of the environment is always present in tourism practices. And there is always a price for commodifying nature and the environment at different magnitudes.

Since tourism development and its associated industries must fit the environmental characteristics of the intended site, developers need to understand the venue and be flexible if they are to create sustainable tourism planning (Dowling, 1993; Lane, 1994). With this in mind, a holistic approach with an environmental planning consideration within tourism planning has the potential to achieve a reasonable tourism destination that demonstrates a closer balance between the needs of tourism and of the environment. The holistic planning approach has been practiced in coastal zone (CZ) planning, which is in a state of continuous change (Post, Lundin, & Mundial, 1996; Sorensen, 1993). A systematic planning approach is needed to improve our understanding of patterns of changes to tourism projects to help us to detect the dynamic interaction of, and fluctuations within, the natural, technological, social, and economic environments (Liu, 1994, 2003).

Researchers encouraged stakeholders to adapt the ecosystem process, modifying it within the context of land use and development to reduce natural and environmental destruction (Berke & Conroy, 2000). For example, the unplanned coastal tourism development in South East Asia provides excellent examples of negative environmental and socioeconomic consequences, because the ecosystem process is not incorporated into the tourism planning process (Wong, 1998). We agree with Liu's (2003) statement about the need to blend information and a transparent, systematic planning approach in working toward sustainable, tourism-related development. Sustainable development is described as a process-oriented function that has the ability to manage changes to improve the conditions for those involved (Butler, 1999). Both sustainable tourism tools and SD are adopting Ian McHarg's (1969) concept of environmental planning, or "design with nature," which takes into consideration human and environmental interaction. Adopting the "design with nature" concept and working toward long-term benefits for future generations may constitute sustainable tourism.

4.3 Tourism in Oman

New development, new buildings, and even roads make Oman more modern; however, they have consequences. It is impossible to have a form of tourism development that does not have impacts upon the location in which it occurs. Tourism in Oman began very conservatively in the late 1980s, when the country cautiously opened its gates to selective tourism. Initially, tourism development policy in Oman focused on quality rather than on a mass tourism approach. The government's policy has been to move slowly in terms of tourism development, keeping development numbers low to minimize environmental impacts (Hazbun, 2004; Mershen, 2006). This decision was also made because only 7% of Oman's land is actually in use, meaning that portion needed to be protected (Al-Shaybany, 2001). According to Subramoniam, Al-Essai, Al-Marashadi, and Al-Kindi (2010), Oman faces a variety of environmental problems, including soil and water salinity, industrial pollution to ground water, desertification, and scarcity of water due to long periods of drought. These challenges indicate the need to be conscious and careful with new tourism-related development in Oman and to be sensitive to impacts on the country's environment and natural resources.

Recently, Oman has been considered as a new tourism destination since emerging in the European travel industry in the mid-1990s (Feighery, 2012; Mershen, 2006). Even though Oman's initial reaction to selective tourism showed concern for the country's environment and culture, the pressure to engage in massive development to diversify the country's income has weakened the selective tourism approach. For that reason, coastal tourism development has increased. In general, the coastal area is recognized as a hub for enhancing the socio-economic status of many around the world. With the Omani goals of diversifying the economy and becoming less dependent on oil revenue, the country has increased its coastal tourism development (Deloitte, 2013). Presently, Oman is moving rapidly within the tourism realm, as is shown by the increase in the number of hotels in the country—from 52 in1996 to 287 in 2014 (NCSI, 2016). According to Oman's tourism site (www.omantourism.gov), a good number of these new developed hotels and resorts are located along the coastal area, for example Barr Al Jissah Resort, Sawadi Beach Resort, The Wave mega-project (Muscat), Millennium Resort (Batinah coast), Salalah Rotana Resort, and Marriot Resort – Salalah Beach (Salalah). This approach to mass tourism, with its corresponding large influx of tourists into the pristine land, poses a great threat to Oman. The main challenges posed by the tourism industry are rising soil salinity, beach pollution from oil spills, and limited natural fresh water resources. In addition, solid waste management, if not carried out properly, will result in irrecoverable loss of beauty of ancient towns and nature (Subramoniam et al., 2010). As Sharpley (2002) stated, it is essential that those involved in Oman's tourism development projects know about and understand the country's coastal resources and its environmental processes.

Since establishing SD principles, Oman has worked hard to apply those principles to the country's development. Recently, Oman has also promoted energy resilience by encouraging the use of renewable resources (solar, wind) to contribute to SD goals (Kazem, 2011). Oman is taking positive steps toward SD, but incorporating these steps into tourism projects is crucial if sustainable coastal tourism is to be achieved. That being said, unfortunately, Oman demonstrates a lack of clear policies that will control environmental damage from tourism and a lack of policies that encourage sustainable tourism (Subramoniam et al., 2010).

Incorporating climate change impacts into plans for tourism development in Oman is a significant step toward creating sustainable coastal tourism. Worldwide, impacts from climate change, including Sea Level Rise (SLR) and natural hazards, are recognized as being among the most significant factors contributing to losses in coastal infrastructural and natural resources (Ayyub & Kearney, 2012; Nicholls & Cazenave, 2010). The implication is that coastal tourism development and the infrastructure in Oman are vulnerable to impacts from SLR and natural hazards. Recent research indicates that Oman will frequently be exposed to storms and heavy rain and will experience warmer temperature at the ocean (Al Hatrushi & Charabi, 2016; Al Rawas, Hewawasam, Al Wardy, & Charabi, 2016; Al Wardy, Al Rawas, & Charabi, 2016). The magnitude of the damage and the loss to the country's built area, infrastructure, and natural resources is likely to vary according to the level of human intrusion and the level of development along the coast of Oman. However, it seems that concerns about SLR and natural disasters are neglected or underestimated by those involved in Omani coastal tourism development.

This research aims to identify the vulnerability of the newly developed coastal tourism resorts and hotels in different SLR scenarios in association with the 2002 storm surge along the coast of Dhofar, Oman.

4.4 Study Site

The Dhofar Governance is located in the southern part of Oman (See Figure 12). Geomorphologically, it consists of a mountainous area, an intermediate zone area, and a plain (Forster & Magnan, n.d.). Land use planning in Dhofar is based on a coastal zone management plan created in 1988 that provided an ecological survey for Dhofar's coastal zone and was used as the basis for current tourism development projects in the area. The survey had also shown that the coast of Dhofar was exposed to seasonal wave action ranging from moderate to heavy. Ecological concerns due to the road construction were noted, because the construction created a significant threat to the lagoon area (Salm & Jensen, 1989).

4.5 Method of Inquiry

The procedure started through mapping some of the newly developed tourism hotels and resorts along the Dhofar coast. According to the latest NCSI report in 2016, the number of places in Dhofar offering accommodation for tourists had reached 29. Some of the newly developed hotels and resorts are located along the coast of Dhofar (See Table 5).

The identified hotels and resorts are then overlaid with layers of different scenarios of SLR associated with the storm surge of 2002's cyclonic event along Dhofar's coast (See Figure 13). Different scenarios of SLR in association with storm surge using 3Di hydrodynamic are modeled and documented in the previous chapter. The outcome of that modeling is overlaid on all hotels and resorts along Dhofar's coast to identify those that are vulnerable(See Table 6). The detailed logic about the mathematics behind 3Di is described in Stelling (2012) paper.

Figure 12. Study site, Dhofar.

Table 5

Hotels and Resorts, Dhofar

Hotel Name	Class	Year	Number of Rooms
Marriot Resort – Salalah Beach	5-star	2010	237
Hilton Salalah Hotel	4-star	1999	147
Crown Plaza Salalah Hotel	5-star	2010	153
Juwirah Hotel	4-star	2013	64
Salalah Beach Villa	1-star	2012	70
Salalah Rotana Resort	5-star	2014	400
Samahrem Village for Hotel Apartment	3-star	2012	204

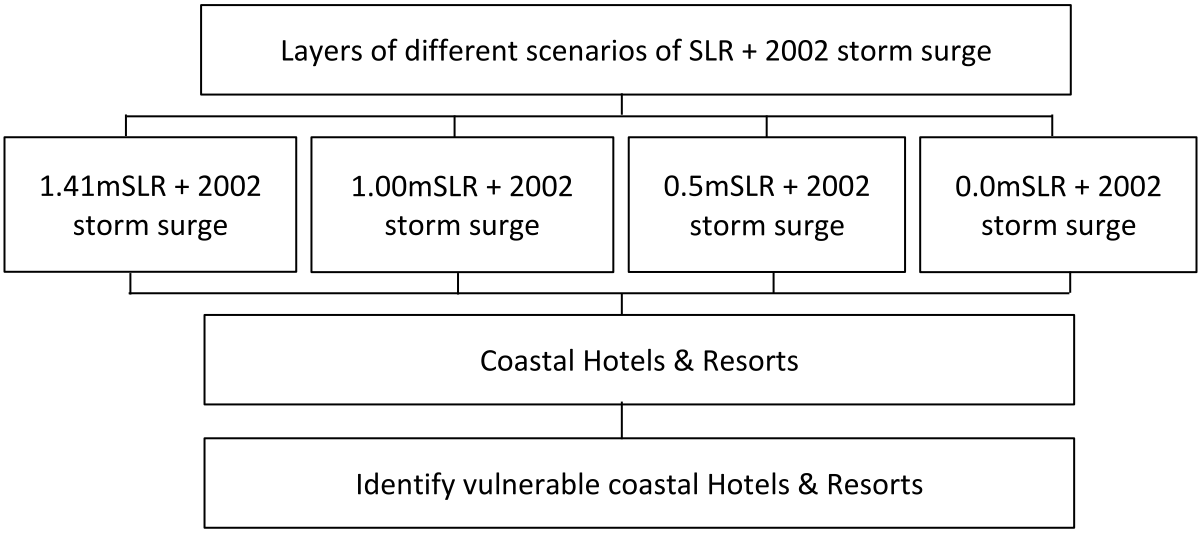

Figure 13. Approach to mapping vulnerable coastal hotels and resorts.

4.6 Results

Oman keeps emphasizing the need to implement sustainable development principles in current and future developmental projects. At the same time, the country continues to push for diversification in the economy to reduce dependence on oil revenue. Focusing on tourism is considered one way to do that. As a result, many hotels and resorts have been built across Oman to boost tourism. However, some of the newly developed coastal hotels and resort developed to contribute to economic diversification show a lack of ability to withstand the next 85 years because of their vulnerability to SLR associated with 2002 storm surge, as is the case with the Rotana Resort (See Figure 14). In contrast, some of the hotels and resorts showed minor impacts and vulnerability to SLR associated with the 2002 storm surge, as was the case with the Crowne Plaza. This research uses “major” to designate impact on built structures and “minor” to refer to the impacts on the landscape within the hotel/resort property limits. In either scenario, whether “major” or “minor,” the impacts will affect tourist accessibility and satisfaction. Moreover, if we consider the effect of SLR on roads or other infrastructure, the impact on tourist accessibility and the economic losses are significant. The current situation adds pressure on the country to maintain and protect infrastructure to ensure accessibility and/or minimize economic loss after an event. Furthermore, for hotels and resorts, this indicates that the life cycle of these projects will be less than 100 years, which is a widely metric used widely to assess the life cycle of a resort or hotel. We argue the current approach to coastal tourism and hotel development in Oman does not fit the definition of sustainable development principles and its core goal: to refrain from compromising the needs of future generations.

Table 6

Impacts of SLR on Coastal Hotels and Resorts Along the Coast of Dhofar

Hotels/Resorts Name	**1.41m SLR +2002 storm surge**	**1.00m SLR +2002 storm surge**	**0.5m SLR +2002 storm surge**	**0.0m SLR +2002 storm surge**
Hilton Salalah Resort	No Impact	No Impact	No Impact	No Impact
Crown Plaza Salalah Hotel	Major Impact	Major Impact	Major Impact	Minor Impact
Juwirah Hotel	Major Impact	Major Impact	Minor Impact	Minor Impact
Salalah Beach Villa	Major Impact	Major Impact	Major Impact	Minor Impact
Salalah Hilton	Minor Impact	No Impact	No Impact	No Impact
Salalah Rotana Resort	Major Impact	Major Impact	Major Impact	Major Impact
Samahrem Village for Hotel Apartment	No Impact	No Impact	No Impact	No Impact
Marriot Resort – Salalah Beach	Major Impact	Minor Impact	Minor Impact	Minor Impact

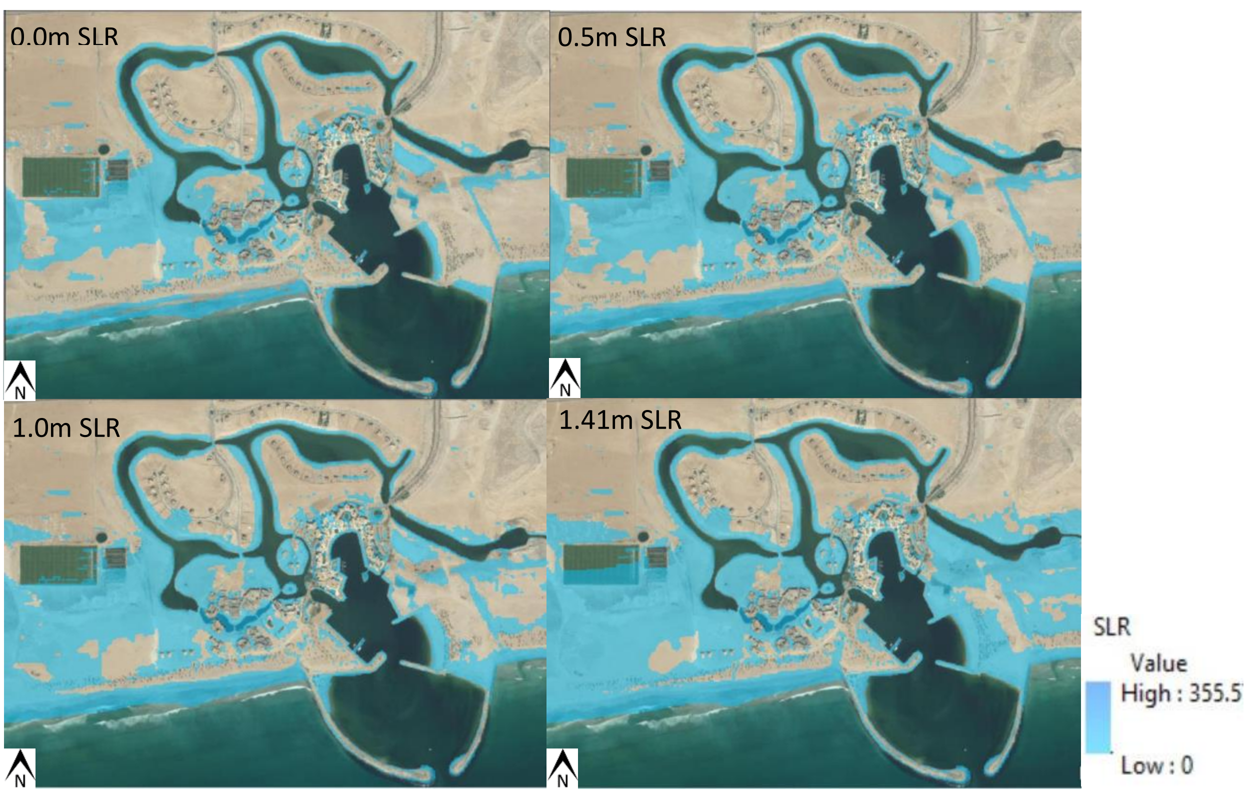

Figure 14. Rotana and Juwirah Hotels' impacts from various scenarios of SLR and storm surge,. (Images from ArcGIS, 2017)

4.7 Conclusion

The aim of this chapter is to demonstrate the importance of integrating science into tourism development and planning in Oman to impacts to sustainable development can be quantified and measured. The government can use such integration to encourage sustainable tourism development across Oman.

Depending on natural resources to attract tourism to Oman will stress the environment and possibly destroy the very element that people find attractive. Expanding tourism development without integrating science with planning and without being sensitive to natural resources generates uncertainty and creates stress on Oman in the long term. Finding a balance that includes protecting the natural environment and integrating science to minimize climate change impacts is significant for maintaining long-term sustainable coastal tourism growth in Oman.

The essence of SD is to “sustain” the natural and physical environment as developments are taking place, and this applies to coastal tourism development. Working with the concepts of living in harmony with nature and preparing for the future is a strategy that could be used to create sustainable coastal tourism. Oman can benefit by adopting strategies that integrate science and consider impacts from climate change such as SLR, both in its current and its future tourism development approach. As these strategies are woven within coastal tourism development, Oman can prosper in the 21st century, and tourism then can contribute to the national economy without destroying so much of what the country has to offer.

CHAPTER 5

5.1 Introduction

The impacts from global warming and climate change can be seen throughout Earth. A few research studies have shown that a warmer climate resulting from climate change increases the risk of frequent flooding globally by 42% (Hirabayashi et al., 2013; Milly, Wetherald, Dunne, & Delworth, 2002). Natural disasters will have an impact on the economy and the infrastructure, and their consequences will increase due to the rising number of people living in, and increasing economic activities located within, areas that are prone to flooding. Researchers from around the world, including the United States, China, Egypt, and Saudi Arabia, understand the importance of quantifying the impacts resulting from the flooding of built areas (Al Saud, 2010; Liang et al., 2011; Mastin, 2009; Youssef, Pradhan, & Hassan, 2011). For example, New Orleans in the United States was exposed to extreme water levels and storm surge in 2005 (Hurricane Katrina), resulting in major physical damage to the city and in social and economic disruption (Hanson et al., 2011). During the last decade in the United States, annual losses from flooding reached tens of billions of U.S. dollars, and thousands of people were killed each year (Hirabayashi et al., 2013). In the Netherlands, two-dimensional hydrodynamic modeling was used to estimate the flood extent and inundation depths for specific floods in order to calculate the damage (Bouwer, Bubeck, Wagtendonk, & Aerts, 2009). The developed countries recognized the magnitude of the damage caused by natural disasters to their infrastructure, and they are studying ways to mitigate the impacts of such events.

Furthermore, about 65% of Asia’s population is living beneath the 100-year flood water level (Guzman, Martine, McGranahan, Schensul, & Tacoli, 2009). Indonesia is another example of a country that has been exposed to major flooding—in 2002, 2007, and 2013—that resulted in displacement of more than half a million of people and the closure of infrastructure, such as highways, airports, and rail lines. For, Jakarata, researchers used two-dimensional hydrodynamic modeling to assess flood risk to estimate the vulnerabilities of the infrastructure and the cities (Budiyono et al., 2015). Many researchers have already discussed the need for quantitative assessments that would measure the impact of climate change on urban areas and infrastructure given the lack of these types of studies in areas throughout North, Central, and West Asia, including Oman (Hijioka et al., 2014; Watson, Zinyowera, & Moss, 1998). These assessments are needed as it is anticipated that the impact of climate change resulting from intense events will have negative consequences on the efforts toward sustainable development pursued by most of the countries in Asia (Hijioka et al., 2014). For example, many Asian coasts are already exposed to threats from flooding and coastal inundation (Hijioka et al., 2014; Revi et al., 2014). These studies reveal the vulnerability of the infrastructure of Asian cities and the threat to future development and populations posed by the effects of climate change on flooding.

In addtion, flash flooding in arid regions is considered one of the most destructive natural catastrophes (Cools et al., 2012). In an arid country, flash wadi flooding is a common phenomenon occurring when an extreme rainfall event is experienced over a short period. Flash flooding takes place rapidly as flood waters flow over rugged watersheds that are already extremely dry (Subyani, 2011). This event causes damage to infrastructure and results in both economic and human loss—as observed in the aftermath of the impacted areas of Makkah in 2005 and of Dhofar (southern Oman) in 2002.

Natural disasters occurring in Oman will have major effects on society. Due to the consequences of climate change, flooding from the coast or the fluvial system is often considered the most hazardous event facing the country's infrastructure and population, and threatens future development. In developing countries, economic and infrastructural losses due to the loss of lives resulting from natural hazards are a major concern since natural hazards account for 85% of lives lost (Dao & Peduzzi, 2004). The exposure to the physical and economic threat of flooding is predicted to increase within developing countries. For example, globally, Oman ranked fourth for coastal flooding, with approximately 11.983% of its population exposed to flooding between 1970 and 2010. The impact of flood events on society, the economy, and infrastructure in Oman is likely to continue to increase as a result of climate change that is projected to increase the frequency and magnitude of flooding.

Oman will undoubtedly be impacted by climate change and flooding. According to Ahmed and Choudri (2012), Oman is vulnerable to the impacts of climate change as a result of the significant increase in average temperatures, precipitation that is both increasingly irregular and reduced in quantity, sea level rise (SLR), and desertification. Recent research indicates that Oman is frequently exposed to storms and heavy rain as a result of warmer temperatures near the ocean (Al Hatrushi & Charabi, 2016; Al Rawas, Hewawasam, Al Wardy, & Charabi, 2016; Al Wardy, Al Rawas, & Charabi, 2016). Oman also has the potential to be exposed frequently to tropical depression and cyclonic storms. For instance, scientists predict that, by 2050, extreme rainfall events will be more frequent, with a return period of between 49% and 52% (Charabi, Al Wardy, & Al Rawas, 2016). In addition, the topographic features of Oman increase the potential for flash wadi flooding that could result in significant societal and infrastructural damage to built areas. Therefore, understanding and simulating the impacts of storm surge and flash wadi flooding simultaneously is significant.

Furthermore, in regard to development and urbanization in Oman, city planning has adapted to the low probability of extreme natural flooding (Belqacem, 2010). Oman also has limited historical loss data and little simulations of loss events. Therefore, spatial models are needed to provide a realistic range of potential damage to infrastructure and threats to urbanization. This is particularly important for southern Oman, which will be exposed to frequent storms and cyclones of higher intensities, as was indicated in a 2013 report of the Ministry of Environment and Climate Affairs (MECA). In addition, researchers have shown that the precipitation intensity in the Salalah area will increase (Al-Habsi, Gunawardhana, & Al-Rawas, 2015). The vulnerability of the country's population and its infrastructure largely runs parallel to its level of development and the quality of its environment (Dao & Peduzzi, 2004; Peduzzi, Dao, Herold, & Mouton, 2009). Though surplus rainfall, exceeding 50 mm per day, rarely falls in Oman, when it does, it brings severe consequences, such as flash flooding, human loss, and land degradation (Kwarteng et al., 2009). The socioeconomic developmental progress that Oman has experienced during the last three decades—especially during the 2000s—has made the country vulnerable to the impacts of climate change. This is due to Oman's frequent exposure to natural disasters, including the 2002 event in Dhofar, which cost the country approximately $50 million in damages to infrastructure, cities, and agricultural lands. For that reason, assessing the impacts of climate change and flooding on development and infrastructure in Oman is important in efforts to create a path toward the creation of resilient infrastructure in Oman's cities.

Because flash flooding has historically been rare, data on the phenomenon is scarce. Therefore, flood simulation using catastrophe models is needed to arrive at a more realistic range of potential damages from extreme flood events. That being said, Dhofar has experienced flash flooding periodically, as is seen in Table 7. Due to Dhofar's rugged mountainous topography and its geological structures, flash flooding resulted in enormous amounts of destruction. Therefore, while the governance is still undergoing development, precise assessment of flood impacts becomes necessary to move toward sustainable developmental planning and a sustainable economy. It is important for the country's developmental planners to consider the impacts of climate change when overseeing major developmental projects and to assess the corresponding infrastructural vulnerabilities related to natural disasters.

Table 7

Cyclonic Storms in Salalah's Plain Resulted in Flash Wadi Flooding

Month	Year	Total rainfall in mm	Max rainfall per 12 hrs in mm	Mean seawater	Max water level
23-26Oct	1948	156.8mm	33.0mm	NA	NA
23-26May	1959	117.2mm	81.8mm	NA	NA
26-9May	1963	269.1mm	134.0mm	NA	NA
12-13Nov	1966	202.3mm	178.1mm	NA	NA
14-18June	1977	122.7mm	70.3mm	NA	NA
4-Apr	1983	NA	127.0mm	NA	NA
11-June	1996	143.0mm	NA	NA	NA
Oct	1999	69mm	NA	NA	NA
9-12May/ARB 01	2002	191.8mm	145.6mm	2.653	3.4
20May_Sal	2003	NA	NA	NA	NA
29-30September	2004	116.2	116.2	2.645	3.1
2-3November/ Keila ARB 02	2011	700mm	200mm (Noos Mountain near Salalah)	2.645	3.4
30 October Chapala cyclone	2015	NA	storm surge7m	NA	NA

The first section of this chapter models the extent and depth of inundation caused by storm surge and flash wadi flooding in the governance of Dhofar during the 2002 cyclonic event, that resulted from excessive rain falling over a short period in tandem with the SLR projection of 0.0 m and 1.41 m. The second section provides an overview of rainfall characteristics in arid regions. The third section presents the study site in Dhofar. The fourth section shows the modeling approach undertaken in this chapter. The fifth section presents the results and some limitations of the research. The sixth section presents the conclusions of this chapter.

5.2 Rainfall Characteristics in Arid Regions

Levels of rainfall in arid and semi-arid regions are marked by variability in space, time, quantity, and duration (Abahussain et al., 2002; da Silva, 2004; Tabari, Abghari, & Hosseinzadeh Talaee, 2012; Watson et al., 1998). For example, Bahrain, an arid and semi-arid country, features extreme cool-wet and extreme hot-dry seasons. This climate has resulted in variation in the rainfall frequency, duration, and intensity because rainfall levels are low, irregular, seasonal, and variable. This high variability has resulted in an inability to achieve water balance. Bahrain's climate variability has shifted the rainfall pattern; some months have become wetter and some drier (Elagib & Abdu, 1997). Moreover, a study by Graef and Haigis (2001) shows that in Niger, which is a semi-arid region, the pattern of rainfall is spatially and temporally variable—the rainfall amount varies within a few kilometers on different time scales, resulting in unpredictable crop yields. This high variability of precipitation in time and space in arid and semi-arid regions is due to the intensity and short duration of flash flooding events in these areas. This results from storms with a high degree of spatial variability, even for large catchments (Mays, 2001; Zeller, 1990).

Oman, as an arid and semi-arid country, is exposed to the variability and fluctuations of rainfall (Abahussain et al., 2002). Rainfall in Oman is highly variable and irregular, and the geographical features in different locations clearly play a role in shaping these variations, due to the levels of average annual rainfall distribution in Oman as they vary throughout the country. For example, the mean annual rainfall in Oman varies from a low of about 50 mm in the desert to a high of 200–300 mm in the mountains. Overall, Oman receives about 9.5 billion m^3 of rainfall per year; 80% evaporates, and the other 20% either flows as surface water or joins directly with the underground reservoirs (MRMWR, 2015). Oman also features three different arid regions of high plains and foothills, that receive between 100 and 250 mm of rainfall; a semi-arid region of the mountain slopes and summits of Northern Oman, that receive rainfall between 250 - 500 mm; and a hyper-arid region along the coasts and plains, which receives less than 100 mm of rainfall (Al-Ajmi, Idrees, & Al-Hatrushi, 2013; Charabi & Al-Hatrushi, 2010; Ghazanfar & Fisher, 2013; Kwarteng et al., 2009).

The high elevation of the rugged mountains extending to the southeast part of the Arabian Peninsula and the seasonal reversal of pressure and winds over the Arabian Peninsula along with the neighboring Arabian Sea, are among the main causes of the varying rainfall distributions over Oman's regions. Because of Oman's geographical location on the southeast part of the Arabian Peninsula, it is affected by the Indian Ocean monsoon winds (Al-Rawas, 2009; MECA, 2013). The exposure to various seasonal reversals of pressure and winds create different climates. The northwest and northeast winds result in rainfall during winter on the mountains and the coastal regions. On the other hand, the summer monsoon winds dominate the south-central areas, that get light showers from both summer monsoons and winter local troughs, while heavier rainfall generally occurs at higher altitudes (Babikir, 1985; Charabi & Al-Hatrushi, 2010). Therefore, Oman experiences two different rainy seasons: summer (from May to October), occurring in Southern Oman; and winter (from November to April), that takes place in Northern Oman (Al-Rawas, 2009; MECA, 2013; Tudhope et al., 1996). Clearly, the climate varies across the country.

Rainfall in Northern Oman results from thunderstorms during the winter due to mid-latitude westerly depression by polar-front jet streams. In contrast, the rainfall in the South results from the monsoon season that dominates the Dhofar Mountains and the Salalah Plain (located on the southern coast) and by the fall season in July and August, due to the southwest monsoon. The rainfall months in the interior region are February and March (Al-Ajmi et al., 2013; MRMWR, 2015).

Due to Oman’s exposure to four meteorological systems of air masses coming from four different directions, different rainfall events occur. For instance, convective rain storms could take place at any time of the year but do so more frequently during the summer months. Cold-frontal storms occur during winter and early spring while on-shore monsoon tides take place from June to September, causing a frequent drizzle in Dhofar. Tropical cyclones approaching from the Arabian Sea develop every 3 years—result in the development of intense storms nearly once every 5 years in Dhofar and once every 10 years in Muscat, the capital of Oman (Charabi & Al-Hatrushi, 2010; Kwarteng et al., 2009; MECA, 2013).

Rainfall in Dhofar reaches its peak in the mountains with an annual average of 184.6 mm, in contrast to the Salalah Plain, which gets a yearly average rainfall of 112 mm. However, the monsoon season in Dhofar brings about rainfall levels of between 100 and 400 mm (Dorvlo & Vijaya Kumar, 2009). A study by Al-Ajmi and colleagues (2013) shows the 50-year prediction for rainfall to be between1,048 and 565 mm in Al Hajar and the Dhofar Mountains respectively; and an average annual maximum rainfall of 338 mm and 304 mm in the Salalah Plain and the northwest coastal regions respectively. Being ready for the impacts of climate change with regard to flooding risks to urban areas, infrastructure, and future developments and determining the likely extent of flooding is important (Guzman et al., 2009). Being prepared for the consequences of climate change on Oman’s development and infrastructure is the most effective resilient approach.

5.3 Study Site

The research site for this chapter is located within the governance of Dhofar in Southern Oman. Dhofar’s coastal plain is divided into three geomorphological areas: the mountainous area, the intermediate zone area, and the plain (Forster & Magnan, n.d.). The peaks of Dhofar’s mountains range from 1000 to 2000 m above mean sea level and dominate the southwestern part of the country. This mountain range is represented by the Qairoon Hairiti station, which is 878.30 m above mean sea level (Al-Ajmi et al., 2013). Topographic effects on precipitation, in addition to the contact with various mountain rims and the presence of several narrow valleys, lead to a range of different local climatic conditions (Charabi & Al-Hatrushi, 2010). Dhofar is known as a tourist site for local and international visitors during its summer monsoon season (from June through September), that allows the governance to contribute meaningfully to Oman’s economy (Charabi, 2009).

This study focuses on the Zayk and Ghadow watersheds in Dhofar. The sites are selected because of rainfall data available at15-minute intervals for ARB01 cyclonic storms in 2002. The Zayk and Ghadow watersheds cover an area of 312.1 and 195.2 km^2 respectively. Figure 15 is a digital elevation map of the Zayk and Gadow watersheds and the built areas within them.

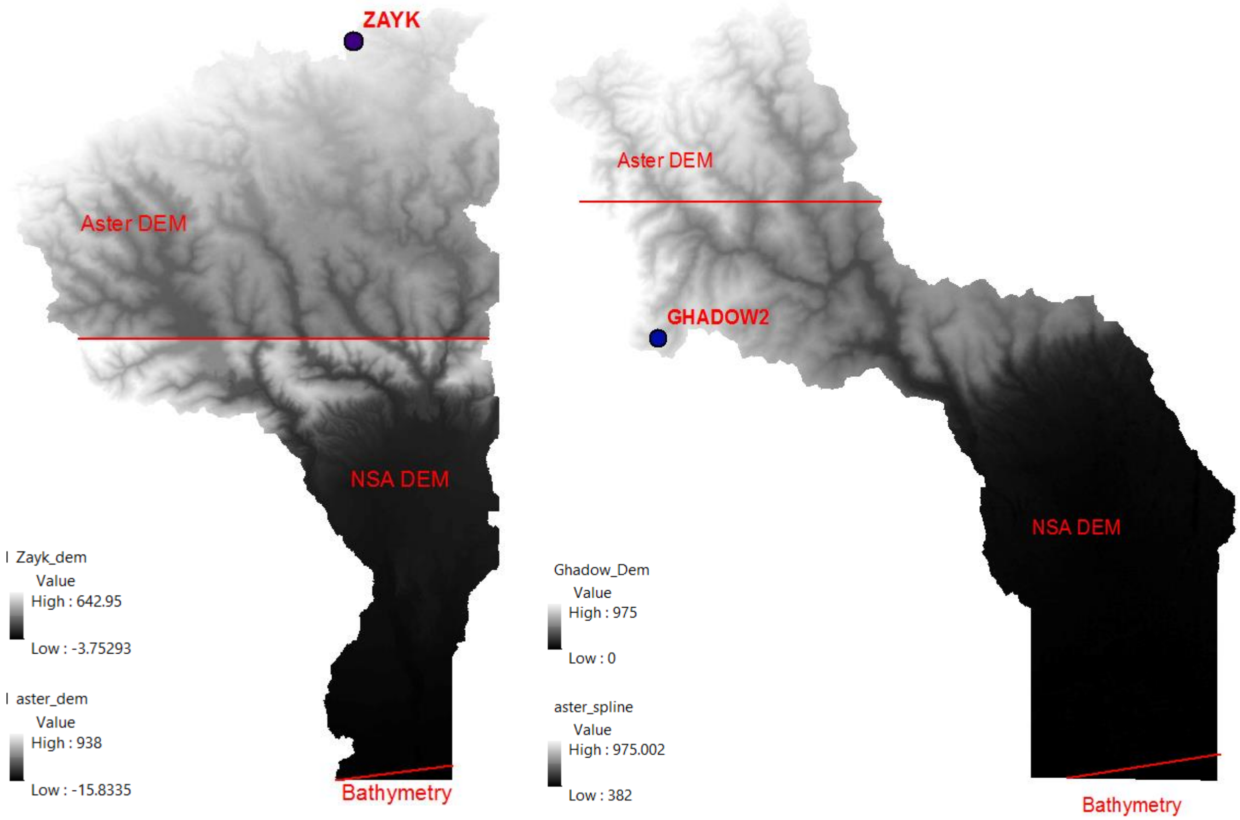

Figure 15. Zayk's and Ghadow's watershed extent.

The storm formed on May 6, 2002, in the Arabian Sea. On May 9, 2002, the storm was classified as cyclonic, exhibiting winds greater than 65km/h; and on May10, 2002, the cyclonic storm hit Salalah. The storm resulted in the heaviest rainfall in Dhofar in 30 years, whereupon the wadi flash-flooded. The storm caused substantial damages totaling $50 million USD in addition to the human losses: Nine people drowned, several others were injured, and many others were displaced (ESCAP, 2004).

The total affected area is estimated to be about 9,460 km^2. Tremendous social, economic, infrastructural, and environmental damages—including damages to property, crops, and transportation networks—were seen (Dartmouth Flood Observatory, 2003). In addition, the cyclonic storm resulted in a storm surge along the coastline of up to 4 meters. In the Zayk and Gadow watersheds, precipitation amounted to 120.2 and 139.8 mm respectively during a period of 24 hours. However, Qairoon accounted for the highest total levels of precipitation in Oman at about 332.8 mm, as is displayed in Figure 16. These data were obtained from the Ministry of Regional Municipalities and Water Resources (2015) in Dhofar.

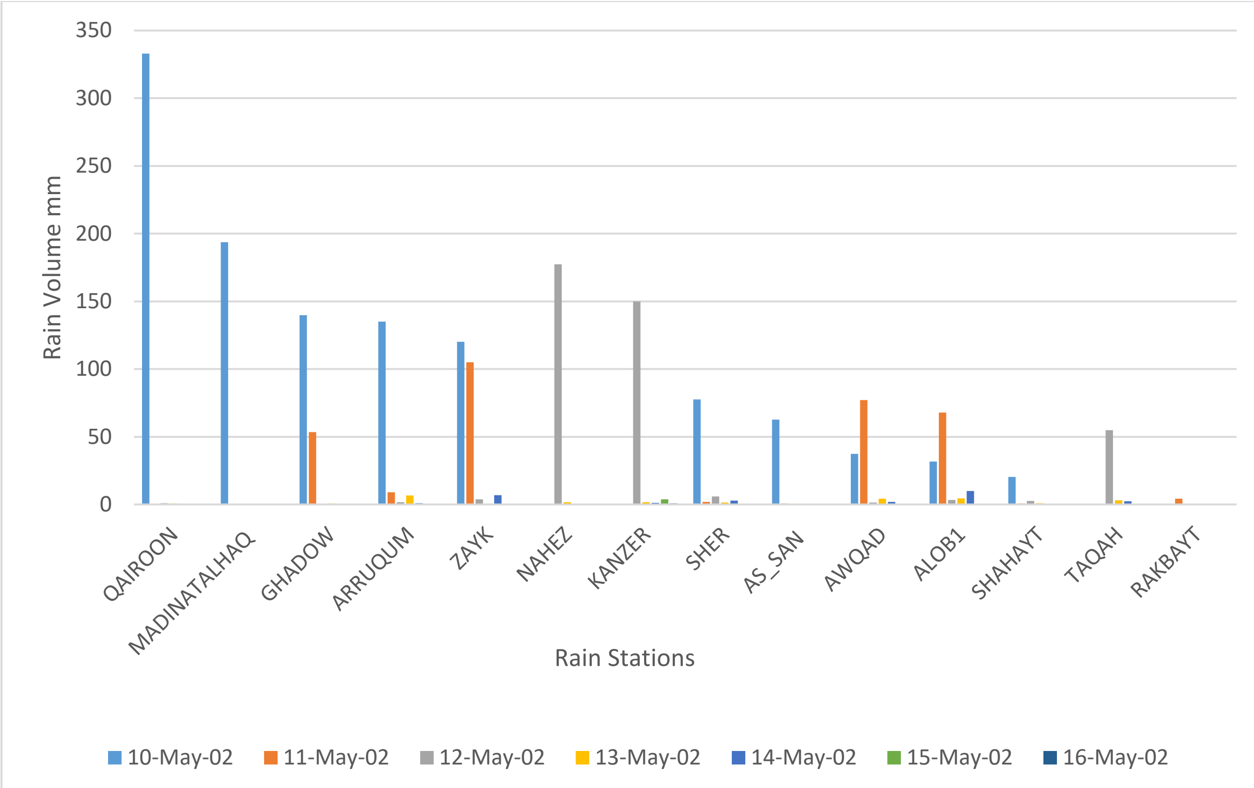

Figure 16. Meteorological rain station readings during 2002 storms.

5.3.1 3Di Model Setup

Similar to Chapter 3, this research uses 3Di, the hydrodynamic model developed by TU-Delft, Netherlands (Stelling, 2012). 3Di uses both quadtree and subgrid techniques to reduce the computational grid number and to maintain computational resolution to the pixel of the DEM (Hsu, Prinsen, Bouaziz, Lin, & Dahm., 2016).

5.3.2 Digital Elevation Model (DEM)

This study obtained DEMs from Oman's National Survey Authority (NSA) and The United States Geological Survey (USGS) that cover the entire watershed areas. The DEM obtained from USGS is an ASTER GDEM at 30 m resolution and is a product of METI and NASA. The NSA's DEM is at 5 m resolution and was created by the Nationwide Orthophoto Coverage and Data Management System project in 2013. Resampling tools were used from ArcGIS over the ASTER DEM to bring the cell size to 5 m resolution in Figure 15.

5.3.3 Bathymetry

This study obtained the bathymetry data for Dhofar's coast from the National Oceanic and Atmospheric Administration (NOAA) dataset. The resolution of the bathymetry grids is nearly 950 m with nearly a 10 m vertical accuracy (Amante & Eakins, 2009). The bathymetry was also resampled to 5 m and then mosaiced with DEM grids to a 5 m^2 horizontal resolution raster to be integrated into the 3Di input.

5.3.4 Water Level

Hourly tidal data were collocated from the National Hydrographic Office (ONHO) in Oman. This study used the tidal and storm surge data from the 2002 event along Dhofar's coast. Two stations reported storm surge levels to be at 3.2 m in Marbat and at 3.12 m in the Port of Salalah.

Since 3Di has the capability of incorporating the data from dynamic tidal and storm surge processes, the movement of changing water volumes over land surfaces over time is included. This study simulated the oceanic storm surge of the 2002 event with SLR projection at 0.0 m and 1.41 m.

5.3.5 Initial Water-Boundaries and Water-Level Data for Watershed

Water boundaries were created to simulate virtual waves in 3Di to provide initial water-level data. Each watershed had its own initial boundary generated along its boundary sections (bathymetry).

5.3.6 Roughness and Infiltration Maps

3Di takes into account the fact that rainfall runoff can occur as interception, infiltration, and evaporation, which makes the software suitable for urban application (Dahm et al., 2014). Both the roughness map and the infiltration map were created by the author from a land-use map of the digitized watersheds. The Manning's n roughness values are shown in Table 8 (Kalyanapu, Burian, & McPherson, 2010). The soil map was obtained from the Ministry of Agriculture and Fisheries in Oman, and the soil infiltration rate is based on FAO guidelines. The infiltration rate is based on the maximum infiltration rate of different land uses given in Table 9. Many factors affect the infiltration rate, including soil type, soil moisture, and surface vegetation conditions. However, the infiltration values in this research are constructed from a land-use map. The 3Di model uses the maximum infiltration rate as a constant rate in time (Hsu et al., 2016).

Table 8
Roughness Values Used in This Study

Land use	Manning's n values
Agriculture/ Green Area	0.044
Developed area/High intensity	0.0404
Developed area/low & medium intensity	0.0678
Roads	0.012

Table 9
Infiltration Values Used in This Study

Land use	Infiltration rate (mm/day)
Agriculture/ Green Area	120
Built Area	0.0

5.3.7 Rainfall Events

Dhofar's coast has a history of exposure to frequent cyclone and storm events. The rainfall event during May 10–12, 2002, has been selected for simulation because it represents the heaviest rain in 30 years. The rainfall data from the two rainfall stations are shown in Figure 17. The maximum precipitation level over a 5-minute period for the Zayk station is 11.4 mm; the maximum level from 12 consecutive periods over the total duration of 1 hour is 38.8 mm; and the daily total is 120.2 mm on May 10th and 105mm on May 11th. On the other hand, the Ghadow station shows the maximum precipitation level over a 5-minute period at 7.2 mm; the maximum level from 12 consecutive periods over the total duration of 1 hour is 42.6 mm; and daily totals were 139.8 mm on May 10th and 53.6 mm on May 11th.

5.4 Results

The 3Di output simulation for the 2002 storm event of wadi Zayk and wadi Ghadow shows the vulnerability of Dhofar's urban area, infrastructure, and agricultural lands. This demonstrates the need for resilient planning and infrastructure in Dhofar as a path toward a sustainable and resilient developmental future. This study provides inundation results of wadi flooding and storm surge during the 2002 event and represents the event in the most realistic way possible, given that the simulation is based on the real 2002 storm event and real rainfall data. The simulation of the 2002 event from this study included the dams constructed at the site after the 2002 event. This means that the results of this simulation show what would happen at the site if a similar storm were to take place at the site today. The 3Di model is able to provide a representation of the entire wadi flooding and storm surge at a relatively high spatial resolution in which land-use influencing infiltration and water movement are integrated.

The extent to which inundation, wadi flooding, and storm surge intersect with the buildings, agricultural lands, and roads for both watersheds in the 3Di output allows the study to show the risk to infrastructure, residential areas, and croplands affected by the inundation. This research recommends that policy-makers and planners adopt design mitigation and adaptation strategies to prevent future economic loss and to promote resiliency in future development projects.

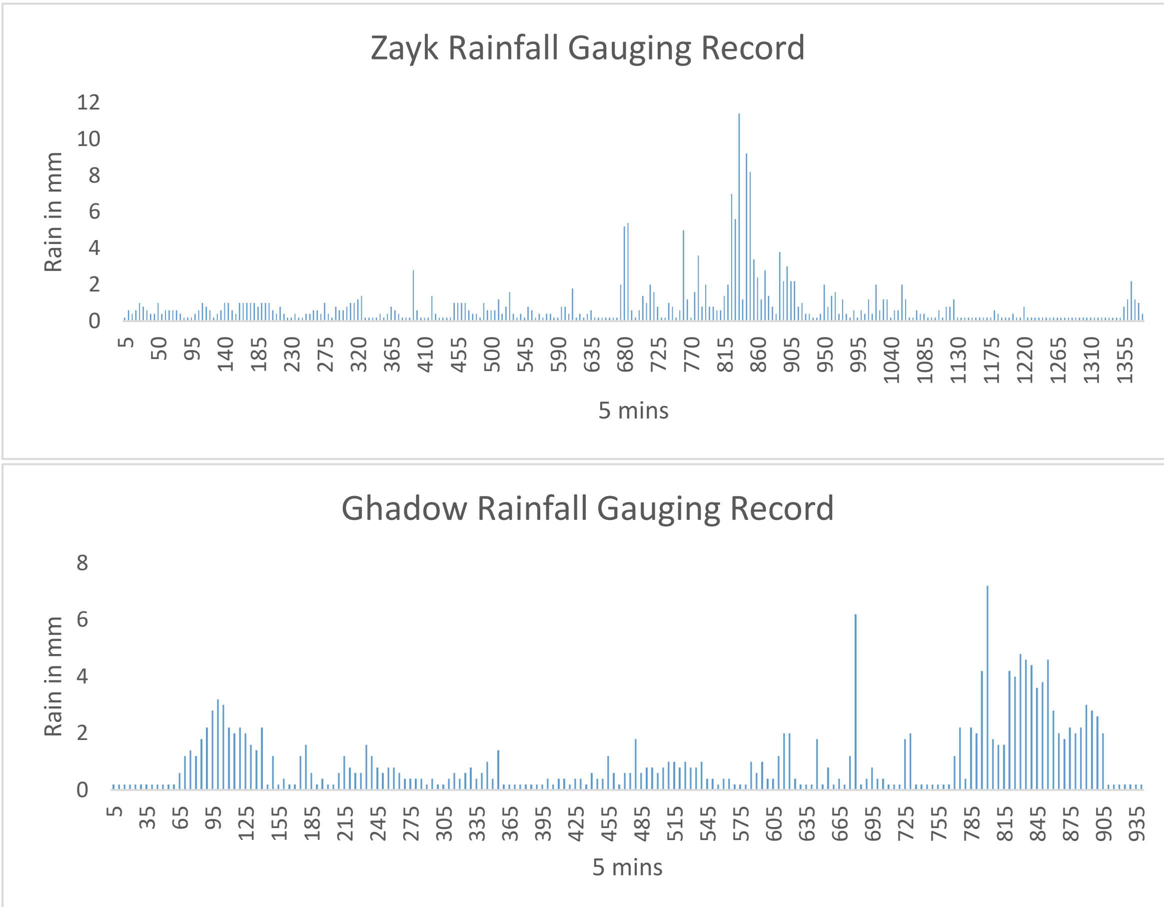

Figure 17. Rainfall gauging record.

5.4.1 Wadi Flash Flooding Damage to Urban Areas

From the results shown, the most damaged land-use classes are residential, industrial, and commercial. The Ministry of Housing in Oman provided an estimate of the average number of land plots across Oman in 2016. Table 10 incorporates this list to estimate the cost of land damaged due to the 2002 event. The prices of the plots are representative only of the land itself without taking into account buildings constructed on the plots.

Table 10
Cost of Land per Meter in Omani Riyal (Ghadow's Watershed)

Wilaya	Region	Residential	Mixed-Use	Industrial	Agricultural	Tourism
Salalah	City Center	51	292	85	16	325
	Suburban	35	171	62	9	200
	Rural	17	89	48.5	5.5	125

5.4.2 Ghadow's Watershed

Ghadow's watershed is significantly affected by the 2002 storm event. Figure 18 displays the maximum inundation depth and the magnitude of flash wadi flooding in association with an SLR of 0.0 m over the 49-hour run of the model. The impacts on Ghadow's watershed from wadi flooding and inundation are shown in Table 11. These results take into account the new buildings and the construction that took place on the site after 2002. The table accurately reflects the impact that wadi flooding of a similar magnitude would have on these new buildings if it were to take place today. In Oman, typically every citizen is granted residential land from the government. The size of this land usually ranges from 600 to 700 m^2. However, for commercial, tourist, industrial, and agricultural land, the size is usually greater than 600 m^2. Because not enough data on this land are available, this study adopts 600 m^2 as the standard. Table 12 shows the estimated cost of damage to the residential land without considering the cost of the buildings built on that land, as the author does not have information concerning construction costs. This study has also identified wadi flooding impacts on 250 agricultural lands and on 53 commercial–agricultural lands. The wadi flooding also resulted in destruction to airports, hotels, roads, and landscaping.

Table 11
Wadi Ghadow's Watershed Flooding Inundation Results:
Number of Impacted Buildings at Maximum Inundation Depth

Wilaya	Region	Residential	Mixed Use	Industrial	Tourism	Govt.	Comm.	Other
Salalah	City Center	1276	+400	106	12	112	49	65
	Suburban	2050	35	351	57		20	
	Rural	127	0	159	0		0	

Table 12
Estimation of Land Cost Based on 600m^2 in Omani Riyal, Ghadow's watershed

Wilaya	Region	Residential	Mixed Use	Industrial	Tourism	Govt.	Comm.	Agri.
Salalah	City Center	30,600	175,200	51,000	195,000	Not Provided	Not Provided	9,600
	Suburban	21,000	102,600	37,200	120,000			5,400
	Rural	10,200	53,400	29,100	75,000			3,300

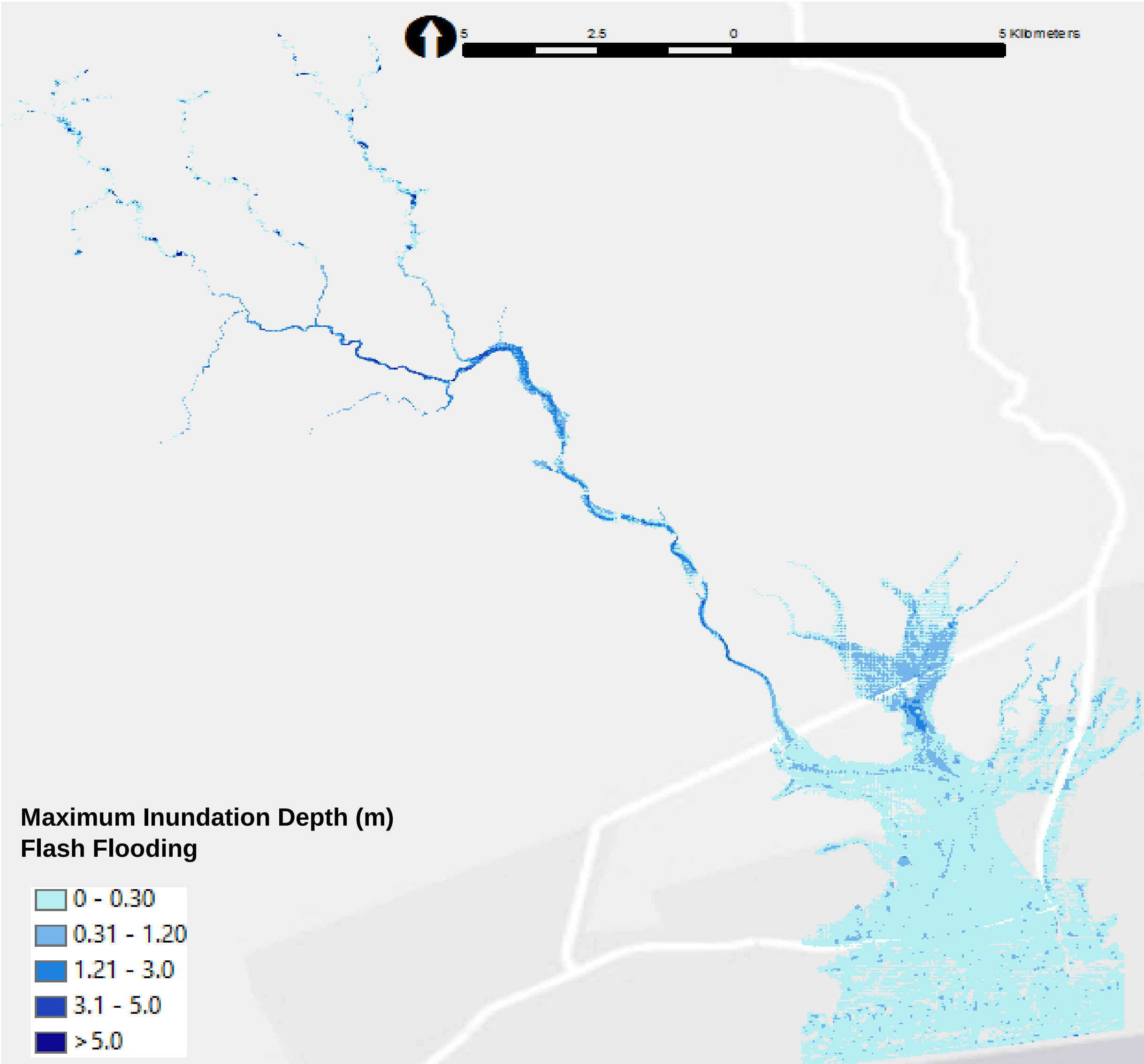

Figure 18. Wadi Ghadow flash flooding maximum inundation, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Wadi Ghadow's watershed flash flooding inundation output. The Ghadow watershed received nearly 193.4 mm of rainfall from May 10 to May 11, while the Zayk watershed received nearly 225.5 mm of rainfall during this time. In Figure 19, a section of Salalah is used as an example of mapping flash wadi flooding inundation extent and depth every 24 hours for the duration of the May 2002 storm event—a scenario in which SLR is at 1.41 m. After 48 hours of the 2002 storm event, major infrastructure and urban areas were inundated, including Salalah's airport, commercial areas, and industrial areas. Figure 20 provides an example of coastal tourism and new developmental vulnerabilities resulting from flash wadi flooding and SLR during the first 48 hours of the 2002 storm.

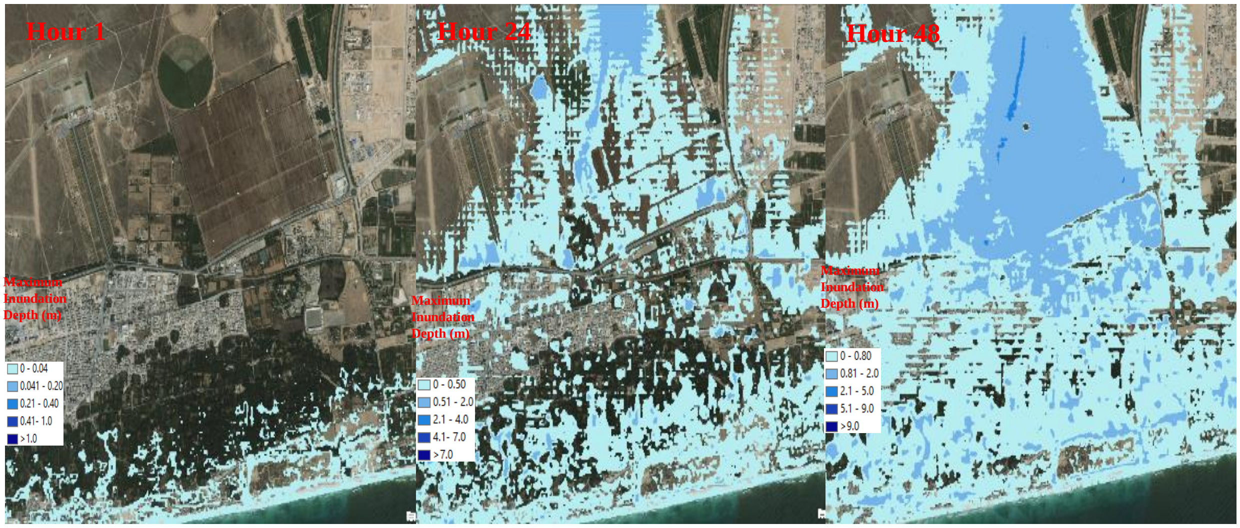

Figure 19. Part of Salalah city. Time-series inundation extent and depth of Wadi Ghadow flash flooding in association with 1.41 m SLR, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Wadi flash flooding inundation damage on roads in the Ghadow and Zayk watersheds. More than 410 km of roads transect the Ghadow watershed, and more than 334.50 km of roads run through the Zayk watershed. Figure 21 shows the extent of the wadi flooding inundation and impacts on the roads in association with SLR scenarios at 0.0 m and 1.41 m from the 2002 storm event. However, of these flooded and inundated roads, over 194 km impacted at the Ghadow watershed were at 0.0 m and 232 km with SLR at 1.41 m. More than 311.3 km of roadway was impacted at the Zayk watershed at 1.41 m SLR and more than 171 km of roadway at 0.0 m SLR.

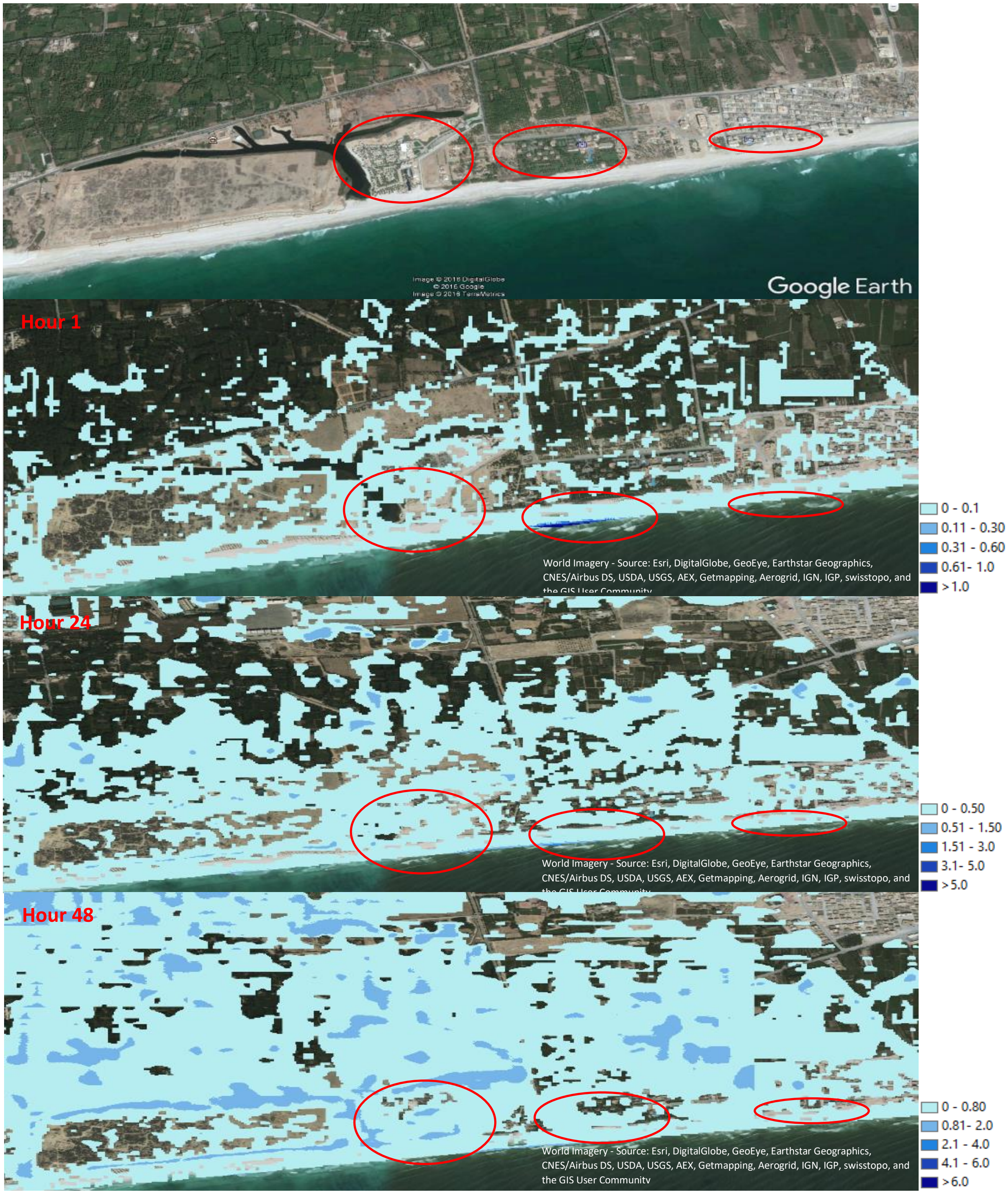

Figure 5. Vulnerable coastal tourism and new development due to flash flooding in association with 1.41 SLR.

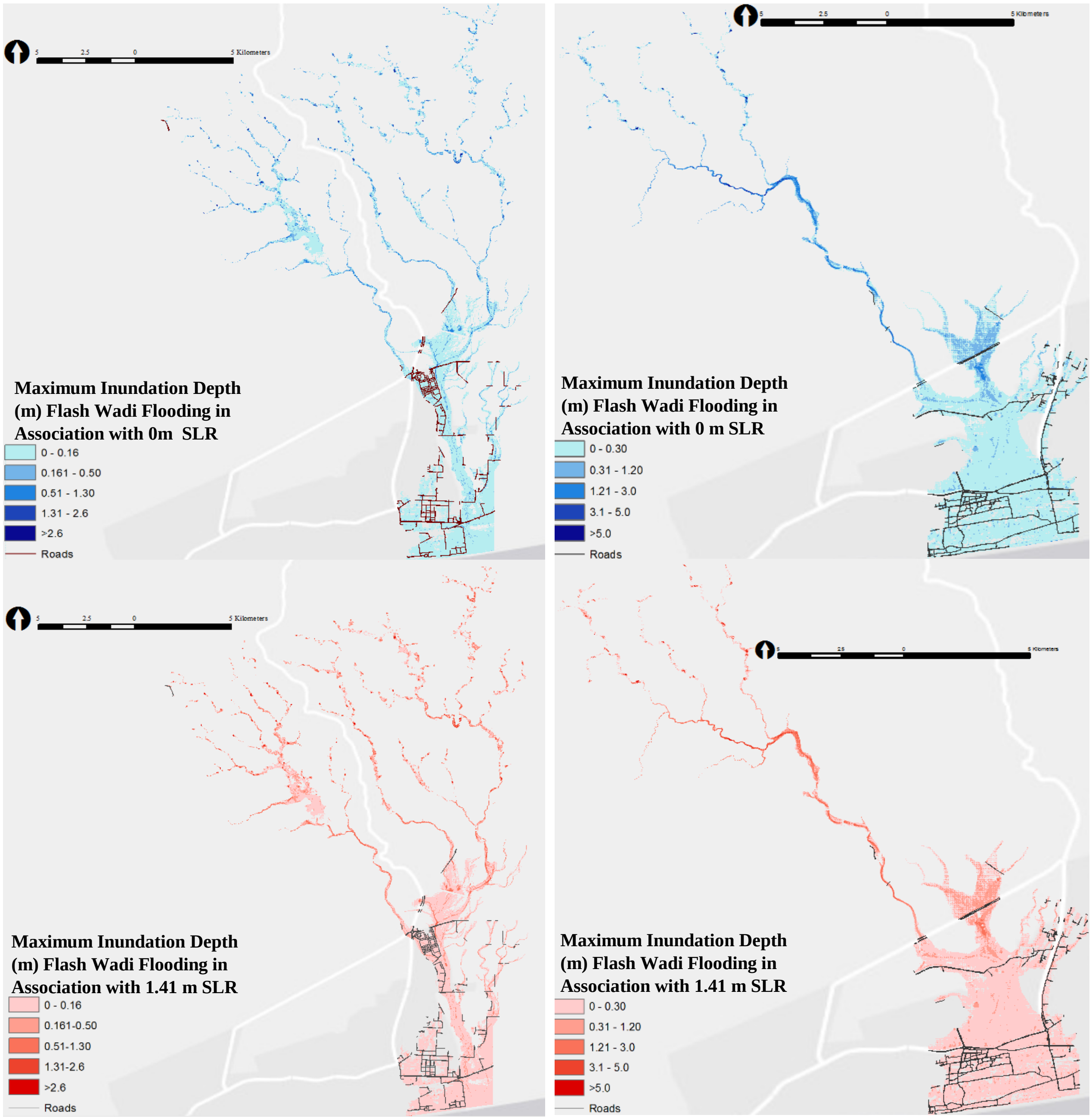

Figure 6. Roads affected by Wadi Zayk flash flooding in association with SLR at 0 m and 1.41 m maximum inundation are shown on the left, and roads affected by Wadi Ghadow flash flooding (same parameters) are shown on the right, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

5.4.3 Zayk's Watershed

Zayk's watershed is significantly impacted by flash wadi flooding, as is shown by the number of impacted buildings throughout the watershed. In addition, storm surge in association with 1.41 SLR resulted in a major impact to coastline infrastructure and buildings. Figure 22 illustrates flash wadi flooding over a period of 96 hours at the Zayk watershed.

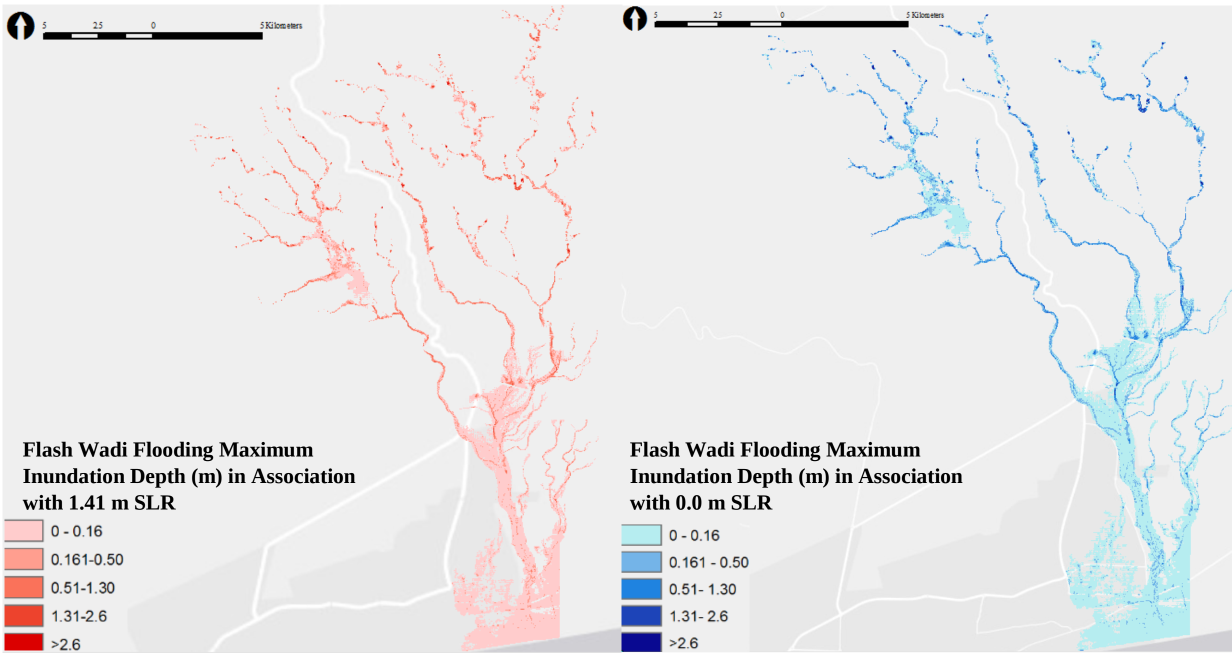

Figure 22. Flash flooding in Wadi Zayk watershed in association with SLR at 0 m and 1.41 m maximum inundation, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

The model 3Di provides a useful representation of the dynamic of flash wadi flooding inundation by helping to show the flooding path over the landscape and the context of the inundation during the 2002 storm event. Figure 22 shows flash wadi simulation for wadi Zayk from May 2002. Because 3Di is a hydrodynamic model, it has the advantage of providing a dynamic representation of flash wadi flooding, which by its nature is a dynamic process. Figure 23 maps the flash wadi inundation extent and depth, every 2 hours for a 24-hour period, over the Sa'adah urban area.

The Sa'adah area is one of the places impacted severely by the 2002 event. The heavy flash wadi flooding is used as an example in mapping inundation extent and depth of the area, every 12 hours for a 96-hour period. Figure 24 shows a portion of Sa'adah starting to get inundated at 62 hours from the storm onset. After 74 hours, water accumulated over the inundated areas, resulting in deeper water levels and further damage. This enlarged time-series output can be produced for every hour over any portion of the watershed.

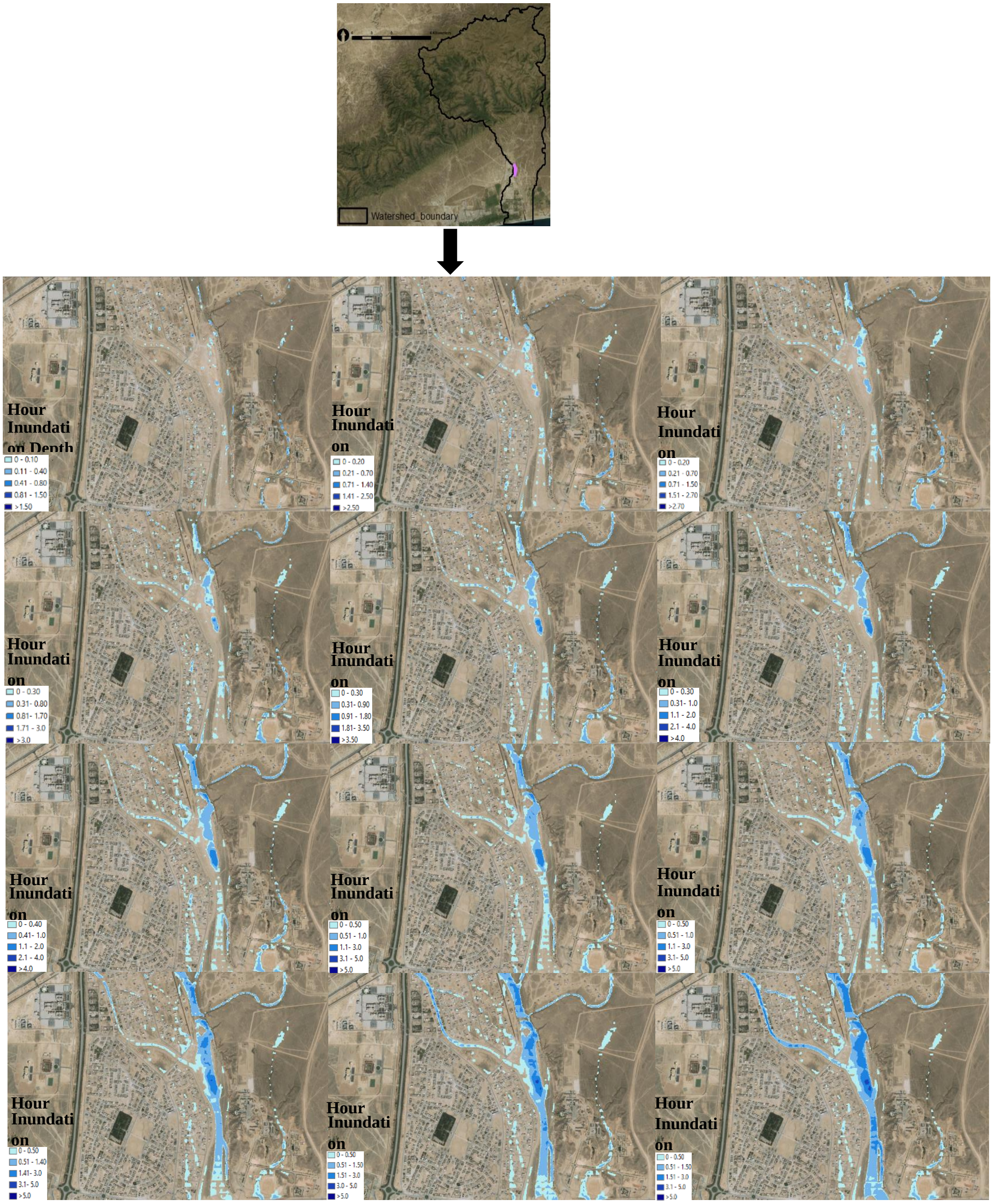

Figure 23. Time-series flash wadi inundation of 2002 storm event, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

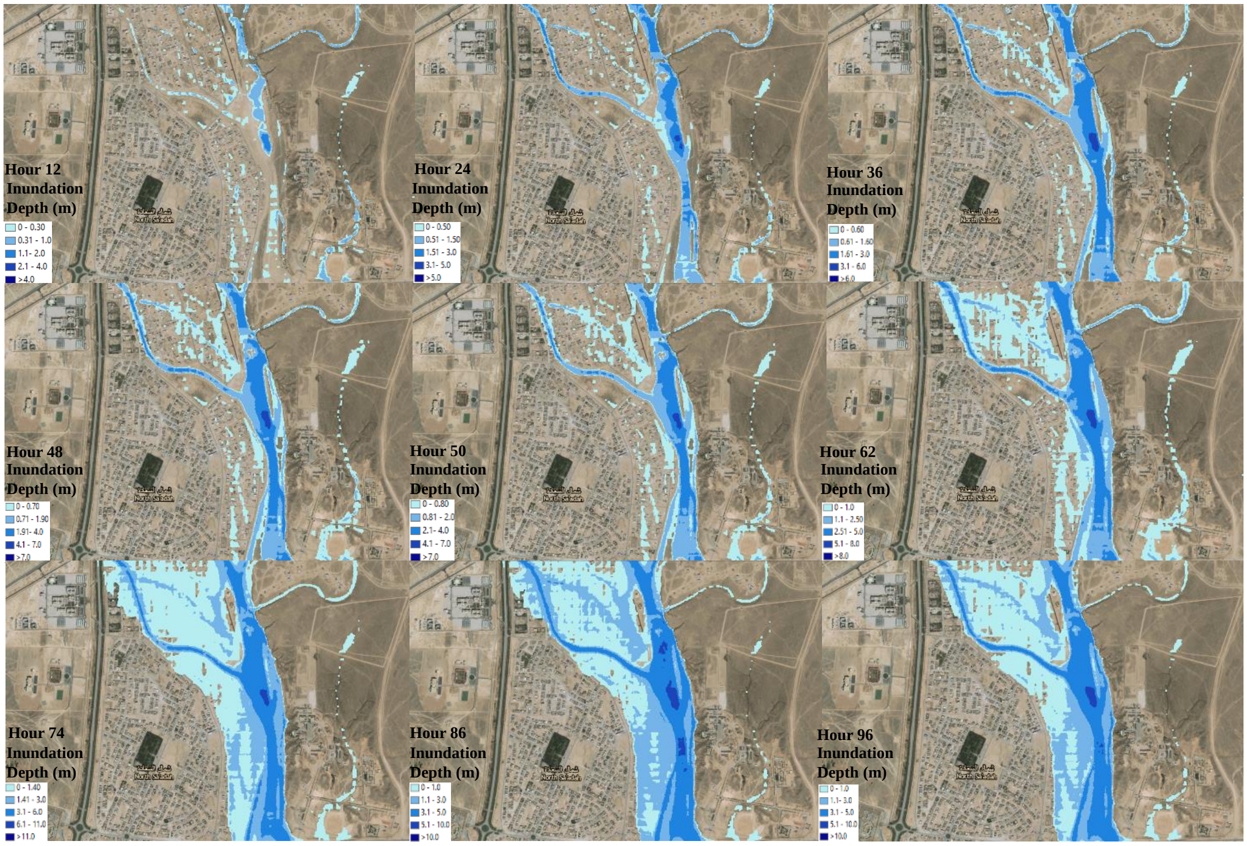

Figure 24. Sa'adah area time-series inundation extent and depth every 12 hours for the duration of the May 2002 event, base map: World Imagery. (Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Zayk's flash flooding damage to urban areas. The results show that the most damaged land-use classes are residential and industrial. In addition, some recent tourism projects are affected by flash wadi flooding. The average estimate of the cost of land in the Zayk watershed is shown in Table 13. Like the data from the Ghadow's watershed, the prices of the plots do not include the cost of the buildings constructed on the land. The Zayk watershed's wadi flooding and inundation impacts are shown in Table 14.

5.4.4 Flash Flooding Impacts on Agricultural Land in the Ghadow and Zayk Watersheds

Agricultural lands showed vulnerabilities to flash flooding equivalent to those of the 2002 storm magnitude. Table 15 provides a comparison of agricultural land losses as a consequence of flash wadi flooding at both watersheds in association with 0.0 m and 1.41 m SLR scenarios.

Table 13
Cost of Land per Meter in Omani Riyal

Wilaya	Region	Residential	MixedUse	Industrial	Agricultural	Tourism
Sadah	City Center	14.5	32	25	Not Provided	Not Provided
	Suburban	8	16.5	15	Not Provided	Not Provided
	Rural	5	12	10	Not Provided	Not Provided

Table 14
Zayk Watershed Wadi Flooding Inundation Results for Impacted Buildings at Maximum Inundation Depth

Wilaya	Region	Residential	MixedUse	Industrial	Tourism	Govt.	Comm.	Other
Sadah	City Center	1980	93	113	28		66	
	Suburban	980	31	69	1	66	12	16
	Rural	200	0	1	0		0	

Table 15
Number of Impacted Areas by Wadi Flooding on Agricultural Land and Other Green Areas at 0.0 m and 1.41 m of SLR

Watershed Name	Zayk		Ghadow	
SLR Scenarios	0.0 m	1.41 m	0.0 m	1.41 m
Agricultural Lands	178	180	296	303
Hotels Landscaping	14	14	29	29
Roads Landscaping	63	63	101	107
Wadi Riparian’s Area	50	63	84	89
Others	142	150	109	111

Preliminary cost estimation for infrastructure, urban, and agricultural impacts. The impacts of climate change on the Omani infrastructure and urban area will increase, mostly due to the frequent storm events. For example, the 2002 storm event cost the country close to $50 million. However, if a similar event occurred today, the cost of the damages would be much higher as Dhofar has undergone major urban development since the 2002 flood event. Tables 16, 17, and 18 show the increases in infrastructure and urban development in Dhofar from 2013 to 2015 (NCSI, 2016) that would likely double or triple the cost should an event similar to the 2002 flood event occur. For example, the cost of the impacts on residential plots within the Ghadow watershed would be in excess of $102 million, while the cost of residential plots at city center of the Zayk watershed would be around $45 million. Furthermore, the destruction to the agricultural land at the Ghadow watershed would cost about $7.4 million.

Table 16
Planned Land Plots in Dhofar and Type of Use

Year	Type of Use	Number
2013	Residential	1140
	Commercial	211
	Mixed-Use	258
	Industrial	475
	Agricultural	0
	Government	290
	Total	2374
2014	Residential	3944
	Commercial	819
	Mixed Use	3
	Industrial	266
	Agricultural	28
	Government	417
	Total	5477
2015	Residential	2819
	Commercial	274
	Mixed-Use	24
	Industrial	20
	Agricultural	0
	Government	247
	Total	3384

Table 17
Land Plots Granted by Type of Use in Dhofar

Year	Type of Use	Number
2013	Residential	1761
	Commercial	41
	Mixed-Use	6
	Industrial	34
	Agricultural	0
	Government	87
	Total	1929
2014	Residential	178
	Commercial	9
	Mixed-Use	0
	Industrial	0
	Agricultural	0
	Government	103
	Total	290
2015	Residential	4056
	Commercial	181
	Mixed-Use	23
	Industrial	122
	Agricultural	0
	Government	100
	Total	4482

Table 18

New Plots Registered for the First Time in Dhofar, and Type of Use

Year	Type of Use	Number
2013	Residential	3112
	Commercial	83
	Mixed-Use	64
	Industrial	56
	Agricultural	6
	Government	31
	Total	3352
2014	Residential	913
	Commercial	39
	Mixed-Use	36
	Industrial	36
	Agricultural	7
	Government	29
	Total	1060
2015	Residential	3034
	Commercial	102
	Mixed-Use	28
	Industrial	38
	Agricultural	8
	Government	5
	Total	3215

Moreover, the vulnerability of roads and railways in Oman is significant, especially given that Oman spent about 52.9% of its 2016 national budget in services sectors that included infrastructure (Central Intelligence Agency, n.d.). Road construction takes priority in infrastructure developmental planning in Oman. For instance, in 2014, 18% of the budget went toward road construction (MEED, 2014). The 8th Five-Year Development Plan for 2011–2015 in Oman outlines a plan to spend US$14.8 billion on infrastructure in the coming years; additionally, railway projects with an estimated cost of $10.5 billion are being undertaken (World Highway, 2013). Although the author is not able to find the cost of the roads that are impacted by flash wadi flooding and SLR at either the Ghadow or the Zayk watersheds, the construction of roads in Oman is quite expensive due to the topography of the country. However, cost estimates obtained are for nearby road projects in the region, including the Taqa-Mirbat road that stretches for 36 km and is set to be completed by March 2018, which cost about OMR40.5 million ("Taqa-Mirbat Road," 2016). Another example is the Hasik/Al Shuaimiyah road, an 87 km road with an estimated cost of OMR104 million. Furthermore, the Aidem/Heroib road is 62 km long and has an estimated cost of OMR15.8 million ("Major Road Projects Okayed for Dhofar," 2013).

Because natural hazards, frequent storms, and flooding appear to pose a long-term threat to the Omani infrastructure, it follows that there is also a long-term risk to development, as roads form the backbone of the country. Potential impacts on the transportation of people, services, and goods raise concern for Oman's developmental future. Major outcomes of this research are the ability to provide high-quality GIS-based modeling—the type of modeling used in the analysis of the 2002 flood event—that will enable us to quantify and map future threats to infrastructure and roads. We conclude that assessing the risk of SLR inundation and flash wadi flooding is a necessity in moving toward sustainable development and resilient infrastructure.

5.5 Limitations and Future Research

This study used non-Lidar-based DEM at 5 m resolution as the research area does not have Lidar product data. A disadvantage of the rough DEM resolution is the difficulty of simplified the topographic characteristics of the research site. Due to this difficulty, the water flow over the landscape is generalized as it is in the cases of the Zayk and Ghadow simulations as the channel disappeared. This approach could result in an overestimation of the impacted area. The influences of DEM resolution on 3Di flooding simulation are studied, and it has been shown that the model accuracy decreases with rough DEM resolutions that result in inundation overestimation. For example, the catchment of Sanyei at Tainan City showed differences in estimating inundation, particularly in areas with an elevated highway and urban buildings, due to the universalization of topographic information at rough DEM resolutions. The model simulation at 1x1 m DEM resolution reported an inundation extent at 603.45 ha, while at 5x5m resolution the inundation extent was 717.49 ha; with 40x40m resolution, 893.38 ha was the extent of the inundation. These results indicate that the accuracy of the flood inundation models is reduced with rougher DEM resolutions (Hsu et al., 2016). Therefore, using a Lidar-based DEM at 1 m resolution is extremely important if Oman is to avoid overestimation and produce the most accurate information for helping planners and decision-makers.

For future research, it will be helpful to study the flood risk estimates over future land use projections by using the damage scanner model. This type of research will be useful in examining the risk from wadi flooding and coastal flooding occurring simultaneously.

5.6 Conclusion and Discussion

The impetus for this research arose from the flash wadi flooding damage that resulted from the 2002 storm event in the Dhofar region. After the storm surge along Dhofar’s coast during the 2002 storm event is modeled in Chapter 3, the underestimation of the damage magnitude to the urban area and infrastructure required an extension of the research to include the impacts from flash wadi flooding that also took place during the event. The overwhelming flooding of the infrastructure and urban area led the country to build more dams for the protection of the area. However, if similar events are to transpire today, the damage would be greater because the amount of urbanization and infrastructure has increased. Even after the construction of dams, the area is still vulnerable to flash wadi flooding resulting from an event of the magnitude of the 2002 storm. Both of the areas in the watersheds in Dhofar are characterized by a pattern of reducing agricultural farmland in favor of increasing industrial, tourism, and urban areas, which increases the vulnerabilities for impacts from climate change. For example, Taihu Basin land use in China underwent major changes due to urbanization and population growth that resulted in tremendous flooding damages and economic loss during a storm event (Liang et al., 2011). With this in mind, this research is intended to model, quantify and predict how much infrastructure and urban areas might be at risk of extreme storm surge and wadi flooding today, and how much would be at risk in the future with a rise in sea level or increased exposure to frequent cyclonic and storm events resulting from climate change.

Adopting informed planning practices that take into consideration the future impact of forecasts through flash wadi flooding modeling in association with different SLR scenarios will help Oman produce more realistic mitigation and adaption plans, infrastructure management strategies, and resilient future infrastructural development.

The importance of this research lies in its quantification and its ability in providing a visual representation of the 2002 storm event with the highest DEM resolution available for Dhofar’s region. This model includes a land-use map that might help to imitate much of the water’s movements and infiltrations during the 2002 storm event. In addition, this research introduces 3Di, a hydrodynamic model that simulates entire rainfall events in association with the tidal cycle along the coast simultaneously that has not been possible using other software (such as the Arc-Hydrology tool in ArcGIS and Geo-HecRas). The 3Di program also has the ability to model a very large region a watershed scale at a very high spatial resolution due to its sophisticated quadtree-based data compression technology. Furthermore, because of 3Di’s quadtree computational capabilities, the model provides the possibility of computing each watershed over a 96-hour period in one simulation for the Zayk watershed and to compute over a 49-hour period for the Ghadow watershed in association with different SLR scenarios. Moreover, this research used real data from the 2002 rainfall storm event and tidal storm surge that was collected from the gauging station throughout the event, which produced realistic outcomes similar to those of the actual event.

From a planning perspective, this research shows the significance of understanding the impacts of climate change over the built areas and the infrastructure of Oman. Incorporating the knowledge of flooding simulations within the planning practices and within the strategic developmental planning will save Oman a large amount of future expenduire. Planning major infrastructural and economic projects in a haphazard manner can hold Oman back rather than encourage progress toward developmental and infrastructural maturity. However, it is not simply a desire to achieve the developmental target that makes this such an important issue, but also the desire to protect future generations, who should not be left with unsafe, nonfunctional systems and spaces.

This study demonstrates the need for flood risk assessments in Oman and the need to pay close attention to the current planning practices and development in efforts to reduce vulnerabilities when facing the impacts of climate change. An accurate coastal flood-inundation map of wadi flooding is important to the government of Oman for any future project planning. With precise flood inundation maps at high resolutions, decision-makers can make better-informed decisions regarding engineering projects, future economic projects, and even the creation and location of new urban areas. Moreover, the value of this research lies not simply in assessing impacts on infrastructure and urban areas, but also in showing the need for making different types of decisions to ensure that evacuation routes are safe and responses are quick during hazardous natural events.

The results of this research are based on the highest DEM resolution available for Oman and have substantial utility for informing future strategic developmental planning in Dhofar. The inundation or flash wadi flooding results have significant utility for modeling other highly developed parts of the country that are at risk of flash wadi flooding or sea level rise and storm surge.

Although 5 m DEM may not be the optimal surface data for an accurate estimation, this study produced a good baseline that should be informative for decision makers and planners. The 5 m horizontal resolution of the DEM provides a sense of damage at the property level that takes into account significant infrastructure and land-use maps that may affect water-flow, infiltration, and inundation impacts. This research helps in assessing future costs of existing infrastructure and for rebuilding and repairing systems. Strategic planning that focuses on proactive mitigation strategies leads to more cost-effective adjustments and better-informed decisions for future infrastructural developments.

This study recommends that Oman invest in creating a Lidar product for the entire country to more accurately measure and quantify future impacts of climate change and achieve the goal of moving toward a more sustainable Oman and a more resilient infrastructure. Using a rough DEM offers an overestimation of inundated areas. Accurate estimation of inundated areas and infrastructures is important for accurate economic loss assessment and for mitigating economic losses.

CHAPTER 6

6.1 Conclusion

Climate change is a threat to current and future sustainable development. The impact of climate change on most systems is challenging the continuation of sustainable development (SD) in some locations (Denton et al., 2014). Recent research has shown that Oman is likely to be exposed to frequent storm and cyclonic events. The results of this research motivate one to help Oman become a better prepared nation for the impacts of sea level rise and storm surge. They encourage the development of resiliency for the country's strategic-development planning as Oman faces an unstable economy and increased vulnerabilities in terms of its urban areas, its growing population, its infrastructure, and its economic projects. Population and economic growth in coastal 100-year flood plains are the leading factors increasing vulnerability (Hijioka et al., 2014). The development and urban expansion in Oman is similar to growth found in vulnerable coastal flood plains in general.

Planning for resilience and building a resilient infrastructure are the main strategies for achieving sustainability in Oman. The main objective of this research is to integrate science that promotes the creation of resilient infrastructure and development into the process of policy-making concerning Oman's strategic-development planning practices as the country is further exposed to climate change impacts and other natural hazards. The research uses 3Di hydrodynamic modeling to visualize the aftermath of the 2002 storm event in the Dhofar region. This modeling provides a visual representation of the 2002 storm-surge impacts in association with different SLR projections at 0.0 m, 0.5 m, 1.0 m, and 1.41 m along the coast of Dhofar. Employing 3Di modeling quantifies and illustrates the impacts of storm surge on the Ghadow and Zayk watersheds, resulting in the aftermath of flash wadi flooding in association with SLR at 0.0 m and 1.41 m. Flash wadi flooding impacts on infrastructure and urban areas are produced and considered in the first visual depiction of the 2002 event impacts. This research demonstrates the significance of integrating and using science in the planning practices and policy-making of Oman. It demonstrates the application of a process that can help Oman move toward sustainable development and develop the creation of a resilient infrastructure. It offers a glimpse into a future in which this knowledge and approach could be informative for the development of Oman and other Gulf countries. This is achieved in four ways: (a) by providing an overview of the principles of sustainable development and the implementation of those principles within the Omani context; (b) by modeling the 2002 storm-surge event in association with various SLR scenarios along the coast of Dhofar; (c) quantifying coastal tourism projects that show vulnerabilities for the 2002 storm-surge event with different SLR projections; and finally, (d) modeling the impacts of flash wadi flooding in 2002 and investigating the effects of this flooding on urbanization and infrastructure. These four objectives were achieved through analysis and discussion in Chapters 2, 3, 4, and 5, respectively.

In Chapter 2, the research focuses on the definition of SD and SD's implementation within Oman's developmental strategy. Oman demonstrates varying levels of SD-principle application in the economy, the environment, and society. Even though Oman is applying these principles, infrastructural resilience is not included in the country's strategic development plans, and the country has shown vulnerability. There has been almost no resilience planning in Oman's infrastructure and urban areas during the extreme events and cyclones of the last decade. To achieve sustainability consistent with SD principles in Oman, it is recommended that the concept of resiliency in regard to Oman's infrastructure be included in planning practices.

Chapter 3 describes modeling of storm surge in association with various SLR scenarios along the coast of Dhofar using the 2002 extreme storm event—considered the storm with the greatest magnitude in 30 years. The 3Di hydrodynamic modeling is used, showing the depth and the extent of the inundation at every hour of the storm. Impacts on infrastructure and urbanization are quantified. The 3Di modeling incorporates the buildings within the simulation area, providing a more realistic representation of storm-surge depth and extent as water movement and channelization through buildings is taken into consideration.

The DEM resolution is found to be an important factor in producing a better prediction of the impacts of flooding, especially given the topography of the Dhofar region. The high-resolution accuracy assessments show a precise flooding estimation at 1m, in contrast to low-resolution assessments at 5m that show an overestimation of the flooding extent. This indicates the need to create a high-resolution DEM for Oman to obtain a precise flooding estimation to make more accurate cost predictions.

This research shows the vulnerability of urban areas and infrastructure increasing as development progresses. In 2013, the Ministry of Environment and Climate Affairs predicted an increase in the frequency of storms and cyclonic events in Dhofar related to climate change. This prediction requires Oman to prepare for climate-change consequences by being ready to adapt to future exposure and by being resilient as development progresses.

Chapter 4 demonstrates the importance of integrating science and incorporating storm-surge and SLR projections into tourism development and planning in Oman. Because coastal tourism in Oman relies on natural assets, placing new resorts in vulnerable areas will not only stress the environment but also deplete the economy. Oman is planning to use tourism as a source of national income to diversify the economy. However, expanding coastal tourism development without considering climate change impacts during the planning stage will economically strain Oman over time. Finding a balanced solution for coastal tourism development that is adaptable and resilient to climate change impacts is significant for maintaining long-term sustainable tourism growth along the coast, a sustainable economy, and a resilient infrastructure for future generations.

Finally, Chapter 5 reveals flash wadi flooding destruction to urbanization, infrastructure, and other land uses in Oman and then quantifies the number of urban, industrial, and commercial buildings and roads that are impacted specifically in the Zayk and Ghadow watersheds of Dhofar. The effects on urbanization and roads are significant and require Oman to take serious action concerning current planning practices, to look for approaches that would reduce vulnerabilities to any future storm events, and to promote resilient infrastructural practices for current and future developments. This chapter undertakes modeling of flash wadi flooding at 5m DEM, which is not an ideal resolution, and recommends the implementation of Lidar-based DEM to acquire more precise surface for evaluating water movement and infrastructure vulnerabilities. Moreover, this research demonstrates that modeling storm surge along the coast alone, without including flash wadi flooding, resulted in underestimation of the destruction magnitude during the 2002 events. For Oman, where storm surge and flash wadi flooding occur simultaneously, the modeling approach needs to reflect this situation and should include flooding from wadi and storm surge to obtain a realistic projections of damage.

Overall, this research indicates that the effect on urbanization, roads, and infrastructure—either from SLR, or flash wadi flooding, or both—is alarming, and that measures for climate change adaption are required. Oman's urbanization, tourism projects, and infrastructure development are increasing, and these changes in land use could lead to higher flash wadi flooding and storm-surge impacts.

Achieving sustainability and resiliency for Oman's infrastructure and urban areas requires that the country adapt to climate change impacts. Because urban areas include not only the human population but also built assets and economic activities, it is essential that planning of this development must adopt resilience measures to the impacts of climate change on a broad spectrum of infrastructural vulnerabilities.

When working to mitigate and reduce flooding impacts on planned buildings and infrastructure, integrating science into land use planning is key to achieving developmental resilience. In general, conscious land use planning would be effective in decreasing future increases in coastal and wadi flooding risk. Using engineered defenses, such as sea walls and dams, to protect infrastructure and human settlements from flooding may have negative consequences for natural ecosystems. Such defenses may not be capable of preventing higher storm magnitude and may not be less costly in the long run—especially given an unstable economy, but they are likely more effective in guarding against disaster. This research recommends that the government and planning agencies in Oman stop granting lands, including residential, commercial, mixed-use, tourism, and industrial lands, that are located within flash wadi flooding plains or SLR and storm-surge-affected areas. The government needs to use science to inform itself about how to overcome these inundation challenges. For example, it can create open spaces (parks or buffer zones) that can collect floodwater before that water hits buildings and infrastructure so that the magnitude of the damage is reduced. Implementing the concept of constructing resilient infrastructure within the current and future developmental strategies could significantly help in reducing both impacts from flooding and vulnerability to the impacts of climate change, especially in high-risk areas.

This research recommends that Oman take the following steps:

1. Increase the precise estimating of future and current exposure to climate change and encourage the critical movement toward implementing a high resolution Lidar project that would cover the entire country of Oman. High resolution Lidar would help in obtaining, more accurate Lidar-based DEM, especially in areas that are currently, or are likely to become, hotspots for development, including residential, commercial, economic, and industrial areas. Taking this step will not only help in facilitating the smarter planning of a more resilient infrastructure but it will also help to insure investment in Oman over time.

2. After obtaining a high resolution Lidar-based DEM, Oman needs to conduct more research to accurately quantify and assess impacts, vulnerabilities, and adaptations needed in urban areas, including emergency evacuation and fuel transportation during events.

3. Oman needs to continue to improve climate models and flooding simulations, and include the sciences in planning and policy-making processes to achieve proactive and robust planning practices that prepare the country to adapt to a constantly changing an uncertain future.

4. Oman must recognize the importance of adapting to climate change now and in the future. It needs to emphasize resilient infrastructure and development in planning current and future strategic development.

5. Oman must continue to create awareness of climate change to affect policy at the political and social levels in order to join the rest of the developed world in transitioning from the awareness phase to a phase of constructing strategies and plans (Mimura et al., 2014).

6. Oman needs to transfer information to the Supreme Council for Planning where policy and legal frameworks can be enlightened. They need to encourage stakeholders to take actions to protect vulnerable areas, and to promote resiliency in infrastructure and urban areas. There is evidence of a disconnect between the Ministry of Environment and Climate Affairs and the Supreme Council for Planning in Oman when there should be coordination between the two agencies. Land use planning does not reflect any adaptive actions either in the current plans or in land-granting for residential, economic, and industrial purposes. In addition, many recent tourism and transportation projects have been developed within vulnerable areas, and many residential areas have been granted for citizens as well. This practice must stop.

7. Oman must practice proactive, event-driven approaches, rather than reactive approaches, in adapting to climate change impacts. The 2002 event in Dhofar is a good example where local governments implemented reactive mitigation plans (dams) in response to the event and that at risk development is still ongoing within flash wadi flooding and storm-surge-vulnerable areas. This response highlights the urgency of new approaches.

8. Oman must improve the quality of rainfall and runoff data, and make these data available at a higher resolution for storm events across the country to provide better simulation results, a better understanding of the hydrological processes of impacted regions, and better science in general.

9. Oman needs to simulate storm surge and flash wadi flooding together to obtain a better picture of the actual storm or cyclonic damage of these events. Flood modeling in Oman will always result in an underestimation when modeling is done for either storm surge or flash wadi flooding alone, and not together.

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