University of Southern Queensland

Faculty of Health, Engineering and Sciences

The Effects of Extreme Weather Events on Flexible Pavement

A dissertation submitted by

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ABSTRACT

Extreme weather events, such as excessive rainfall causing flooding and elevated maximum temperatures, are becoming a regular occurrence each year in Australia and are increasing in frequency. These weather events can possibly be contributed to climate change, which is a major issue that is likely to worsen in the years to come as we continue to burn more fossil fuels.

Flexible pavements are designed with consideration to the surrounding environment and to an extent, the current climate conditions known to the area. Heat is a known factor that can severely affect the design life of flexible pavements. It can cause surface cracks that, if left untreated, can allow moisture ingress to the sub-base and/or sub-grade layers of the pavement. However, this report will primarily focus on excessive rainfall resulting in flooding as it is a more quantifiable cause of pavement deterioration.

This research project aims to analyse pavement deterioration that can be attributed to by extreme weather events by comparing data collected from the City of Gold Coast (Council's) Pavement Management System. The primary focus of this project, flooding events, looked to compare road deterioration rates between frequently flooded sections of road to less-affected sections of the same road. This methodology allowed the elimination of variables which may have contributed to pavement deterioration such as increasing AADT, pavement age, and surface age, and ensured the only considerable contribution to the pavement's deterioration was due to exposure to flooding events. This analysis was performed on four roads in the form of case studies.

Analysis of the results revealed that the road sections which experienced flooding did show evidence of greater deterioration in comparison to the non-flood prone road sections. These deteriorations appeared in the forms of cracks, rutting and stripping. However, not all case studies showed the same intensity of damage or even the same damage type. It was proven though, that in all four case studies, there was a reduction in PCI values and an increase in roughness. A cost analysis was also conducted to better understand the financial impact these weather events may have on Council's flexible road pavements.

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CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Ahmed Gadalla

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LIST OF ABBREVIATIONS

CoGC - City of Gold Coast

PMS - Pavement Management System

SMEC - Snowy Mountain Engineering Corporation

AADT - Annual Average Daily Traffic

TMR - Department of Transport and Main Roads

BoM - Bureau of Meteorology

PCI - Pavement Condition Index

HMA - Hot Mix Asphalt

DMU - Disaster Management Unit

Recon - Reconstruction

LoS - Level of Service

SPMP - Sustainable Pavement Management Plan

WMAPT - Weighted Mean Annual Pavement Temperature

CHAPTER 1 - INTRODUCTION

1.1 Brief Introduction

Climate change is widely considered to be a major issue in recent years and is predicted to worsen in the years to come. The summer seasons are experiencing an increase in maximum recorded temperatures, while the winter seasons are getting colder. This can primarily be contributed to by global warming, which is attributed largely to the increased levels of carbon dioxide in the atmosphere caused by the burning of fossil fuels. Climate change is a long-term shift in global or regional climate patterns. Climate change often refers specifically to the rise in global temperatures from the mid-20th century to present (National Geographic, 2019). Furthermore, increasing frequency of excessive rainfall events can be considered as a product of climate change. Much of the damage to road infrastructure in Australia appears to be due to rising water tables and high saline contents (McRobert and Foley, 2003).

As extreme weather events such as excessive rainfall causing flooding and excessive heat continue to increase, it is important to consider impacts that these events may have on our road pavements. This is even more significant as flexible pavements in particular are designed with consideration to environmental aspects, such as weather and may experience significant deterioration or possible failure due to such weather events. Australia is one of the most vulnerable developed countries in the world to the impacts of climate change (Paun et al, 2019). Heatwaves are becoming longer, hotter and starting earlier in the year. Furthermore, there has also been an increasing trend over recent decades in the proportion of total annual rainfall stemming from heavy rainfall days. Queensland is experiencing Q100 rainfall events on a regular basis causing flooding. Precipitation patterns have changed markedly in the south eastern and south western regions of Australia, with a pronounced drying trend during the cool season (April – October), which is also the growing season. In the southeast of Australia, rainfall has declined by around 11 percent since the late 1990s (Climate Council, 2019).

Pavement design is a topic of major importance in the engineering world, primarily in the Civil engineering discipline. An adequate road infrastructure network is an important aspect of any developing country and forms a vital contribution to the economy. By world standards Australia has an extensive network of roads which is about 0.06 kilometres per capita compared with 0.03 kilometres per capita in both Canada and New Zealand. The total length of this network is over 800,000 kilometres (Australian Bureau of Statistics, 2012). Yet technological advances have not yet been able to produce roads that are not susceptible to surface/pavement damage due to weather events. By analysing sections of the same road which have been affected by flooding with sections that have not experienced the same frequency of flooding, we are able to understand exactly what types of pavement failure occur due to flooding and to what degree. The Pavement Management System used in this research project is developed by Snowy Mountain Engineering Corporation (SMEC) and is currently being widely used by Australian Local Governments to manage over 20,000 km of roads and 100,000 road sections around Australia. The data used in this study was sourced from the City of Gold Coast Council.

1.2 Idea Development

Within the last 10 years, the frequency of extreme weather events, such as flooding and elevated temperatures, has increased in Australia and specifically in Queensland. As pavements are directly impacted by climatic conditions, the idea of analysing what effects these weather events have on our road network was something that intrigued me and was yet to be investigated in this capacity. Over the last decade, heavy rainfall resulting in flooding has been occurring with increased frequency within the Gold Coast Region. Furthermore, some pavements had shown signs of exacerbated deterioration, especially within areas that had been affected by extreme weather events. Could these weather events have such an impact on flexible pavements, and if so, to what extent?

The Department of Transport and Main Roads, Transport and Main Roads technical specifications place limits on temperatures and weather conditions for placing pavement layers. These requirements aim to limit the detrimental effects that adverse weather conditions can have on the quality and/or performance of the constructed pavement (TMR, 2018). It is known that extreme temperature variations can cause rutting and cracking in flexible pavement. This is primarily due to repeated expansion and contraction of the pavement. Pavements, like all other materials, will expand as they rise in temperature and contract as they fall in temperature. Small amounts of expansion and contraction are typically accommodated without excessive damage. However, extreme temperature variations can lead to catastrophic failures (Pavement Interactive,2020).

For this reason, the investigation into the effects of extreme weather events on flexible pavements was selected. This research paper will primarily look into the effects of excessive rainfall causing flooding, for a better understanding of how to overcome these issues and possibly increase pavement life.

1.3. Research Objectives

For this research to be successfully completed there are a number of objectives that must be achieved. The objectives set out below will be used as a tool to make sure all aspects are covered and to keep the project on track. These objectives are:

- Investigate current literature relating to the different pavement failure types
- Investigate the current trends in weather patterns, focusing on excessive rainfall and increasing maximum temperatures within the South East Queensland Region.
- Collect and compare data relating to specific roads sections that have been affected by these extreme weather events and compare them to sections of the same roads that have not been affected by these weather events.

- Analyse the types of pavement deterioration evident on these road sections and attempt to associate a specific type/s of pavement failure for each extreme weather event.
- Attempt to quantify how much deterioration is being caused by each flood event
- Perform a cost analysis to understand how much these weather events are costing the CoGC annually.

1.4 Project Aim

The aim of this research project is to provide insight into the effects extreme weather events have on flexible pavements. As it is difficult to perform laboratory experimentation for this type of research, it was decided that the most efficient way would be to perform theoretical experimentation in the form of case studies and compare sections of the same roads that did and did not experience the selected extreme weather events. This will be achieved by analysing the SMEC PMS data from CoGC and a detailed comparison will be completed. To allow for a better understanding of how extreme weather events effect flexible pavements the following aims are to be completed.

- Determine the effects of excessive heat on flexible pavements
- Determine the effects of excessive rainfall causing flooding on flexible pavements
- Compare road sections that were frequently inundated due to flooding and sections along the same road that were not.
- Produce a cost analysis to determine the financial costs associated with repairs due to extreme weather events.

1.5 Expected Outcomes

The expected outcomes of this research project are that extreme weather events, specifically excessive rainfall causing flooding and excessive heat, how quantifiable impacts on flexible pavements and significantly reduce the pavements useful life. Furthermore, it is expected that specific type/s of pavement failure/damage can be attributed to particular extreme weather events.

It is a known fact that weather has adverse effects on pavements. But to what extent and severity are the currently experienced pavement failures attributed to by these specific weather events.

CHAPTER 2 - LITERATURE REVIEW

2.1 Flexible Pavements

There are primarily two types of pavement designs, flexible pavements and rigid pavements. A flexible pavement is composed of a bituminous material surface course and underlying base and subbase courses. The bituminous material is more often asphalt whose viscous nature allows significant plastic deformation. Most asphalt surfaces are built on a gravel base, although some 'full depth' asphalt surfaces are built directly on the subgrade (Jamal, 2017).

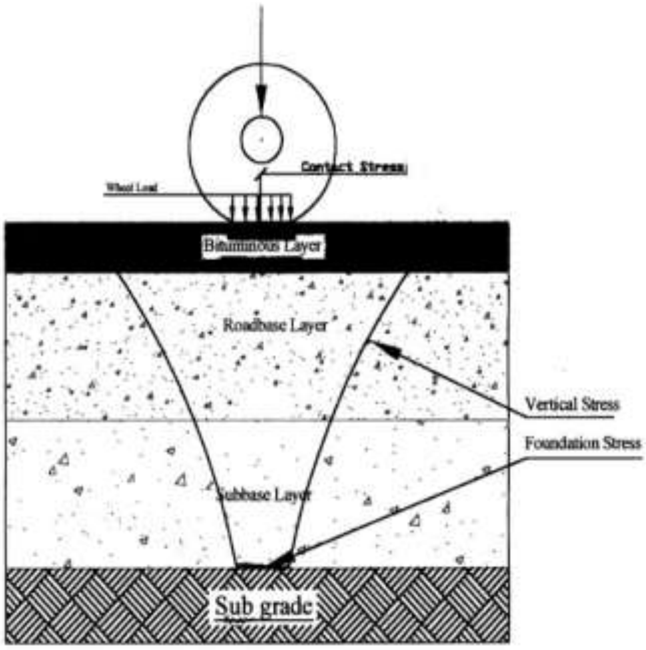

Figure **2.1: Stress distribution in flexible pavements (Jamal, 2017)**

Flexible pavements transmit loads applied by vehicles travelling on the road surface to the subgrade through a combination of layers known as the base course and sub base course. Flexible pavement distributes load over a relatively smaller area of the subgrade beneath. The initial installation cost of a flexible pavement is quite low, which contributes to why this type of pavement is more commonly seen universally. However, the flexible pavement requires maintenance in the form of routine inspections and repairs every few years. In addition, flexible pavement deteriorates rapidly; cracks and potholes are likely to appear due to poor drainage and heavy vehicular traffic (Jamal, 2017).

2.2 Types of flexible pavements

The choice of pavement type varies markedly with the function of the road, traffic loading, availability of materials, and the environment. Lightly-trafficked roads usually consist of unbound granular pavements with thin bituminous surfacing. Where an asphalt surfacing is provided it is common for the thickness of asphalt to be 25–50 mm. More heavily trafficked roads may require the asphalt to extend to more than the surface layer, with the asphalt commonly supported by a granular subbase (Austroads, 2017).

2.2.1 Granular Pavements with Sprayed Seal Surfacing

Unbound granular pavements with a sprayed seal surfacing are the major pavement type in rural Australia, comprising some 90% of the length of all surfaced roads. They form the majority of light and moderately trafficked rural roads and have also been successfully used on heavily-trafficked roads, subject to suitable materials, environments and construction and maintenance standards. This pavement type is extensively used due to its low initial cost (Austroads, 2017).

2.2.2 Granular Pavements with Thin Asphalt Surfacing

Unbound granular pavements with single thin asphalt surfacings are structurally similar to sprayed seal pavements except that asphalt surfacing may fatigue crack. For this pavement type the asphalt surface makes little contribution to the overall strength of the pavement but provides greater resistance to minor traffic damage as well as a smoother and more durable surface. These attributes make it particularly suited to residential streets and other light traffic urban applications where risk of fatigue cracking is lower (Austroads, 2017).

The most common surfacing types are dense graded asphalt 7 or 10 mm in size for lightly-trafficked pavements or lower speed environments, and 10 or 14 mm aggregate for more heavily trafficked applications. Detailed asphalt selection criteria are provided in Austroads Guide to pavement technology: Part 3 Pavement surfacings (Austroads 2009a).

2.2.3 Asphalt over Granular Pavements

These pavements consist of multiple asphalt layers over a granular base and/or subbase. In these pavements the purpose of the asphalt layers is to provide a wearing surface and to make a significant contribution to the structural capacity of the pavement. Where the asphalt thickness is less than 150 mm, the granular base layer(s) provides a substantial proportion of the load carrying capacity and both deformation and fatigue distress mechanisms are possible. Therefore, the asphalt and granular base materials must be of appropriate quality to ensure the intended service life results. The main application for asphalt on granular pavement is on medium traffic urban roads. It may also be suitable for rural highways and main roads depending on climate and traffic loads (Austroads, 2017).

2.2.4 Flexible Composite, Deep Strength and Full Depth Asphalt Pavements

In this case asphalt is used in both the surface and bound base layers to provide a significant proportion of the load carrying capacity. Deep strength asphalt pavements may also incorporate a cemented or lean-mix concrete subbase. Granular subbases and/or selected subgrade materials may be provided under the bound layers to provide an improved layer (Austroads, 2017).

2.3 Types of Pavement Failure

There are a variety of pavement failures that can occur on flexible pavements. These failures are primarily due to environmental and structural distress. The environmental distresses are caused due to environmental factors such as climate, weather conditions, UV exposure and problems with aging. However, the structural aspects are primarily the physical failures that are evident on the pavement surface and the sub-base layer/s. These structural failures occur due to overloading, wet subgrade, frosting effect or lower standards of design (Arjun, 2020). The following types of pavement failures were identified as possible failures that could occur due to environmental or weather events and therefore were required to be identified.

2.3.1 Rutting

Rutting is a form of deformation typically evident in flexible pavements; it is caused by the passage of loaded wheels over the pavement surface. It is manifested as a longitudinal depression along wheel paths. Rutting may occur in one or both wheel paths (Austroads, 2019). The rut depth is usually measured from the pavement surface to the lowest point within the rut. Rutting is a pavement defect which may also present a safety hazard as it can cause vehicles to aquaplane in the event of rainfall when ponding occurs within the ruts.

Figure 2.2: Pavement rutting (TMR, 2017)

2.3.2 Shoving

This is usually bulging of the road surface generally parallel to the direction of traffic and/or horizontal displacement of surfacing materials, mainly in the direction of traffic where braking or acceleration movements occur. Transverse shoving may arise with turning movements. Some possible causes of shoving include (AAPA, 2010):

- Inadequate strength in surfacing or base.
- Poor bond between pavement layers.
- Lack of containment of pavement edge.
- Inadequate pavement thickness.

Figure 2.3: Pavement shoving (TMR, 2017)

2.3.3 Cracks

Cracks are fissures resulting from partial or complete fractures of the pavement surface. Cracking of road pavement surfaces can happen in a wide variety of patterns, ranging from isolated single cracks to an interconnected pattern extending over the entire pavement surface. The detrimental effects associated with the presence of cracks are manifold and include (AAPA, 2010):

- Loss of waterproofing of the pavement layers
- Loss of load-spreading ability of the cracked material
- Pumping and loss of fines from the base course
- Loss of riding quality through loss of surfacing
- Loss of appearance.

The loss of load-spreading ability and waterproofing will usually lead to accelerated deterioration of the pavement condition. There a number of cracks that can occur on pavement surfaces, these are listed below:

2.3.3.1 Block Cracks

Interconnected cracks forming a series of blocks, approximately rectangular in shape commonly distributed over the full pavement. Cell sizes are usually greater than 200mm and can exceed 3000mm. Joints in pavement layers may reflect through the surface layer and appear as rectangular blocks, particularly joints in concrete pavements overlaid with asphalt (AAPA, 2010).

Figure 2.4: Block Cracks (TMR, 2017)

2.3.3.2 Crescent shaped cracks (slippage or shear cracks)

Half-moon or crescent shaped crack, commonly associated with shoving, often occurring in closely spaced, parallel group, mainly associated with asphalt (AAPA, 2010).

Figure 2.5: Crescent shaped crack (Grover Allen, 2017)

2.3.3.3 Crocodile cracks (Fatigue cracking)

Also known as alligator cracks. Interconnected or interlaced cracks forming a series of small polygons resembling a crocodile hide. Usually associated with wheel paths and may have a noticeable longitudinal grain. Cell sizes are generally less than 150mm across but may extend up to 300mm (AAPA, 2010). This may be caused by insufficient pavement layer thickness, brittle base or wearing course due to age or cemented base. The failure can also be due to weakness in the surface, base or sub grade or poor drainage (TMR, 2017)

Figure 2.6: Crocodile Cracking (TMR, 2017)

2.3.3.4 Longitudinal Cracks

These are defined as cracks running longitudinally along the pavement. This can occur singly or as series of almost parallel cracks and some limited branching may occur. These cracks are primarily due to contraction and shrinkage of the surfacing layer or reflection from the underlying base layer joints, poorly constructed surfacing layer joints or subgrade settlement (TMR, 2017)

Figure 2.7: Longitudinal cracks (TMR, 2017)

2.3.4 Ravelling

Initially fine aggregate breaks loose and leave small patches in the pavement surface, leading to progressive disintegration of the pavement surface by loss of both binder and aggregates. Possible causes include insufficient adhesion between the asphalt and the aggregate, deterioration of binder and/or stone, inadequate compaction or construction during wet or cold weather, and hydrophilic aggregates used during the constructions (TMR, 2017)

Figure 2.8: Ravelling (TMR, 2017)

2.3.5 Stripping Seal

Removal of the coarse aggregate of a sprayed seal leaving the binder exposed to tyre contact – can happen as the loss of individual stones, or as the complete loss of stone in a localised area. Possible causes include: Low binder contents, poor binder to stone adhesion (dirty or hydrophilic aggregates, without effective pre-coating with adhesion agent or wet stone etc.), aging or absorption of binder, stone deterioration, incorrect blending of binder, inadequate rolling before opening the seal to traffic (TMR, 2017)

Figure 2.9: Stripping seal (TMR, 2017)

2.3.6 Potholes

Potholes are bowl-shaped depressions in the pavement surface resulting from the loss of wearing course and base course material. They generally have sharp edges and nearly vertical sides at the top of the hole. Potholes are produced when traffic abrades small pieces of the pavement surface (cracking, delamination etc.) allowing the entry of water (AAPA, 2010).

Figure 2.10: Potholes (TMR, 2017)

2.3.7 Flushing, bleeding seal

Presence of excess bitumen in the pavement surface layer which creates patches with low skid resistance due to inadequate tyre-to-stone contact. Possible causes include, excessive application rate of binder, with respect to stone size, excessive prime coat being incorporated into the seal, excess binder in underlying patch or flushed area, penetration of aggregate into low strength base and primer seal covered before volatiles in primer binder have evaporated (TMR, 2017)

Figure 2.11: Flushing, Bleeding seal (TMR, 2017)

2.3.8 Isolated Depressions and Bumps in Bituminous surface

Localised depressed sections within a pavement, the depression not necessarily limited to wheel paths and may extend to entire lane width. Depressions are clearly visible after a rain when they fill with water. Bumps are a localised upward movement in a pavement. Possible causes include, settlement of widening trenches, poorly compacted isolated sections of subgrade or base, volume changes in subgrade materials due to various reasons such as drying out due to tree roots, or change in moisture content of expansive soil.

2.4 Climate change

The Earth's climate is controlled by the exchange and storage of heat through the ocean, land, atmosphere and snow/ice. It is influenced by interactions between the sun, ocean, atmosphere, aerosols, clouds, ice and land (Department of Environment and Resource Management, 2010).

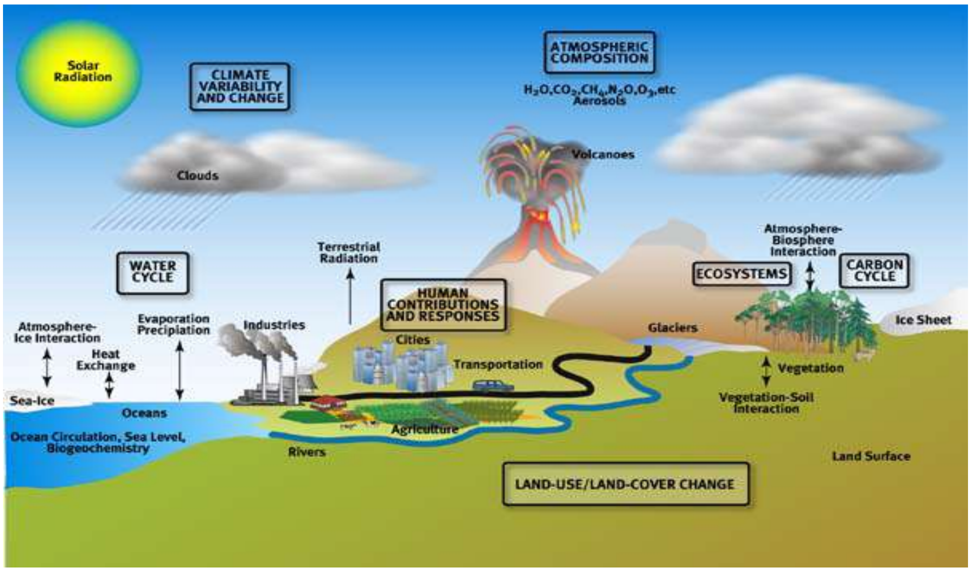

Figure 2.12: The climate system (Department of Environment and Resource Management, 2010)

Human activities have affected the climate for a long time, but it is only after the Industrial Revolution, and especially since 1950, that human activities have become so significant that they are changing the climate on a global scale. The most important human influence is the emission of greenhouse gases to the atmosphere from the burning of fossil fuels; human activities have increased the amount of carbon dioxide in the atmosphere by 40% since the beginning of the Industrial Revolution (Climate Commission, 2013).

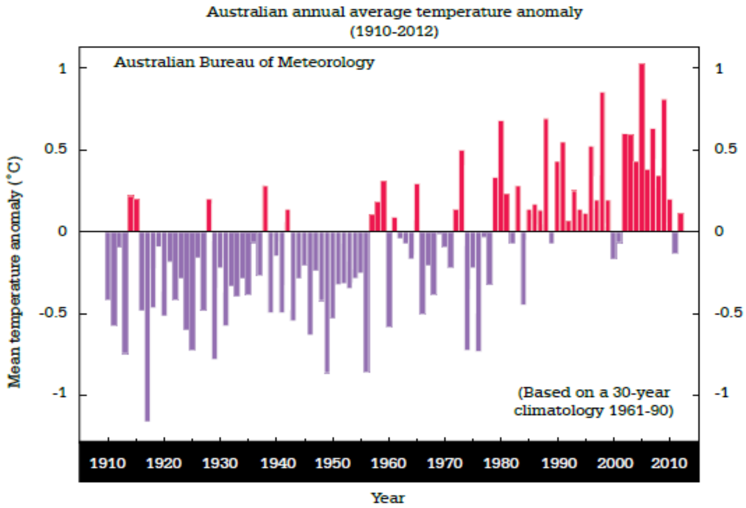

Figure 2.13: Time series of the annual average temperature anomaly for Australia from 1910 to 2012 (BOM, 2013)

The air temperature trend for Australia over the last century largely mirrors the global trend (Figure 2.13), with a rise in average temperature of about 0.9°C from 1910 to the present. The temperature increases have been larger in the interior of the continent and lower along the parts of the coasts (Figure 2.14). However, it is also evident that the prominent temperature increase has been within the eastern side of Australia, this includes Queensland, New South Wales and Victoria.

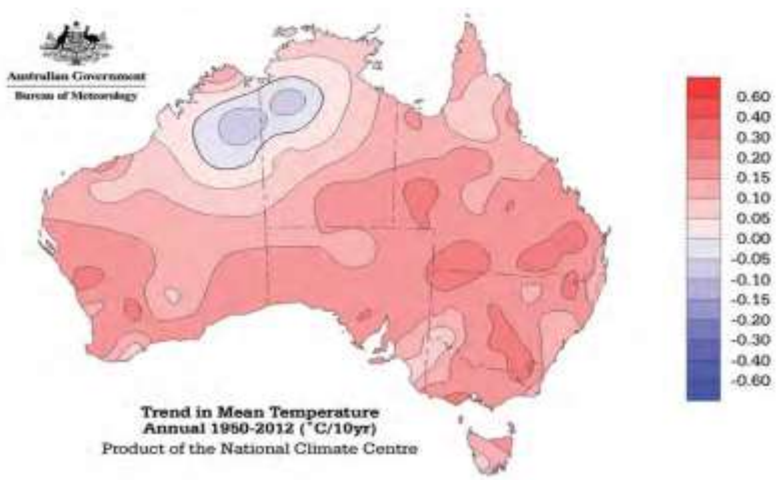

Figure 2.14: The trend in average annual temperature for Australia from 1950 through 2012 (BOM, 2013)

According to NASA, the heat-trapping nature of carbon dioxide and other gases was demonstrated in the mid-10th century. There is no question that increased levels of greenhouse gasses must cause the Earth to warm in response (NASA, 2019).

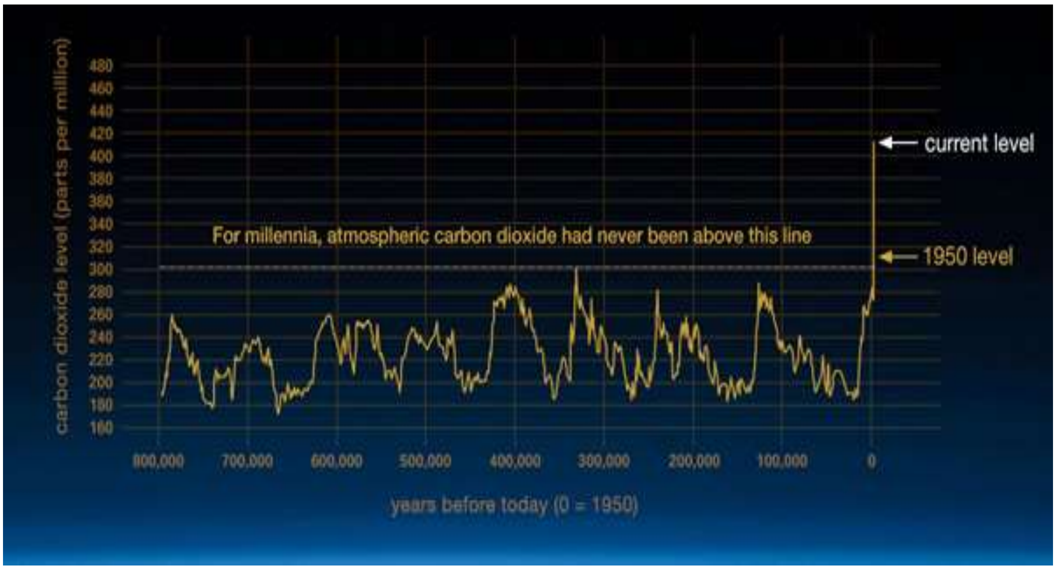

Figure 2.15: Comparison of atmospheric samples contained in ice cores and more recent direct measurements (NASA, 2019)

Hira (2017), investigated the effects of climate change on road infrastructure and development of adaption measures, and concluded that the rapid climate change associated with the increased traffic loads causes the main factor for pavement deterioration. Gudipudi et al. 2017, also produced an article investigating the effects of future weather change on pavement surfaces. The authors compared the results achieved by inputting baseline/historic climate data vs future climate data into (AASHTOWare) pavement design ME software. The impacts of climate change using both sets of data were then compared. In short, the study findings suggest, like others, that there may be a substantial impact on the pavement infrastructure due to the climate change. As global warming is exacerbated, pavements designed based on historical data will suffer from a faster deterioration rate. The results also show that precipitation always has negative impact on the condition of the pavement at all-time dimension (Gao et al. 2019).

Extreme weather events are often short-lived, abrupt events lasting only several hours up to several days; they are 'shocks' within the climate system. Examples include extremely hot days, very heavy rainfall, hail storms, flooding and tropical cyclones. These are 'acute' extreme events. A few extreme events can last for much longer periods of time and are usually termed extreme climate events. These are 'chronic' extreme events (Climate Commission 2013). A heavy rainfall event is a deluge of rain that is much longer and/or more intense than the average conditions experienced at a particular location. The amount of rainfall in a day is also referred to as rainfall intensity. An extreme rainfall event may also be defined by its 'return period'. A 1-in-20-year event at a site is the daily rainfall total that would be on average expected to occur once in 20 years. The magnitude of such an event would vary from site to site (Climate Commission 2013).

The effects of climate change on pavements were also investigated by the U.S. Department of Transport (2015), and some key performance parameters were associated with climate change on pavements including both flexible and rigid pavements. For instance, current work in Washington State shows that for a majority of well-constructed, high-volume asphalt pavements, rehabilitation is eventually triggered by rutting distresses, while for most low-volume pavements, rehabilitation is eventually triggered by cracking distresses. In general, changes in these trends (whether in the rate and/or type of distress development) over time may be influenced by climate change and may instigate a strategic change to more rut resistant materials, such as stone matrix asphalt (SMA) and polymer-modified binders in surface courses. Table 2.1 lists key pavement indicators that should be monitored for asphalt and concrete pavements.

Asphalt Pavement Indicators	Concrete Pavement Indicators
Rutting of asphalt surface	Blow-ups (JPCP)
Low temperature (transverse) cracking	Slab cracking
Block cracking	Punch-outs (CRCP)
Raveling	Joint spalling
Fatigue cracking and pot holes	Freeze-thaw durability
Rutting of subgrade and unbound base	Faulting, pumping, and corner breaks
Stripping	Slab warping
	Punch-outs (CRCP)

Table 2.1: Key pavement indicators to monitor for climate change impacts (USDT, 2015)

In summary it is clear the climate is changing and the affects the climate has on flexible pavements is devastating. Temperature, temperature ranges, and groundwater level may be critical climate stressors for pavements. Thus, the long-term/extreme changes of temperature (e.g., local warming or more frequent heat waves) and high groundwater level (e.g., due to flooding, storm surge, or sea level rise) are of particular concern (Qiao et al., 2020).

2.5 South East Queensland Climate

South East Queensland often experiences climate extremes such as floods, droughts, heatwaves and bushfires. Climate change is likely to exacerbate the frequency and severity of these events. We will increasingly be affected by changes in temperature, rainfall, sea level and extreme weather conditions. In the future, the region can expect (Department of Environment and Science Queensland, 2019)

- Temperatures to continue to increase year-round
- Hotter and more frequent hot days
- Harsher fire weather
- Reduced rainfall

- More intense downpours
- Rising sea levels
- More frequent sea-level extremes

Maximum, minimum and average temperatures are projected to continue to rise. For the near future (2030), the annually averaged warming is projected to be between 0.6 and 1.3°C above the climate of 1986–2005. By the year 2070, the projected range of warming is 1.1 to 3.3°C, depending on future emissions (Figure 2.16). There is likely to be a substantial increase in the temperature reached on the hottest days, and an increase in the frequency of hot days and the duration of warm spells.

By 2070, projections of total rainfall show little change or a decrease, particularly in winter and spring. Rainfall is naturally highly variable and this will continue to be a major factor in the next decade. However, the intensity of heavy rainfall events is likely to increase (Department of Environment and Science Queensland, 2019).

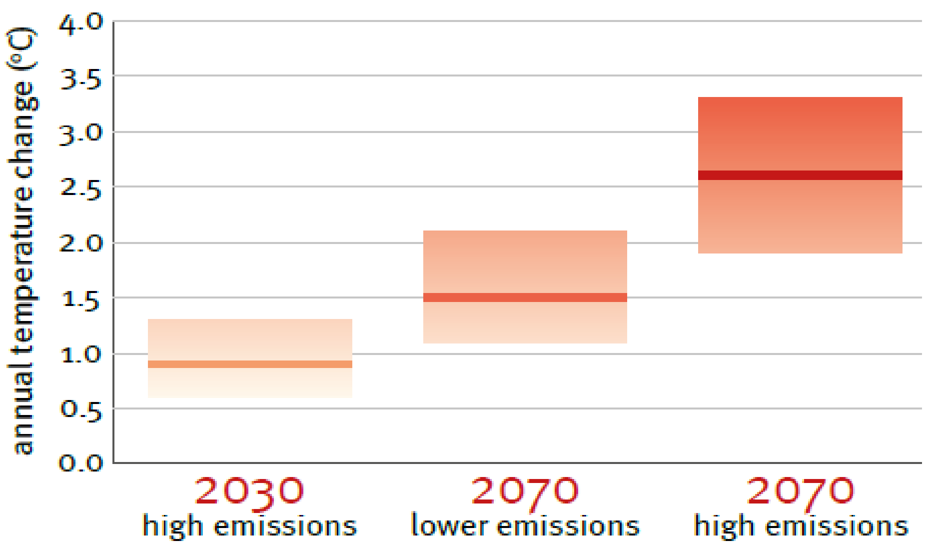

Figure 2.16: Projected annual average temperature changes for the South East Queensland region (Department of Environment and Science Queensland, 2019)

2.5.1 Temperature Changes

According to the Bureau of Meteorology (BoM), the annual mean temperature (Figure 2.17) and the annual max temperature (Figure 2.18) have been increasing and occurring more frequently since 1980. From the data, it is evident that the intensity and frequency of hot days are increasing. The increase in global average temperatures has increased the probability of hot extremes (including record-breaking hot temperatures). The annual number of hot days (above 35°C) and very hot days (above 40°C) has also increased strongly over most areas since 1950. Heatwaves are also lasting longer, reaching higher maximum temperatures and occurring more frequently over many regions of Australia (Climate Council, 2019).

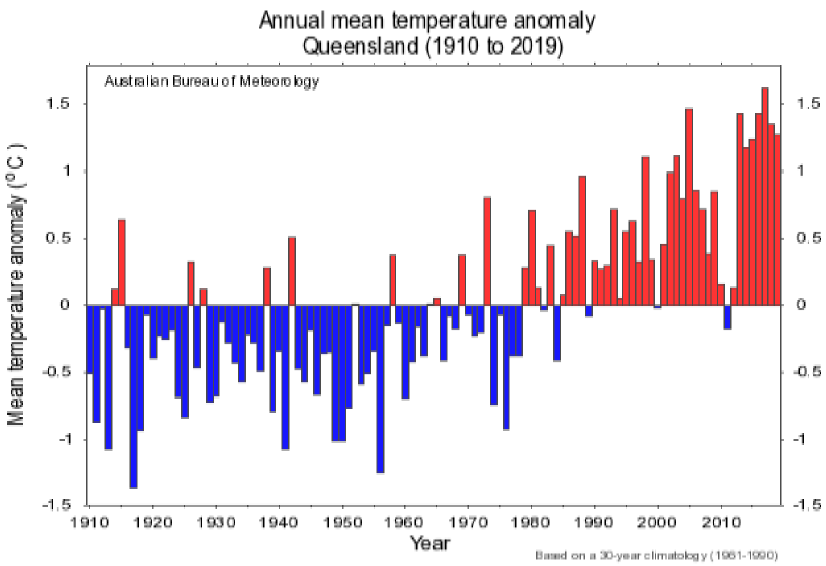

Figure 2.17: Annual mean temperature anomaly for QLD between 1910 - 2019 (BoM, 2020)

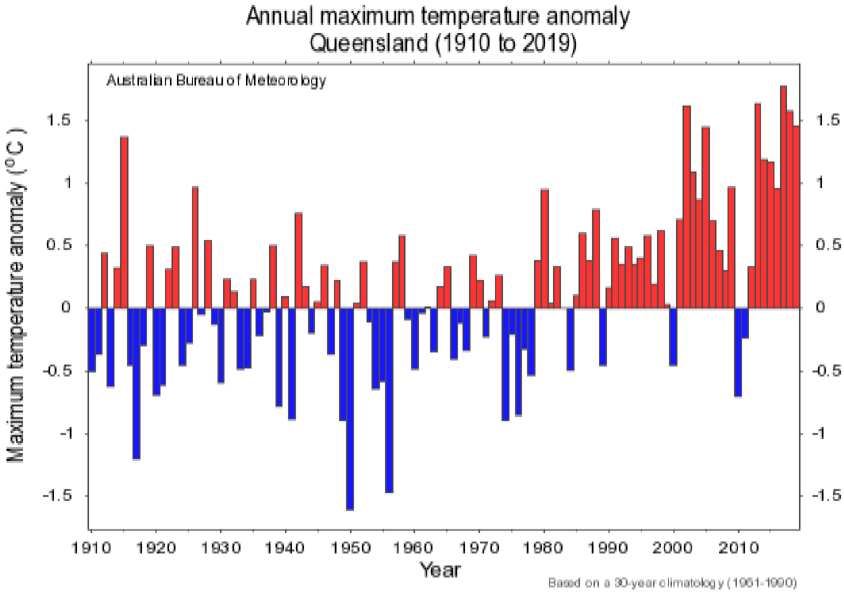

Figure 2.18: Annual maximum temperature anomaly for QLD between 1910 - 2019 (BoM, 2020)

2.5.2 Precipitation Changes

The Gold Coast is subject to flood risks and past flood events have caused moderate to extensive damage to private property, community buildings, bridges and roads. Flooding is generally understood as the inundation of land from rivers and creeks breaking their banks usually as a result of extensive rainfall. Elevated sea levels and extreme storm tides in response to cyclonic weather events can also result in land being inundated by water The Gold Coast is subject to existing, future and residual flood risks and has experienced more than 20 floods since 1958 (City of Gold Coast, 2019).

Figure 2.19: Alan Wilkie Bridge 2017 (CoGC, 2017)

The effects of climate change were felt in Queensland in 2011, when major flooding of areas in Brisbane and Gold Coast occurred. The Bureau of Meteorology reported, over the twelve-month period, Central and Northern Queensland were the only extensive areas of very much above average rainfall. This was partly due to record rainfall in late-January and February 2011 associated with an intense and very slow-moving monsoon low (BOM, 2019).

According to the Department of Environment and Resource Management, there will not be much change in the total annual Queensland rainfall, but the issues is how and when the rain falls during the year. The HiGEM model was used to examine how Queensland's climate might change in the future. The findings show that the wet season's duration is projected to shorten. Although the wet season is projected to shorten, its intensity is therefore projected to increase as the overall rainfall will not change (Department of Environment and Resource Management)

In Australia, there has also been an increasing trend over recent decades in the proportion of total annual rainfall stemming from heavy rainfall days. The physical relationship between temperature and the moisture holding capacity of the atmosphere suggests that for each 1°C rise in global average temperature, the atmosphere can hold approximately 7 percent more moisture. In Australia, the magnitude of extreme daily rainfall (mm/day) is increasing in line with this rate, whilst the magnitude of extreme hourly rainfall (mm/ hour) is increasing at double this rate, and more than triple this rate in the tropical north (Climate Council, 2019).

2.6 Impacts of flooding on flexible pavements

The occurrence of flooding due to excessive rainfall events has been increasing in recent years. Excessive rainfall events equalling Q100 or close have become increasingly common especially within the Gold Coast Region. The effects such events have on flexible pavements can be devastating. According to Sultana et al., climate change and extreme weather events, such as flooding and frequent intense heavy rainfall events, will have impacts on pavement performance and will influence the rate of pavement deterioration. The effects of extreme climate on pavement deterioration can significantly influence planning and management for road maintenance and rehabilitation.

The flood events which occurred in 2010-2011 in South-East Queensland raised the importance of monitoring road pavements subject to frequent flooding. It is therefore imperative to have an in-depth understanding of the structural performance of pavements under flooding conditions. Long-term observation of pavements is also instrumental in providing answers to why some roads survived flooding but others were highly impacted by the events.

Pavement damage due to flooding can vary depending on many factors. There are various loads that apply to the pavements during a flood event, these including flood depth, duration, velocity, debris and contaminants, which can potentially impact pavement damage (Table 2.2) (van de Lindt et al. 2009). The effect of flood depth and duration on pavement damage is due to pavements' absorption of flood water. Damage caused by flood velocity is due to the force of water.

Load Type	Description of Pavement Damage
Flood depth	**Absorption of water**
Flood duration	**Absorption of water**
Flood velocity	**Force of water**
Flood debris	**Debris carried by water**
Flood contaminants	**Absorption or adhesion of contaminants carried by water**

Table 2.2: Loads on Flooded pavements (van de Lindt et al. 2009)

Lu et al. 2018, analysed the flood characteristics, pavement damage patterns and impact factors. A case study was performed to simulate the impact of flood events on pavement performance. Precipitation depth, duration, number of cycles and pavement structure designs are taken as variables in the performance simulation. The study concluded that the Pavement damage ratio increases as the number of event increased. The extreme events can potentially result in the loss of pavement life, which indicates the value losses of pavement assets.

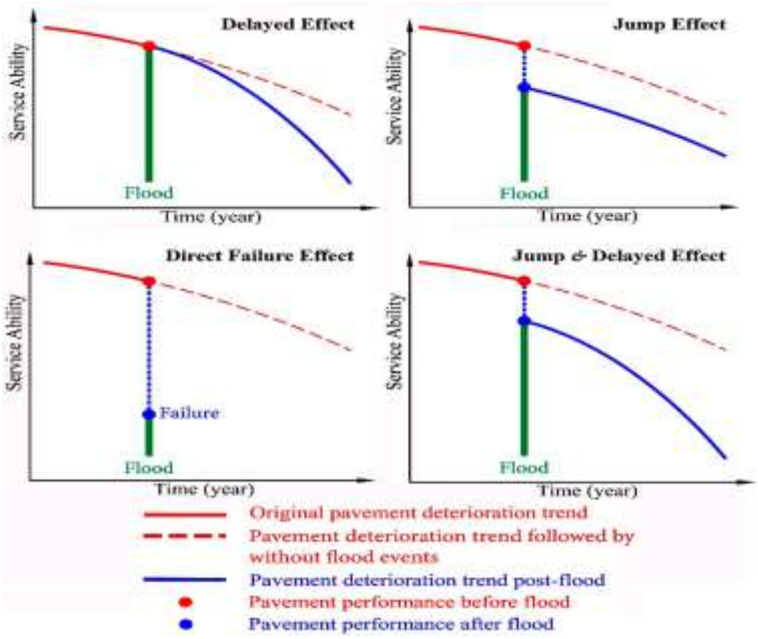

Figure 2.20: Pavement damage patterns with the occurrence of flood hazards (Lu et al. 2018)

Damage can be caused by pavement water saturation, debris and current. The ingress of excessive flood water, especially if the pavement has cracks and joints, can result in accelerated pavement degradation. Pavement performance change caused by floods is composed of different damage components. Layer material degradation, surface texture losses, interlayer bonding losses and layer movement are the major sources of pavement damage (Lu et al. 2018).

When water gets trapped under the base or seeps into the cracks, it starts to damage the structure of the pavement. That deterioration might not show itself until the area has caved in or dipped dramatically, which is harder to repair with services like patching since it affects the structure. In some cases, the water can also strip the pavement of its binder, which leaves it more vulnerable to natural corrosion, and start to leave a depression in the pavement where wheels often go over it.

Asphalt must drain in order to safeguard the space from moisture damage. Water is capable of dissolving nearly every substance if it stays in place long enough. If the asphalt does not have proper drainage, the moisture will eventually cause erosion. Asphalt damaged by moisture will endure distress that can lead to ravelling, cracking, stripping and rutting. Water that seeps down into the structure of the pavement as a result of rain, water flow or groundwater will be absorbed by the pavement and wear away at the bond between the pavement's aggregate and the asphalt binder. This is precisely why the structure of pavement is so important (ACPLM, 2019)

Pavement saturation during flooding is a key deterioration processes that result in degradation of pavement materials. When HMA (Hot Mix Asphalt) pavement layers are saturated, the adhesive and cohesive forces between the asphalt and the aggregate and between molecules within the asphalt film can be weakened (Little et al. 2003). The segregation of aggregates changes the properties of the mix and accelerates deterioration, affecting the performance of asphalt pavements (Baqersad et al. 2016, 2017). Furthermore, saturation can reduce the stiffness for unbounded pavement layers. Resilient behaviour of the unbounded pavement layer can also be affected significantly when full saturation is approached (Vuong 1992). At high degrees of saturation, it has been shown that the resilient modulus is significantly dependent on moisture content (Heydinger et al. 1996).

Flood water also carries debris and fine particles that can clog the pavement surface. This may alter the texture of the pavement surface which can lead to possible reduction in surface friction factor. A reduction in the pavement friction factor would render the surface smooth thus leading to major safety hazards for vehicles using the road. Pavements are a multi-layered composite system that transfers and distributes the traffic load to the subgrade. The saturated pavements may lose interlayer bonding, which results in a low capability for transferring traffic load, leading to pavement distresses including rutting, slippage cracking and potholes (Leng et al. 2008). According to Sultana et al. 2016 there is an increase in roughness, rutting and cracking in some sections of flooded pavements, and the reduction of subgrade CBR value and structural number can be up to 67 and 50%, respectively

In 2016, a study conducted by ARRB in a collaborative research agreement between ARRB and Sultana, which was done to understand the impacts of flooding on pavement deterioration by examining the structural performance of flooded pavements using Falling Weight Deflectometer (FWD) deflection and surface condition data sourced from Brisbane City Council, Transport and Main Roads and Roads and Martine Services. The deflection data was analysed using the CIRCLY5 program (Wardle 2009) to back-calculate the stiffness moduli of the various pavement layers including the California Bearing Ratio (CBR) of the subgrade. With stiffness modulus, the structural numbers of pavement sections can then be calculated. The preliminary findings indicate that the reduction of strength of the road pavements due to floods range from 1.5% to 50.0%. The changes occurred within a relatively short period of time (approximately six weeks). These results indicate that the strength of inundated pavement sections is significantly impacted by the flood (Sultana et al. 2016)

Moisture content in the unbound granular layers and subgrade can be significantly affected by the groundwater level in regions where the existing groundwater level is high. Due to flooding or heavy rain, the pavement subgrade or even unbound layers may be submerged, resulting in significant moisture levels. Water in the pavements can also move in the form of vapour in capillaries, depending on temperature (Dempsey et al., 1976). In regions where precipitation (or even flooding) will increase, stripping may become more frequent, especially when drainage is inadequate (Qiao et al., 2020). Extreme rainfall events causing flooding can affect flexible pavements through the reduction in structural capacity of unbound bases and subgrade when pavements are submerged (Meyer et al., 2014).

Furthermore, it was found that pavements with low pre-flood rutting had significantly lower post-flood rutting than pavements with high pre-flood rutting in the TMR observational data. This indicates that pavements with low pre-flood rutting are more likely to survive well after the flooding while a pavement with high pre-flood rutting (pavement in poor condition) is more likely to deteriorate following the flooding event and flood affected pavements were found to be deteriorated rapidly rather than gradually as anticipated by many available deterioration models (Sultana et al., 2016)

From the literature it is evident that flooding has detrimental effects on flexible pavements and causes extensive damage in the forms of rutting, stripping, cracking, potholes, and reduction of subgrade CBR value. However, these damages could be much greater if the pavement surface experiences flooding in the form of fast moving water. In this case the entire pavement surface can be washed away exposing the base and/or subbase materials. Stripping (ravelling) at the asphalt surface can be caused by various factors, such as poor materials, construction, environmental factors. It was found that saturation in asphalt layers (e.g. after a rainfall event) can accelerate stripping (Zhang et al., 2015). Furthermore, these mentioned pavement failure types affect the roughness and quality of ride for users of the road. More importantly, rutting can be a major safety hazard as it can cause vehicles to aquaplane if ponding occurred within the rutts after a rainy day.

2.7 Impacts of excessive heat on flexible pavements

As the average annual recorded temperature keeps increasing it is imperative to investigate the effects extreme heat has on flexible pavements. High temperature is the greatest climate concern as flexible pavements are highly sensitive to high temperature, and the impacts can accumulate over the complete service life (Qiao et al., 2020). There are a number of research papers outlining the implications high temperatures have on flexible pavements.

According the American Association of State Highway and Transportation Officials (AASHTO), It has been widely accepted in the pavement research field that temperature mainly impacts the asphalt layers, where increases in temperature can reduce the stiffness of asphalt materials, which can limit the stress-strain response of the pavement and reduce the ability of a pavement structure to spread loads (AASHTO, 2009). In addition, even if the change in the stiffness of these materials is not significant over the length of a single day, changes in stress-strain response and load spreading ability can exhibit their effects in the long term and may accelerate load-related deterioration. Furthermore, the ability of asphalt materials to resist permanent deformation reduces as temperature increases (Qiao et al., 2020). In extreme cases, when temperature has significant daily/hourly increases, accelerated development of permanent deformation can be expected (Qiao et al., 2020). In addition, higher temperature can lead to faster aging of asphalt mixtures, and pavements can become more prone to cracking due to brittleness (Navarro et al., 2018)

Alkaissi, 2020, examined the effects of pavement rutting due to increased pavement temperature using finite element analysis (ABAQUS). The obtained results demonstrated that; there is a significant effect of both thermal and traffic loading conditions on rutting damage of flexible pavement and higher temperatures will provide high rut depth by 2.29, 3.1 and 4.3 times for Asphalt layer, base layer and subgrade layer respectively (Figure 2.21). Furthermore, from the finite element analysis it's clear from both figures (Figure 2.22 and Figure 2.23) of deformation distribution for flexible pavement that the both thermal and traffic combined effects have more severe damage in the form of rutting.

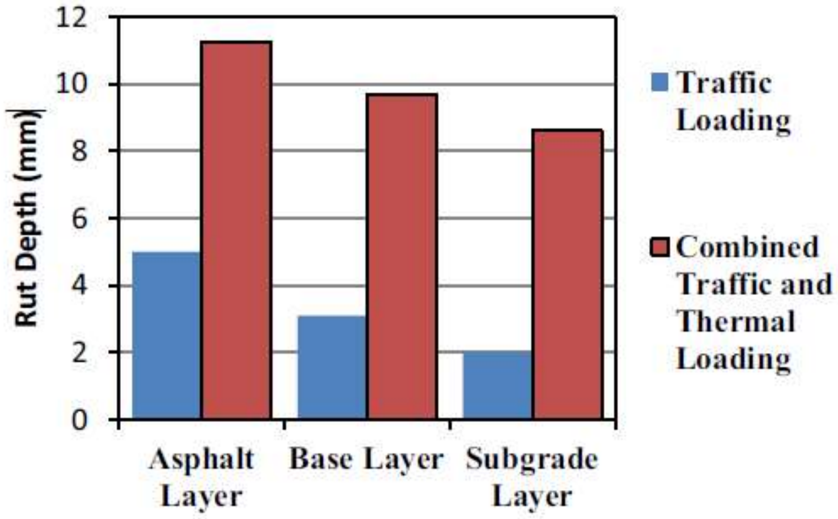

Figure 2.21: Rut depth at flexible pavement layers under the combined effect of traffic and thermal loading (Alkaissi, 2020)

Pavement damage is possible when the temperature rises and falls. Shifts in atmospheric temperature directly relate to pavement surface temperature and can spur pavement expansion and contraction. When the pavement surface temperature increases, pavements expand. The opposite occurs when the pavement surface temperature drops, the pavement contracts. While minimal contraction and expansion are not a major threat to the integrity of pavement, significant shifts in temperature can cause failure. It is possible for such temperature variations to lead to significant transverse cracks in rigid and flexible pavements when the weather turns cold (ACPLM, 2019).

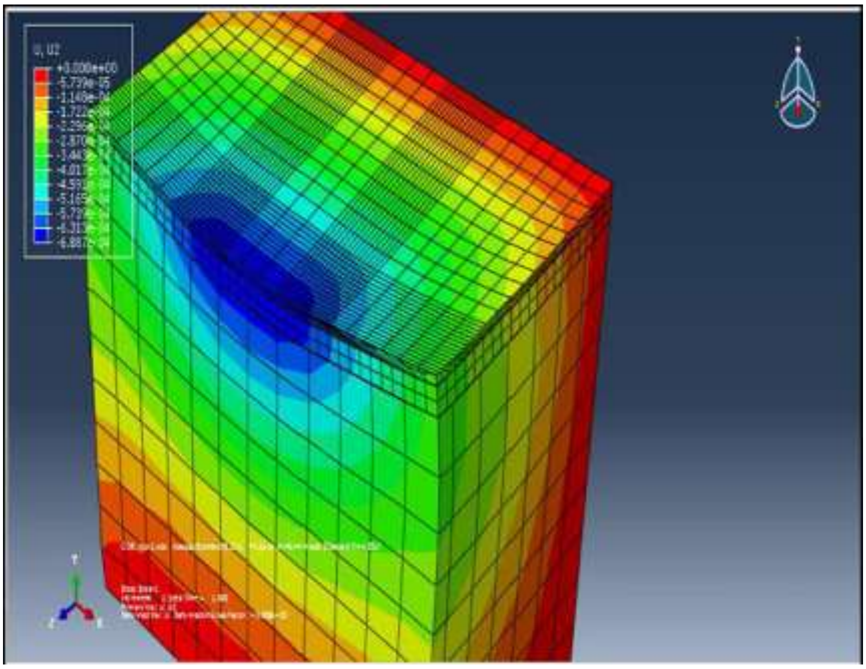

Figure 2.22: Rutting deformation of flexible pavement under effect of traffic loading (Alkaissi, 2020)

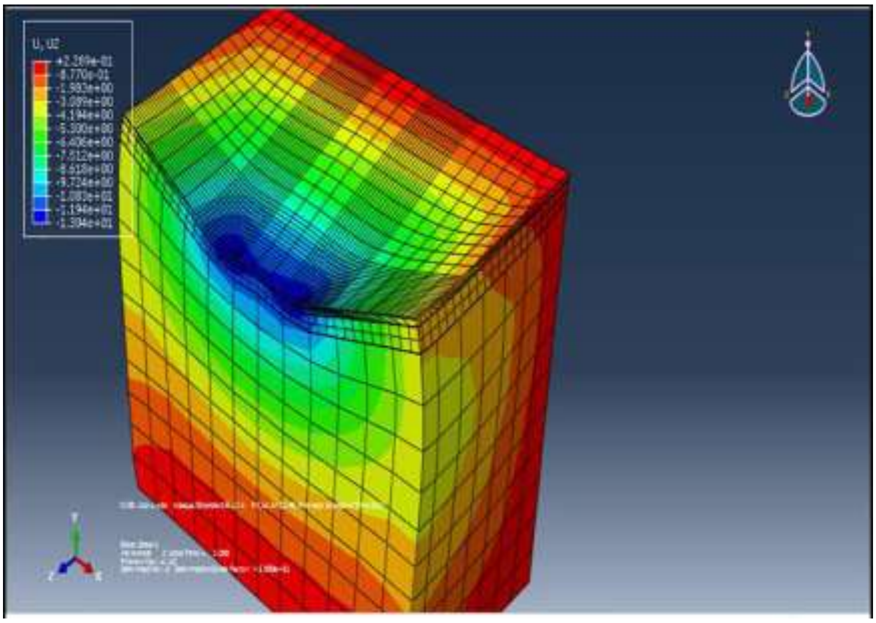

Figure 2.23: Rutting deformation of flexible pavement under combined effect of traffic and thermal loading (Alkaissi, 2020)

The vertical strains are important factor affecting on the rutting damage of flexible pavement. Where vertical strains developed at large values and wide spread within base layer of pavement resulting in rutting deformation. Rutting deformation is considered to be main distresses in flexible pavement in Iraq. Additionally, the number of load repetitions to cause rutting failure of flexible pavement under both traffic and thermal loading conditions was investigated using ABAQUS. The results (Figure 2.24) illustrated that the model under combined traffic and thermal conditions provide lower resistance against rutting failure. It can be said that when the local temperature increased to about 45 °C on the surface of flexible pavement result in reduction of maximum number of repetitions to cause rutting by about 3 times. This demonstrated that resistance to rutting of flexible pavement depends on the high temperature as well applied traffic loading (Alkaissi, 2020).

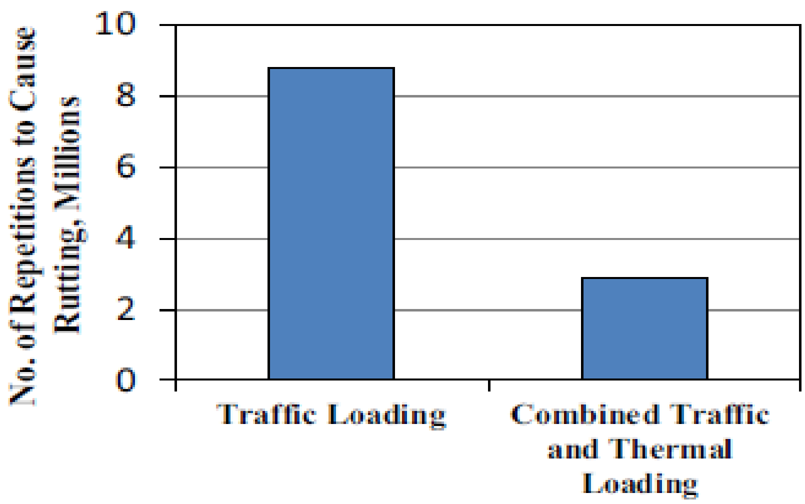

Figure 2. 24: Number of repetitions to cause rutting under both models of traffic and combined loading conditions (Alkaissi, 2020)

Higher temperatures are expected to result in the need for increased period of resealing/resurfacing due to more rapid oxidation of the bitumen. Temperature can affect the aging of bitumen resulting in an increase in embrittlement of the surface chip seals used in more than 90% of the rural sealed roads in Australia (Cechet, 2005).

In the design of thick asphalt pavements (i.e. thickness > 150mm), the asphalt is characterised in terms of its stiffness at Weighted Mean Annual Pavement Temperature (WMAPT) for a given location. Note that an increase in WMAPT necessitates a decrease in the stiffness of asphalt. CSIRO (2001) has predicted that climate change may result in WMAPT increasing, resulting in thicker asphalt to accommodate the lowering of the asphalt stiffness. This applies especially to deep asphalt pavements (depth > 60mm) for highway applications (CSIRO 2001).

The side effects of higher average temperatures, and higher extreme maximum temperatures on flexible pavements is expected to cause an increase in the potential for rutting and shoving, requiring more rut resistant asphalt mixtures. Furthermore, such extreme temperatures can cause increased age hardening of asphalt binder (Meyer et al., 2014)

From the literature, it is clear that extreme heat has detrimental effects on flexible pavements. Pavement failures to be expected from such extreme weather include, rutting, shoving and cracking.

CHAPTER 3 - METHODOLOGY

3.1 Overview

Chapter 2 of this report was the Literature Review, which is essential as it will serve as the bases of understanding which type/s of pavement failure/damage to note when collecting the SMEC PMS data from the City of Gold Coast (Council).

The methodology process which will be utilised for this research report will occur in the following process:

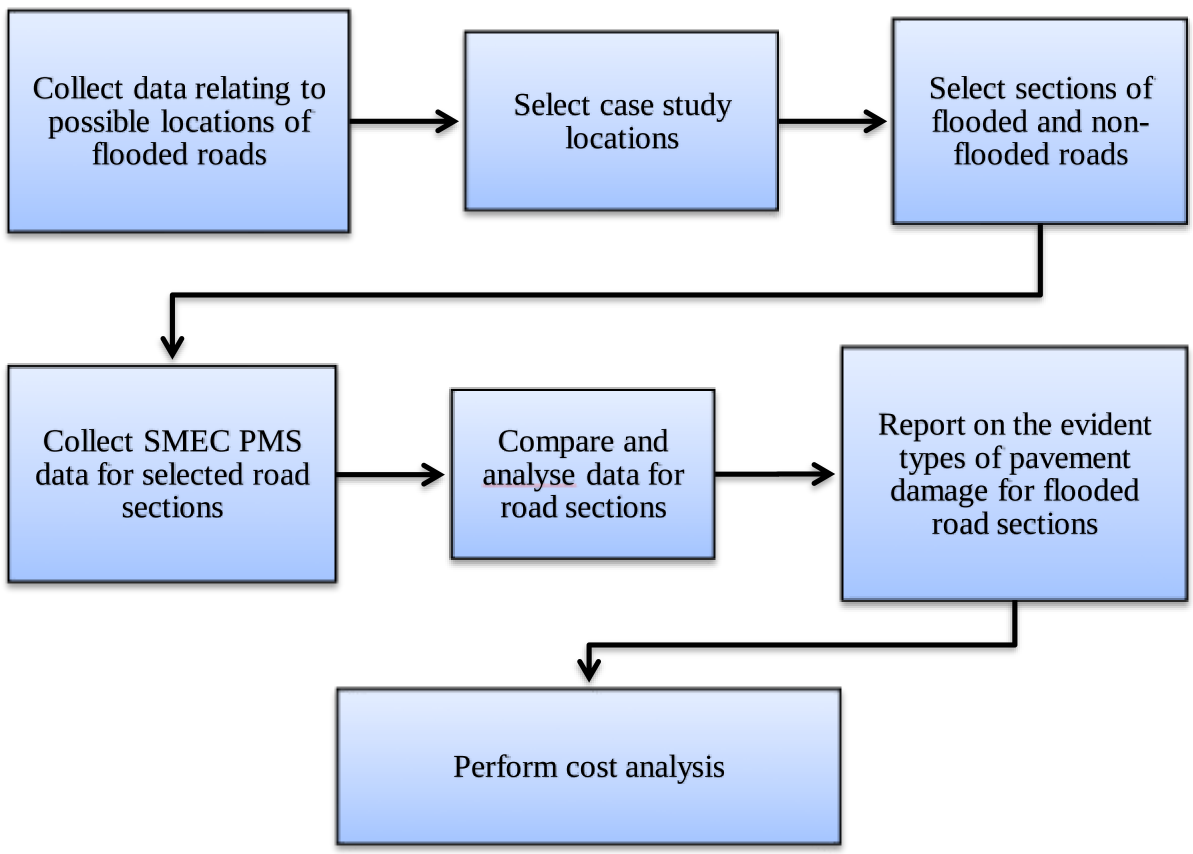

Figure 3.1: Chart illustrating the sequence of methods

Initially this report was to investigate the effects of extreme weather events including extreame heat and extreme rainfall causing flooding. However, due to time constraints, COVID-19, and the lack of the required data, only extreme weather events causing flooding will be investigated in this report. The effects of extreme heat can be investigated as a continuation of this report for future studies.

3.2 Collection of Data

The collection of pavement condition data was possible through the City of Gold Coast (CoGC) Pavement Management System (PMS). The PMS system utilised by the CoGC is the Snowy Mountain Engineering Corporation (SMEC) PMS. The data available in the SMEC PMS was collected by means of laser profilometers and visual inspections by CoGC engineers. This data is portrayed in a live excel spreadsheet which is regularly updated. Access to this data was granted to me for research purposes under certain conditions. The SMEC Pavement Management System is a powerful database designed to store and easily access a large range of information relating to roads, paths and road inventory items existing in the road corridor (SMEC, 2018). This data included:

- Surface age
- Pavement age
- Surface type
- Lane AADT
- Roughness
- Rutting
- Ravel/Stripping %
- Cracks %
- Pothole %
- PCI
- Road hierarchy type
- Section length and width

The analysis of data for both road sections will be based on the following indicators:

- Rutting: The rutting measured is the depth of the rut from the original level of the pavement surface in (mm).

- Cracks %: The cracks measured are generally a percentage of the pavement area experiencing cracks with regards to the chainage of the road section.

- PCI (Pavement Condition Index): This is a calculation to numerically indicate the condition of the pavement. The PCI is a convenient measure to quickly indicate the condition of the road. A value of 10 is a brand new pavement, whereas 1 or less is considered a “Failed” pavement.

- Roughness: Pavement roughness is generally defined as an expression of irregularities in the pavement surface that adversely affect the ride quality of a vehicle (and thus the user). The units used for roughness are counts per km (NAASRA).

3.3 Site Selection for Flood Affected Roads

The selection of flood affected roads to be analysed as case studies was carefully selected. Assistance from members of the Asset Management, Roads and Infrastructure and Disaster Management Unit teams at the CoGC, enabled the production of a list of roads under CoGC custodianship, which are regularly inundated by flooding due to excessive rainfall. An assortment of these roads that met specific criteria were then selected as case studies which form the basis of this research report. The criteria the selected roads had to satisfy include the following points:

- The road pavement must be a flexible pavement
- The road must have a section of flexible pavement either before or after the flooded section that does not get affected by flood events.
- This section mentioned above must have the same if not similar AADT, thus limiting the variables that affect any evident pavement damage.
- Both flood and non-flood affected sections must have the same pavement age and pavement surface age.
- Both sections must not have had any rehabilitation or repair work completed recently.
- Data for road sections must be available through SMEC PMS and therefore must be a CoGC city asset.

3.4 Cost Analysis

A cost analysis will be conducted to identify the financial impact associated with each excessive rainfall event which resulted in flooding. This cost analysis will be performed by initially calculating how much each flood event is reducing the Pavement Condition Index (PCI) of each case study road section. Once the reduction of PCI per event is calculated, a simple calculation will be performed to calculate how many events are required before intervention in the form of either a pavement reconstruction (recon) or a resurface is required. In this report we will focus primarily on two types of treatment methods, pavement recon and pavement resurface. For each case study an approximate treatment cost will be calculated by multiplying the area (m^2) by the cost per m^2. The cost per event will then be calculated by dividing the total treatment cost by the number of events until intervention is required.

The information relating to the indicative PCI at which each road hierarchy would require intervention was sourced from the CoGC Sustainable Pavement Management Plan 2020 – 2030. This document stated that road hierarchies which are considered “low order” such as residential access, residential collector and minor collector, require intervention when their PCI reaches 7.5. This intervention would be in the form of a basic treatment method such as a road resurface and rehabilitation. However, for road hierarchies such as collector and industrial a proposed PCI before intervention is 8.0.

As a cost analysis will be conducting for two common types of treatment methods, two sets of PCI values will be used to identify when intervention might be required and to calculate the costs associated with each treatment method. For basic treatment methods such as reseal and rehabilitation, the PCI values mentioned above will be used. However, a PCI of 4.0 will be used to identify when intervention in the form of a pavement recon is required. This was determined by analysing the data in Figure 3.2, which was sourced from the Sustainable Pavement Management Plan (CoGC). In both cases the cost analysis will only consider the damage caused by the flooding events and for that reason the initial PCI of each case study will be assumed as 10.

The approximate costs associated with each type of treatment method were also obtained from the CoGC Asset Management Team. This included the following treatment methods and costs:

- $110 - $120 for Mil & Fill (Resurface)
- $200 for Minor Reconstruction
- $400+ for Major Reconstruction

Using these values, it was possible to approximate the values for treatment methods such as reseal/rehabilitation, which was assumed to have a cost value of $\$110/m^2$, while for a recon it was assumed a cost value of $\$350/m^2$ would be adequate. Figure 3.3, demonstrates the steps that were taken in order to perform the cost analysis.

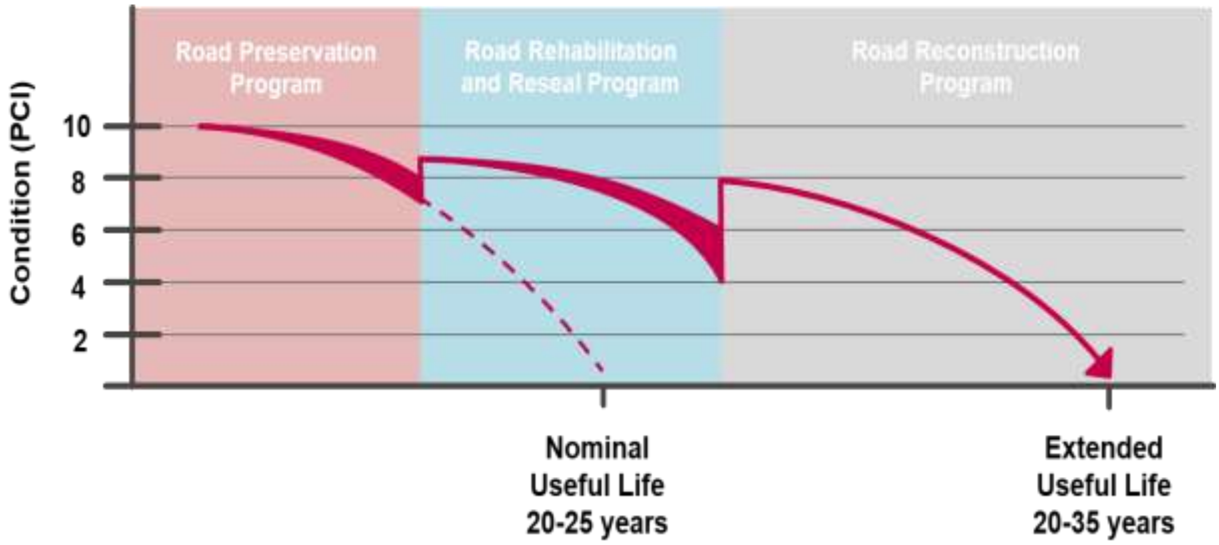

Figure 3.2: Types of intervention with the corresponding PCI (Sustainable Pavement Management Plan, 2019)

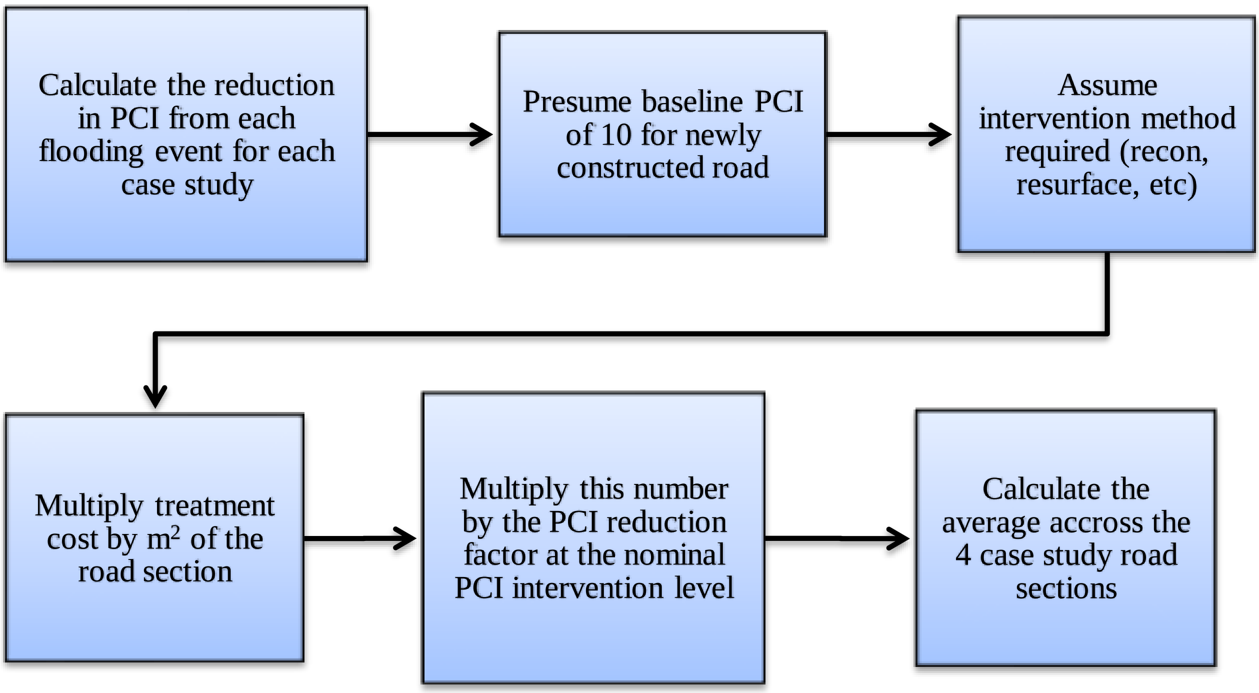

Figure 3.3: Chart illustrating sequence for conducting cost analysis

3.5 Risk Assessment

Risk assessment is vital for any project. It allows for possible risks to be identified and a mitigation strategy to be put in place before the initiation of the project. To analyse the possible risks involved, a risk assessment matrix will be used as shown in Appendix E. This will ensure any possible hazards are mitigated to a reasonable amount. Furthermore, there are other types of risks that are associated with the project itself, these are considered project risks and are listed in Appendix E

CHAPTER 4 - CASE STUDIES

4.1 Flood Affect Road Case Studies

The following case studies have been selected for analysis. These roads were selected from the list titled 'Natural Disaster Flood Storm Affected Areas", which was obtained from Shaun Hardy at the CoGC Disaster Management Unit. For more details regarding the list please see the full list attached in the Appendix section of this report. Each case study has a flooded and non-flooded road section. The data for each road section was collected from CoGC SMEC PMS and a comparison between both road sections was carried out to attempt to identify common deterioration factors associated with pavements affected by regular flooding.

4.2 Selected Roads for Flood analysis

After selecting the four roads that will form the basis of the case studies for the flood analysis, details regarding the historic flooding that took place was required. By contacting Rebecca Boga, from the Disaster Management Unit, the required data was acquired. This data included the location of where the flooding occurred on each road (Table 4.1) and the frequency of the flooding events (Table 4.2).

Furthermore, Figures 4.1 - 4.4, below display the intensity of the flooding for each case study. The darker red sections display the origin of the flooding and where the intensity of the flooding is highest, while the lighter red sections are sections where the flooding begins to ease and is considered light.

Street Name	Suburb	Location	Road Authority	Condition	Catchment
Somerset Drive	Mudgeeraba	Between North of Bonogin Rd and Gold Coast-Springbrook Rd (Franklin Dr)	Council	Road subject to flooding	Nerang
Siganto Drive	Helensvale	Between Helensvale Rd and Grey Gum St	Council	Road subject to flooding	Coomera
Highfield Drive	Merrimac	210m north of Breakwater Road	Council	Normal conditions	Nerang
Vince Hinde Drive	Worongary	Between Charles Kurz Drive and Harry Mills Drive	Council	Normal conditions	Nerang

Table 4.1: Data relating to the location of the selected flooded roads

Street Name	Suburb	Times Reported Flooded	Within (years)	Last Updated
Somerset Drive	Mudgeeraba	24	8	Dec-18
Siganto Drive	Helensvale	17	8	Dec-18
Highfield Drive	Merrimac	11	8	Dec-18
Vince Hinde Drive	Worongary	2	8	Dec-18

Table 4.2: Frequency of flooding events for each road

Table 4.3 demonstrates the road geometric data for the four case study road sections. Data such as area will be used later in this report for the cost impact analysis. The data from this table was sourced from the CoGC SMEC PMS excel sheet.

Street Name	Length	Width	Area (m2)
Somerset Drive	229	9.60	2198.4
Siganto Drive	272	10.00	2720
Highfied Drive	91	11.50	1046.5
Vince Hinde Drive	103	7.60	782.8

Table 4.3: Road geometric data

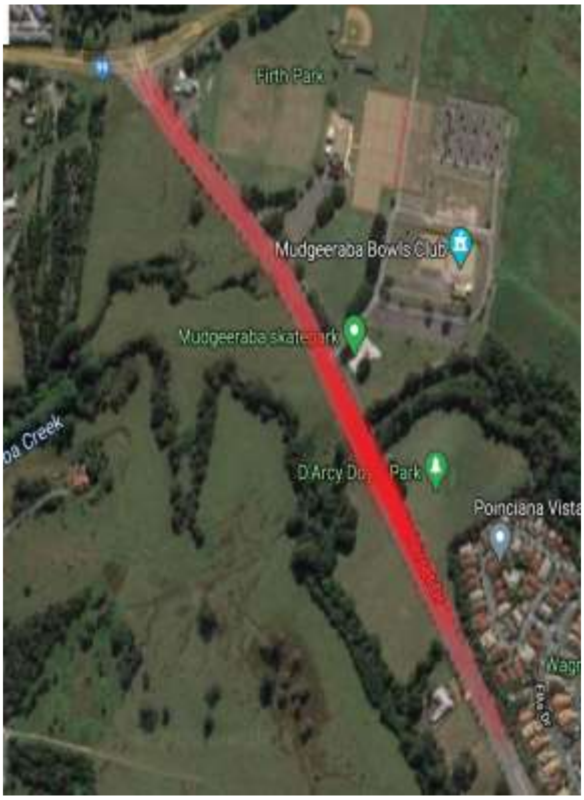

Figure 4.1: Satellite image of Somerset Drive showing intensity of flooding (Google Maps, 2020)

Figure 4.2: Satellite image of Siganto Drive showing intensity of flooding (Google Maps, 2020)

Figure 4.3: Satellite image of Highfield Drive showing intensity of flooding (Google Maps, 2020)

Figure 4.4: Satellite image of Vince Hinde Drive showing intensity of flooding (Google Maps, 2020)

Case Study 1

Somerset Drive, Mudgeeraba, Queensland, 4213

<u>Flooded road section</u>

Figure 4.5: Satellite image of flooded section for case study 1 (Google Maps, 2020)

<u>Non-flooded road section</u>

Figure 4.6: Satellite image of non-flooded section for case study 1 (Google Maps, 2020)

	Flooded Road Section	Non-Flooded Road Section	Difference
Section Length (m)	173	229	NA
Lane AADT	2894	2894	0
Surface Age (years)	10	10	0
Pavement Age (years)	10	10	0
Rutting (mm)	11.1	7.1	4
Ravel/Stripping	0	0	0
All Cracks (%)	0	0	0
Surface type	Asphalt	Asphalt	/
Roughness (counts/km)	93.5	78.1	15.4
Potholes	0	0	0
PCI	7.84	8.90	1.06
Road Hierarchy	Collector	Collector	/

Table 4.4: Comparison of flooded to non-flooded road sections for Case Study 1

Rutting

According to the data in Table 4.4, the flooded road section has a substantial amount of average rutting depth of 11.1mm. Even though both pavement sections experience the same AADT, have the same pavement age, surface age and, the same surface type, the difference in rutting between the flooded and non-flooded sections is 4mm. This indicates that the flooded section has experienced a deeper rut depth which may be attributed by the flooding events.

As the road has been flooded on 24 different occasions within the last 8 years, we can assume that each flooding event causes approximately 0.17mm increase in average rutting or 0.5mm annually (assuming the road floods an average of 3 times annually). As the data in Table 4.2

only goes back 8 years we must assume that the road has not flooded in the first 2 years since its construction.

Cracks

The data in Table 4.4 indicates that there is no difference in the percentage of cracks between both flooded and non-flooded sections.

Roughness and PCI

The difference in the roughness and PCI values evident in Table 4.4 between the flooded and non-flooded sections are substancial given that the pavement and surface age are both only 10 years old. The increase in pavement rutting is more than likely to be the main contributor to the increase in pavement roughness and the reduction of PCI between both sections.

By comparing the data relating to the frequency of the road being flooded (Table 4.2) with the data in Table 4.4. It can assume that each flooding event caused an increase in roughness of approximately 0.65 per flooding event and a reduction in PCI of approximately 0.05 per flooding event. Annually this would equate to increase in roughness of approximately 3 and reduction in PCI of approximately 0.15 (assuming the road floods 3 times per year).

Case Study 2

Vince Hinde Drive, Worongary, Queensland, 4213

<u>Flooded road section</u>

Figure 4.7: Satellite image of flooded section for case study 2 (Google Maps, 2020)

<u>Non-flooded road section</u>

Figure 4.8: Satellite image of non-flooded section for case study 2 (Google Maps, 2020)

	Flooded Road Section	Non-Flooded Road Section	Difference
Section Length (m)	103	220	NA
Lane AADT	756	756	0
Surface Age (years)	29	29	0
Pavement Age (years)	29	29	0
Rutting (mm)	2.0	2.0	0
Ravel/Stripping	0	0	0
All Cracks (%)	0.4	0.4	0
Surface type	Asphalt	Asphalt	/
Roughness (counts/km)	96.8	77.4	19.4
Potholes	0	0	0
PCI	9.45	9.68	0.23
Road Hierarchy	Residential Access	Residential Access	/

Table 4.5: Comparison of flooded to non-flooded road sections for Case Study 2

Rutting

According to the data in Table 4.5, there is no difference in the recorded average rutting depth between the flooded and non-flooded road sections. It is also noticeable that the recorded average rutting depth for both sections was reasonably low being only 2.0 mm deep. These figures were surprising as the pavement and surface age are 29 years old, thus more rutting was to be expected. However, a possible reason for the low average rutting depth for both sections could be attributed due to the low traffic volume which the road sections cater for, as they both only cater for an AADT of 756.

Cracks

From the data in Table 4.5, there is no difference in the percentage of cracks between the flooded and non-flooded sections. Again the percentage of cracks for both sections are surprisingly low considering such a mature pavement and surface age. This can again be due to the low AADT value of 756.

Roughness and PCI

It was surprising to see the difference in roughness and PCI values between the flooded and non-flooded sections in Table 4.5. The difference in roughness was a substantial 19.4, this clearly indicates that flooding affects the roughness of the road pavement even though there was no difference in rutting or cracking between both road sections. Both PCI values were surprisingly very good being 9.45 and 9.68 for the flooded and non-flooded sections respectively. It must also be noted that for a pavement surface age of almost 30 years to maintain such a high PCI value is extremely good. However, again this can be attributed to the low AADT value recorded for both road sections.

By comparing the data in Table 4.5 and the data in Table 4.2, some assumptions can be made. As the road had been flooded 2 times within the last 8 years, it can assume that an increase in roughness of 9.7 per flood event occurs. This equates to an increase of approximately 2.43 per year. As the change in PCI was 0.23 we can assume that a reduction in PCI of 0.12 occurs with each flood event and approximately a reduction of 0.03 per annum for the last 8 years. Again this is based on the assumption that the road has not flooded in the years other than the 8 years recorded in Table 4.2.

Case Study 3

Siganto Drive, Helensvale, Queensland, 4212

Flooded road section

Figure 4.9: Satellite image of flooded section for case study 3 (Google Maps, 2020)

Non-flooded road section

Figure 4.10: Satellite image of non-flooded section for case study 3 (Google Maps, 2020)

	Flooded Road Section	Non-Flooded Road Section	Difference
Section Length (m)	272	274	NA
Lane AADT	5,759	5,759	0
Surface Age (years)	12	12	0
Pavement Age (years)	22	28	6
Rutting (mm)	6	5	1
Ravel/Stripping	2.2	2.1	0.1
All Cracks (%)	11.7	0	11.7
Surface type	Asphalt	Asphalt	/
Roughness (counts/km)	82.3	60.1	22.2
Potholes	0	0	0
PCI	6.21	9.33	3.12
Road Hierarchy	Minor Collector	Minor Collector	/

Table 4.6: Comparison of flooded to non-flooded road sections for Case Study 3

From the SMEC PMS data in Table 4.6, it is clear that the flooded road section has deteriorated in multiple ways compared to the non-flooded road section. This is further evident considering that the flooded road sections pavement age is younger than the non-flooded road section.

Rutting

According to Table 4.6, both sections have moderate amounts of rutting evident throughout the lengths of the sections. However, the flooded road section has an extra 1mm average rut depth. Even though the difference is minimal, we must keep in consideration that the pavement age of the non-flooded road section is 6 years older.

By comparing the data from Table 4.6 and Table 4.2, some assumptions can be made. As the pavement has flooded 17 times within the last 8 years we can assume that an increase in average rutting of approximately 0.06 mm occurs with each flood event. This equates to an approximate 0.13 mm increase annually for the last 8 years. This is of course assuming we disregard any flooding which may have occurred prior 2010.

Cracks

It is clear from the data in Table 4.6 that the main form of deterioration for the flooded road section in this case study is cracking. The flooded section has extensive cracks evident throughout its length. Table 4.5 indicates that the flooded road section has cracks equalling 11.7% of the section length, compared to 0% for the non-flooded road section.

By comparing this data with the data from Table 4.2 an approximation of how much cracking occurs from each flood event can be determined. It was determined that each flood event caused an increase of approximately 1% in cracks which equated to approximately 1.46% annually for the last 8 years. This is of course assuming all flooding which may have occurred prior to 2010 is disregarded

Roughness and PCI

It is reasonable to conclude that for the roughness and PCI values to differ in each section, they are impacted by the large difference in the percentage of cracks (11.7%) and the rutting (1mm). A difference of 22.2 was recorded for the roughness and a drop of approximately 30% (3.12) was recorded for PCI between both sections. Again this difference is substantial considering the non-flooded section's pavement age is 6 years older. The non-flooded section had a PCI of 9.33, which is almost considered as a new pavement. Whereas, the flooded section had a PCI of 6.21, which is still within the "good" range.

By comparing this data and Table 4.2, it can be assumed that each flood event causes an increase of 1.31 in roughness and an increase of 2.78 per year. It can also be assumed that for each flood event causes a reduction in PCI of 0.18 which is approximately 0.39 per year for the last 8 years.

Case Study 4

Highfield Drive, Merrimac, Queensland 4226

Flooded road section

Figure 4.11: Satellite image of flooded section for case study 4 (Google Maps, 2020)

Non-flooded road section

Figure 4.12: Satellite image of non-flooded section for case study 4 (Google Maps, 2020)

	Flooded Road Section	Non Flooded Road Section	Difference
Section Length (m)	91	271	NA
Lane AADT	2934	2934	0
Surface Age (years)	15	15	0
Pavement Age (years)	31	31	0
Rutting (mm)	1.0	1.0	0
Ravel/Stripping	0	0	0
All Cracks (%)	3.8	1.3	2.5
Surface type	Sprayed Seal	Sprayed Seal	/
Roughness (counts/km)	63.1	60.5	2.6
Potholes	0	0	0
PCI	9.23	9.65	0.42
Road Hierarchy	Residential Collector	Residential Collector	/

Table 4.7: Comparison of flooded to non-flooded road sections for Case Study 4

By analysing the data obtained from CoGC SMEC PMS in Table 4.7, it is again clear that the flooded road section has experienced more deterioration than the non-flooded road section. This is evident even though the surface type is sprayed seal, which is different to the 3 other case studies which had an asphalt surface type.

Rutting

According to the SMEC PMS data shown in Table 4.7, the average rutting evident in the non-flooded road section and the flooded road section are both 1mm. This contradicts the initial expectations that rutting would be more prevalent in the flooded road sections. However, there could be more than one reason for this to have occurred. Firstly, it could be due to data collection error or data input error. Secondly, it could be due to the pavement surface type, which in this case study is sprayed seal. However, the more logical and reasonable assumption would be due to the subbase and/or subgrade material.

Cracks

The data relating to cracks in Table 4.7 shows that the flooded road section exhibited more cracks compared to the non-flooded section. The flooded section had a crack percentage of 3.8% compared to the non-flooded section which only recorded 1.3%. By comparing this data to the data in Table 4.2, we can assume that each flooding event caused an increase of 0.23% in cracks. This equates to an approximate 0.31 % increase in cracks annually for the last 8 years. Assuming the road did not flood prior 2010.

Roughness and PCI

The difference in roughness between both flooded and non-flooded sections as shown in Table 4.6, is 2.6 which does not seem to be much. This is also the same for the PCI value which is calculated to be 0.42. Both road sections have relatively good PCI values even though they have both attained approximately half their design life. The difference in PCI value between both road sections can be attributed to the difference in cracks

By comparing this data to the data in Table 4.2, some assumptions can be made. As the road flooded 11 times within 8 years it can be assumed that each flooding event increased the roughness by approximately 0.24 which equates to approximately 0.33 per year for the last 8 years. For the PCI value, a reduction of 0.04 per flood event and a reduction of approximately 0.053 per year for the last 8 years. This is assuming the road did not flood prior to 2010.

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CHAPTER 5 - RESULTS AND DISCUSIONS

5.1 Analysis of Results

From the four case studies that were selected, the outcomes of each analysis were compared to determine if there were any similarities or common pavement failures evident. These pavement failures include, rutting, cracks, stripping, roughness and PCI. The difference in pavement damage/failure for the flooded compared to the non-flooded sections for the four case studies is displayed in Table 5.1. A positive difference value would indicate that the flooded section had a higher value compared to the non-flooded section. While a negative value indicates that the non-flooded section had a higher value than the flooded section. However as evident in the data in Table 5.1, the latter does not exit, which indicates that for all four case studies the flooded road section was in some way more damaged than the non-flooded road section.

Furthermore, some assumptions can be made relating to the frequency of the flooding events and the amounts of failures evident in Table 5.1. It is safe to assume that as the frequency of flooding increases so does the average rutting. This can be seen where Case Study 1 had 24 instances of flooding and had an increase in average rutting of 4 mm. This is also the case for Case Study 3, where the frequency of flooding was 17 times within 8 years and the increase in average rutting is 1 mm. Similarly, the difference in PCI also increased as the frequency of flooding events increased. This is primarily evident in Case Study 1 and Case Study 3, where the frequency of flooding events exceeded 15 within 8 years and the difference in PCI values between the flooded and non-flooded road sections were between 1.0 and 3.5.

	Surface Type	Rutting (mm)	Cracks (%)	Stripping (%)	Roughness (counts/km)	PCI	Floods / 8 years
Case Study 1	Asphalt	4	0	0	15.4	1.06	24
Case Study 2	Asphalt	0	0	0	19.4	0.23	2
Case Study 3	Asphalt	1	11.7	0.1	22.2	3.12	17
Case Study 4	Sprayed Seal	0	2.5	0	2.6	0.42	11
Average	/	1.25	3.55	0	14.9	1.21	/

Table 5.1: Difference between flooded and non-flooded results for all case studies

As demonstrated in Figure 5.1, it is clear that there was an increase in the average rutting in the flooded sections of two of the case studies. One of these was Case Study 1, where the difference in average rutting was a substantial amount of 4mm. Whereas; Case Study 3 only had a difference of 1mm. However, Case Studies 2 and 4 did not have any difference in the recorded average rutting. It must also be noted that the three case studies with asphalt surfaces (Case Studies 1,2 and 3), had an average rutting greater than 1mm for both the flooded and non-flooded road sections.

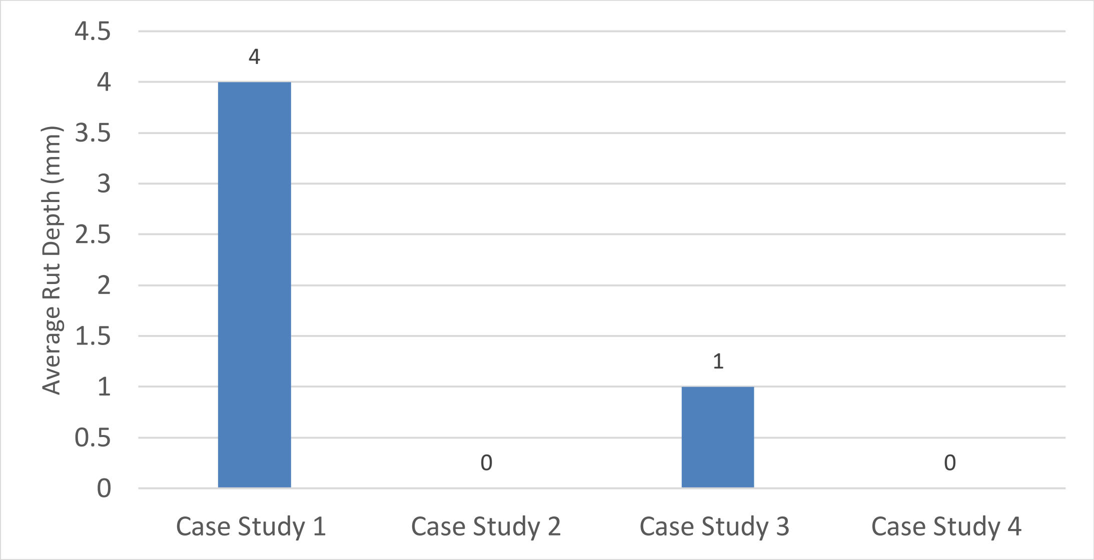


Figure 5.1: Graph of rutting difference between flooded and non-flooded sections

The difference in percentage of cracks between the flooded and non-flooded sections are displayed in Figure 5.2. It is clearly evident that Case Study 3 had a significant increase in the percentage of cracks in the flooded road section compared to the non-flooded road section. That being said, the only other case study with a recorded difference in percentage of cracks was Case Study 4. Case Study 1 and 2 both recorded no difference in the percentage of cracks between the flooded and non-flooded sections.

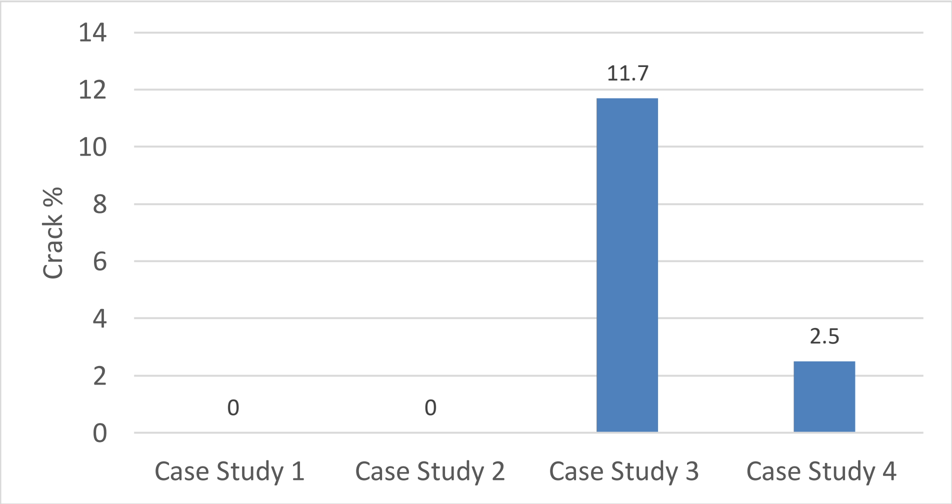


Figure 5.2: Graph of crack % difference between flooded and non-flooded sections

According to the data displayed in Figure 5.3, only Case Study 3 had a difference in stripping between both road sections, and the difference was negligible as it was only 0.1. From this it can be assumed that flooding does not have much impact on pavement stripping/ravelling.

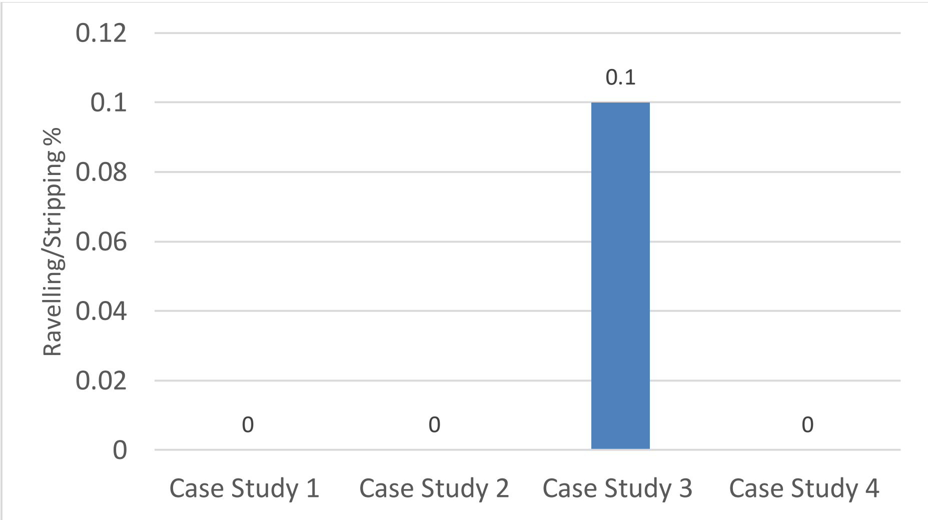


Figure 5.3: Graph of stripping difference between flooded and non-flooded sections

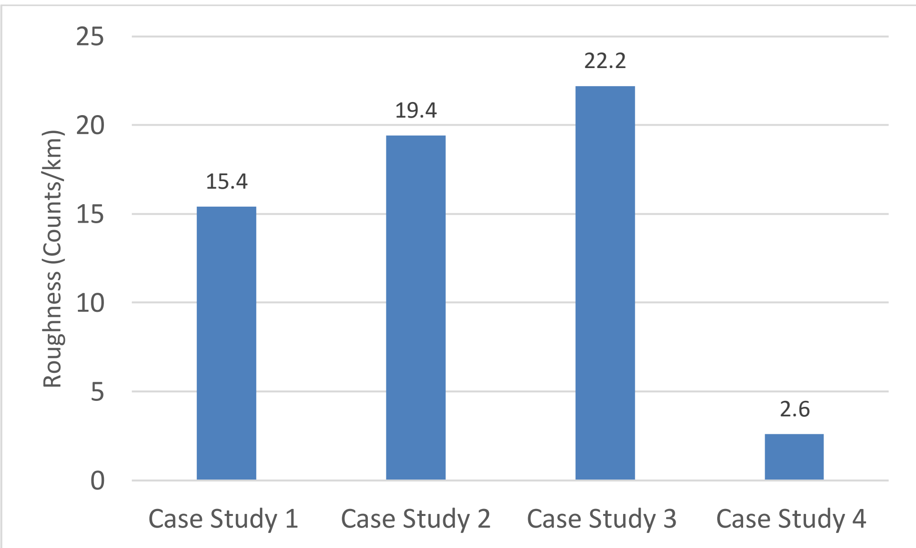


Figure 5.4: Graph of roughness difference between flooded and non-flooded sections

From the data displayed in Figure 5.4, it is clear that all case studies recorded a difference in the roughness between the flooded and non-flooded sections. The three asphalt surface types (Case Studies 1, 2 and 3), recorded a substantial difference in roughness compared to Case Study 4 which had a sprayed seal surface type. From this data analysis two assumptions can be made:

- Pavements with an asphalt surface type, are more prone to damages resulting in an increase to roughness from flooding events compared to pavements with a sprayed seal surface type, and;

- Road pavements that experience flooding regardless of whether they are of an asphalt or sprayed seal surface type will result in an increase to the roughness.

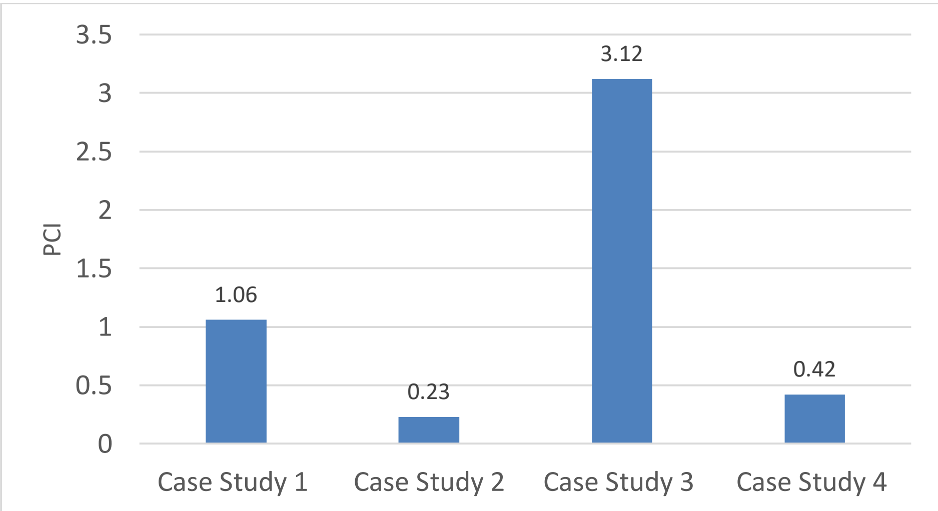


Figure 5.5: Graph of PCI difference between flooded and non-flooded sections

Figure 5.5 displays the difference in the PCI values between the flooded and non-flooded sections of the four case studies. From the data it is clear that all four case studies had a reduced PCI value for the flooded road sections. It is also evident that Case Study 3 had a significant difference (3.12) in the PCI value between the flooded and non-flooded road section. From the data displayed in Figure 5.5, an assumption can be made relating to the difference in PCI values, which is that flooding of the road pavement affects the overall pavement condition for the worse. This also indicates that the pavement design life is drastically reduced as the PCI value is a calculation to numerically indicate the overall condition of the pavement, and can often indicate whether a pavement requires repairs/maintenance.

By comparing the flood frequency for each road within the last 8 years and relating that to the data collected from the SMEC PMS, some calculations can be made to estimate the extent of damage caused from each flooding event and to approximate the damage per year. This data is displayed in Table 5.2 below. However, some assumptions must be made before considering this data. An assumption must be made that no flooding occurred prior to 2010 as the flood frequency data collected from the Disaster Management Unit only goes as far back as 2010.

		Per Flooding event				**Per year**			
Case Study #	**Street Name**	**Average Rutting (mm)**	**Cracking (%)**	**Roughness (counts/km)**	**PCI**	**Average Rutting (mm)**	**Cracking (%)**	**Roughness (counts/km)**	**PCI**
1	Somerset Dr	0.17	0	0.65	0.05	0.5	0	3	0.15
2	Vince Hinde Dr	0	0	9.7	0.12	0	0	2.43	0.03
3	Siganto Dr	0.06	1	1.31	0.18	0.13	1.46	2.78	0.39
4	Highfield Dr	0	0.23	0.24	0.04	0	0.31	0.33	0.05

Table 5.2: Comparison between pavement damage per flood event and per year

5.2 Cost Impact Analysis

A cost impact analysis was conducted to approximate the cost associated with each flooding event at the location of the case studies. Two methods of treatment were analysed, a road recon (reconstruction) which is considered to be a major treatment method, and a resurface which is considered as a more minor treatment method. The two treatment method are analysed in Table 5.3 and Table 5.4 below.

A road recon is considered to be a major treatment method and is usually required to treat structural and geometric issues within the pavement. The average cost associated with this treatment method is approximately \$350.00 per m^2 of paved surface. For this treatment method to be justified, the PCI threshold was to be set at 4.0, as indicated by the CoGC Sustainable Pavement Management Plan. Therefore, this cost analysis will take into consideration the amount of flooding events required to reduce the PCI value from 10.0 (brand new pavement) to 4.0. The cost calculated is the area of the pavement multiplied by the cost per m^2. Then to calculate the cost per event, the total cost will be divided by the number of events required to reduce the PCI from 10.0 to 4.0.

By using this method, it will be possible to calculate the approximate cost associated with each flood event and make an approximation of how many flooding events are required before intervention in the form of a full road recon will be required. This is under the assumption of no deterioration by any other factors, thus isolating the financial impact of frequent flooding events. Furthermore, the average cost per flood event for all four case studies can then be approximated. It should be considered that this methodology would increase in accuracy if the sample size was larger and has been noted for further work in the following chapter.

By analysing the data in Table 5.3, it is clear that there is a large variation between the cost per event values. This is primarily due to the case study area and the required number of events until intervention is required. However, to overcome this variation to an extent, the average can be taken. By doing this the average cost per event is $10723.36. for the treatment methodology of road reconstruction, as demonstrated in Table 5.3.

Cost Analysis for Road Reconstruction									
Case Study #	**Street Name**	**Hierarchy**	**PCI reduction/ event**	**Events Until Intervention**	**Treatment Method**	**Cost/ m^2 ($)**	**Area (m^2)**	**Treatment cost ($)**	**Cost/event ($)**
1	Somerset Dr	Collector	0.05	120	Recon	350	2198.4	769440	6412
2	Vince Hinde Dr	Residential Access	0.12	50	Recon	350	782.8	273980	5479.6
3	Siganto Dr	Collector	0.18	33.3	Recon	350	2720	952000	28560
4	Highfield Dr	Residential Collector	0.04	150	Recon	350	1046.5	366275	2441.83
Average			0.10						10723.36

Table 5.3: Cost analysis for road reconstruction treatment method

The same cost analysis method, was also completed for road resurface treatment methods, as demonstrated in Table 5.4. This intervention type is considered a smaller treatment method. However, some difference in the PCI threshold values were used. The PCI values at which intervention was required in this case was adopted from the CoGC Sustainable Pavement Management Plan (SPMP). This document proposed an average PCI value at which intervention in the form of resurface (mill and fill) would be required for each road hierarchy class. In the case of the selected four case studies the road hierarchies were, collector, residential access, collector, and residential collector for Case study 1, 2, 3 and 4 respectively. According to the SPMP, these roads would require intervention when their PCI reaches 8.0, 7.5, 8.0, and 7.5 respectively.

Furthermore, the selected treatment method, which is a road resurface primarily consisting of overlays and mill & fill treatments, has an approximate cost of $110 per m^2. This cost estimation was confirmed by members of the Asset Management Team at CoGC. From Table 5.4, Case Studies 1, 2 and 4 have an average cost/event of approximately $4000. Whereas, Case Study 3 has a substantial cost/event value of $26928. The primary reason for this is the significantly larger PCI reduction/event, reducing the amount of events before intervention is required. Also, it must be noted that the paved area of Case Study 3 is substantially larger than the other 3 case studies.

The average cost per event for all four case studies as shown in Table 5.4 is $9737.16. This is almost $1000 less than the average cost per event (Table 5.3) if the intervention was left until a full road recon treatment method was performed.

Cost Analysis for Road Resurface									
Case Study #	**Street Name**	**Hierarchy**	**PCI reduction/ event**	**Events Until Intervention**	**Treatment Method**	**Cost/ m^2 ($)**	**Area (m^2)**	**Treatment cost ($)**	**Cost/event ($)**
1	Somerset Dr	Collector	0.05	40	Resurface	110	2198.4	241824	6045.6
2	Vince Hinde Dr	Residential Access	0.12	20.8	Resurface	110	782.8	86108	4133.18
3	Siganto Dr	Collector	0.18	11.1	Resurface	110	2720	299200	26928
4	Highfield Dr	Residential Collector	0.04	62.5	Resurface	110	1046.5	115115	1841.84
Average			0.10						9737.16

Table 5.4: Cost analysis for road resurface treatment method

CHAPTER 6 - CONCLUSIONS

In conclusion, it is clearly evident from this research report that flooding increases the rate of deterioration of flexible pavements. It is shown to increase the amount of rutting and cracking in most cases, while increasing stripping in some cases. Furthermore, it is proven to increase roughness in all case studies and also reduce the PCI value in all case studies.

It was also calculated that the average reduction in PCI values across the four case studies was approximately 0.10 per flooding event. However, this value and the values mentioned above are approximations and should not be taken as exact figures.

A cost impact analysis determined that the average cost associated with each flooding event is approximately $9737 for each road section investigated if the method of intervention is a resurface. However, this number would be approximately $10700 if the intervention method utilised is a road reconstruction.

CHAPTER 7 - FUTURE RESEARCH

To improve the accuracy of this research report or to continue further work, it is recommended to conduct this case study base analysis with a larger sample size. With a larger sample size (possibly 50+ road sections) a more accurate understanding of what flooding does to flexible pavements would be achievable. This includes which specific forms of pavement deterioration should be expected and to what degree. Furthermore, a more accurate estimate of the average reduction in PCI values would be obtained. This would also allow for a better cost impact analysis to be conducted which could lead to a more accurate approximation of how much each flooding event costs as a dollar figure.

Another area of research that can be investigated is the effects of flooding events on rigid pavements. This would be useful as most culverts or bridge crossings are designed as rigid pavements and are usually the first sections to be inundated by flooding. These sections usually consist of rigid pavements with flexible pavements on either side.

Alternatively, a comparison of the deterioration between flexible and rigid pavements on the same road where both sections are side by side, might even provide some valuable insight into the rate of deterioration between both types of pavements. A cost analysis can also be produced for this type of research and would yield some valuable data in relation to a comparison in cost of maintenance or repairs for both types of pavements when damaged by floods.

REFERENCES

AAPA (Australian Asphalt Pavement Association), 2010, Flexible Pavement Maintenance and Rehabilitation, viewed 15th March 2020

American Association of State Highway and Transportation Offcials (AASHTO). 2009, Mechanistic-Empirical Pavement Design Guide (MEPDG), Version 1.1; National Cooperative Highway Research Program: Washington, DC, USA.

Arjun, N, 2020, Types of Failures in Flexible Pavments and their Causes and Repair Techniques, The Constructor Civil Engineering Home, viewed 15th March 2020, <https://theconstructor.org/transportation/types-failures-in-flexible-pavements-repair/16124/>

Asphalt & Concrete Parking Lot Maintenance (ACPLM), 2019, How Weather Can Affect Asphalt, News Letter, USA, Florida, viewed 11th March 2020, <https://www.acplm.net/how-weather-can-affect-asphalt/>

Australian Bureau of Statistics, 2012, History of Roads in Australia, viewed 3rd November 2019. <https://www.abs.gov.au/ausstats/abs@.nsf/0/2e904c15091c39a5ca2569de0028b416?OpenDocument>

Austroads, 2017, Guide to Pavement Technology Part 2: Pavement Structural Design, Sydney, Australia.

Austroads, 2019, Guide to Pavement Technology Part 5: Pavement Evaluation and Treatment Design, Sydney, Australia

Baqersad, M., et al., 2016. Comparison of coupled and uncoupled consolidation equations using finite element method in plane-strain condition. Civil Engineering Journal, 2 (8), 375–388.

Baqersad, M., et al., 2017. Asphalt mixture segregation detection: digital image processing approach. Advances in Materials Science and Engineering, 2017, 1–6. Article ID 9493408.

BOM, Climate of the 2018–19 financial year, 2019, viewed 6th October 2019, <http://www.bom.gov.au/climate/updates/articles/a034.shtml>

Cechet, Bob (2005) "Climate Change Impact on the Pavement Maintenance and Rehabilitation Costs associated with the Australian National Highway Network" Paper by Risk Research Group, Geospatial and Earth Monitoring Division, Geoscience, Australia, PP 489-496

City of Gold Coast, 2017, Flood History, viewed 2nd August 2020, https://www.goldcoast.qld.gov.au/council/flood-history-49697.html

Civil Engineering Notes, 2014, Failures of Flexible Pavements, viewed 22nd March 2020, <http://transportationengineering2012onwards.blogspot.com/2014/05/failures-of-flexible-pavements.html>

Climate Change in South East Queensland Region Version 1, 2019, Department of Environment and Science, Queensland Government, Australia, viewed 11th April 2020, https://www.qld.gov.au/__data/assets/pdf_file/0023/67631/seq-climate-change-impact-summary.pdf

Climate Change, National Geographic Society, 2019, viewed 1st October 2019, <https://www.nationalgeographic.org/encyclopedia/climate-change/>

Climate Change: How Do We Know?, 2019, Earth Science Communications Team at NASA's Jet Propulsion Laboratory, viewed 6th October 2019, <https://climate.nasa.gov/evidence/>

Climate Commission, 2013, The Critical Decade 2013 (Climate change science, risks and responses, Produced by the Commonwealth of Australia, viewed 14th February 2020 <http://www.climatecouncil.org.au/uploads/b7e53b20a7d6573e1ab269d36bb9b07c.pdf>

CSIRO (2001) Climate projections for Australia. Climate Impact Group, CSIRO Atmospheric Research, Melbourne, 8 pp. <http://www.dar.csiro.au/publications/projections2001.pdf>

Dean, A, Rice, M, Steffen, W, 2019, Weather Gone Wild: Climate Change-Fuelled Extreme Weather in 2018, Climate Council, Australia.

Dempsey, B.J.; Elzeftawy, 1976, A. Moisture Movement and Moisture Equilibria in Pavement Systems; Project IHR-604; Illinois Cooperative Highways and Transportation Research Program; University of Illinois: Chicago, IL, USA.

Department of Environment and Resource Management, 2010, Climate Change in Queensland What the Science is Telling Us, Research Publication, viewed 5th October 2019

Department of Environment and Resource Management, Queensland rainfall—past, present and future, research report summary, Queensland Government, viewed 20th August 2020, <https://data.longpaddock.qld.gov.au/static/about/publications/pdf/walker-report-summary-brochure.pdf>

Gao, L., et al 2019, Impacts of Seasonal and Annual Weather Variations on Network-Level Pavement Performance, Infrastructures Article, viewed 10th March 2020.

Google Maps, satellite map, Google Maps, 2020, Australia, viewed on 14th August 2020, https://www.google.com.au/maps/

Grover, A, 2017, The Curious Case of Slippage, Blacklidge, viewed 2nd July 2020, https://blacklidge.com/asphalt-slippage-causes-prevention/

Gudipudi, P, Underwood, S, Zalghout, A, Impact of Climate Change on Pavement Structural Performance in the United States, Transportation Research Part D: Transport and Environment, Vol 57, pp 172-184

Heydinger, A, et al., 1996. Analysis of resilient modulus of dense- and open-graded aggregates. Transportation Research Record: Journal of the Transportation Research Board, 1547, pp 1–6.

Hira, M, 2017, Effects of climate change on road infrastructure and development of Adaptation Measures, viewed 5th October 2019

Jamal, H, 2017, Flexible Pavement Definition and Explanation, About Civil Engineering, viewed 12th January 2020 < https://www.aboutcivil.org/flexible-pavement-road.html>

Little, D. N., et al., 2003. Chemical and mechanical processes of moisture damage in Hot-mix asphalt pavements. In: Moisture sensitivity of asphalt pavements, Washington, DC: Transportation Research Board of the National Academies, pp 37–74.

McRobert, F, Foley, G, 2003, The Impacts of waterlogging and salinity on road assets: a Western Australian case study, Main Roads, Western Australia.

Meyer, M., M. Flood, J. Keller, J. Lennon, G. McVoy, C. Dorney, K. Leonard, R. Hyman, and J. Smith. 2014. NCHRP Report 750. Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System. Transportation Research Board of the National Academies, Washington, D.C.

Moreno-Navarro, F.; Sol-Sánchez, M.; García-Travé, G.; Rubio-Gámez, M.C. 2018, Fatigue Cracking in Asphalt Mixtures: The Effects of Ageing and Temperature. Road Mater. Pavement Des. pp 561–570.

Paun, A, Acton, L, Shrivastava, A, Pomeroy, J, Soliman, T, 2019, Fragile Plant (Climate change global research), HSBC Global Research, The politics and economics of the low-carbon transition, published online article, viewed 12th January 2020.

Padhi, S, 2015, Types of Failures of Flexible Pavement, Civilblog.org, viewed 21st March 2020, https://civilblog.org/2015/09/18/10-different-types-of-failures-of-flexible-pavement/

Pavement Interactive, 2020, Pavement Distresses, web document, viewed 22nd March 2020, <https://pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/>

Qiao, Y, Dawson, A, Parry, T, Flintsch, G, Wang, W, 2020, Flexible Pavements and Climate Change: A Comprehensive Review and Implications, Sustainability Review.

SMEC, 2018, Pavement Management System (PMS), viewed 11th May 2020, http://www.smecsoftware.com.au/AssetMgmt/pms

Sultana et al., 2016, ASSESSMENT AND MODELLING DETERIORATION OF FLOOD AFFECTED PAVEMENTS,

Sustainable Pavement Management Plan 2020 – 2030, 2019, City of Gold Coast Council, Asset Management Document, Gold Coast, Queensland, viewed 10th September 2020.

TMR, 2017, Department of Transport and Main Roads – Routine Maintenance Guidelines, Queensland Government.

U.S. Department of Transport (Federal Highway Administration), 2015, Climate Change Adaptation For Pavements, Tech Brief (FHWA-HIF-15-015), <http://www.fhwa.dot.gov/pavement>

Van de Lindt, J, Taggart, M, 2009, Fragility Analysis Methodology for Performance-Based Analysis of Wood-Frame Buildings for Flood, Natural Hazards Review, pp 113–123.

Vuong, B, 1992. Influence of density and moisture content on dynamic stress-strain behaviour of a low plasticity crushed rock. Road and Transport Research, pp 88–100, viewed 4th January 2020.

Whitfield, L, et al, Department of Environment and Resource Management Queensland Climate Change Centre of Excellence, 2010, Climate Change in Queensland, What the science is telling us, Queensland Government Investigative Report, viewed 18th July 2020

Zhang, J.; Apeagyei, A.K.; Airey, G.D.; Grenfell, J.R.A. 2015, Influence of aggregate mineralogical composition on water resistance of aggregate–bitumen adhesion. Int. J. Adhes. Adhes. 62, 45–54.

APPENDIX A

Project Specification

ENG4111/4112 Research Project

Project Specification

For:	Ahmed Gadalla
Title:	The Effects of Extreme Weather Events on Flexible Pavements
Major:	Civil
Supervisor:	Dr Andreas Nataatmadja
Sponsorship:	No official sponsorship but support and data from CoGC (City of Gold Coast)
Enrolment:	ENG4111 – EXT S1, 2020
	ENG4112 – EXT S2, 2020
Project Aim:	To investigate the effects extreme weather events such as excessive rainfall causing flooding and extreme heat have on flexible pavements.

Programme: Version 1, 18th March 2020

1. Research the background information relating to the effects of specific extreme weather events has on flexible pavements.
2. Identify locations where extreme weather events have occurred, preferably within the Gold Coast Region
3. Analyse data from BOM to predict the probability of the occurrence of such weather events and if it's increasing/decreasing and its intensity.
4. Once the location of these extreme weather events has been identified, data relating to the pavement can be collected at selected sites. This data will be from SMEC PMS at the Gold Coast City Council pavement data such as, pavement age, surface type, surface code, base code, road hierarchy type, rutting, cracking %, PCI, lane AADT, roughness, ravelling/stripping %, potholes %.
5. After collecting all the data required to associate types of pavement failures to specific extreme weather events, I will compare a road (preferable a stretch of the same road) that didn't experience the effects of the weather event, with a similar design, AADT and CBR and compare them to each other. This will be primarily for flooding events.
6. Once each extreme weather event has been associated with a type/s of pavement failure, I will aim to produce a cost analysis to produce an annual cost figure as to how much these weather events are costing the GCCC.

If time and resources permit:

7. Perform laboratory testing to see how these weather events damage pavements within a controlled environment.
8. Allocate a solution to specific types of failures that regularly occur due to regular or increasing weather events at specific locations.

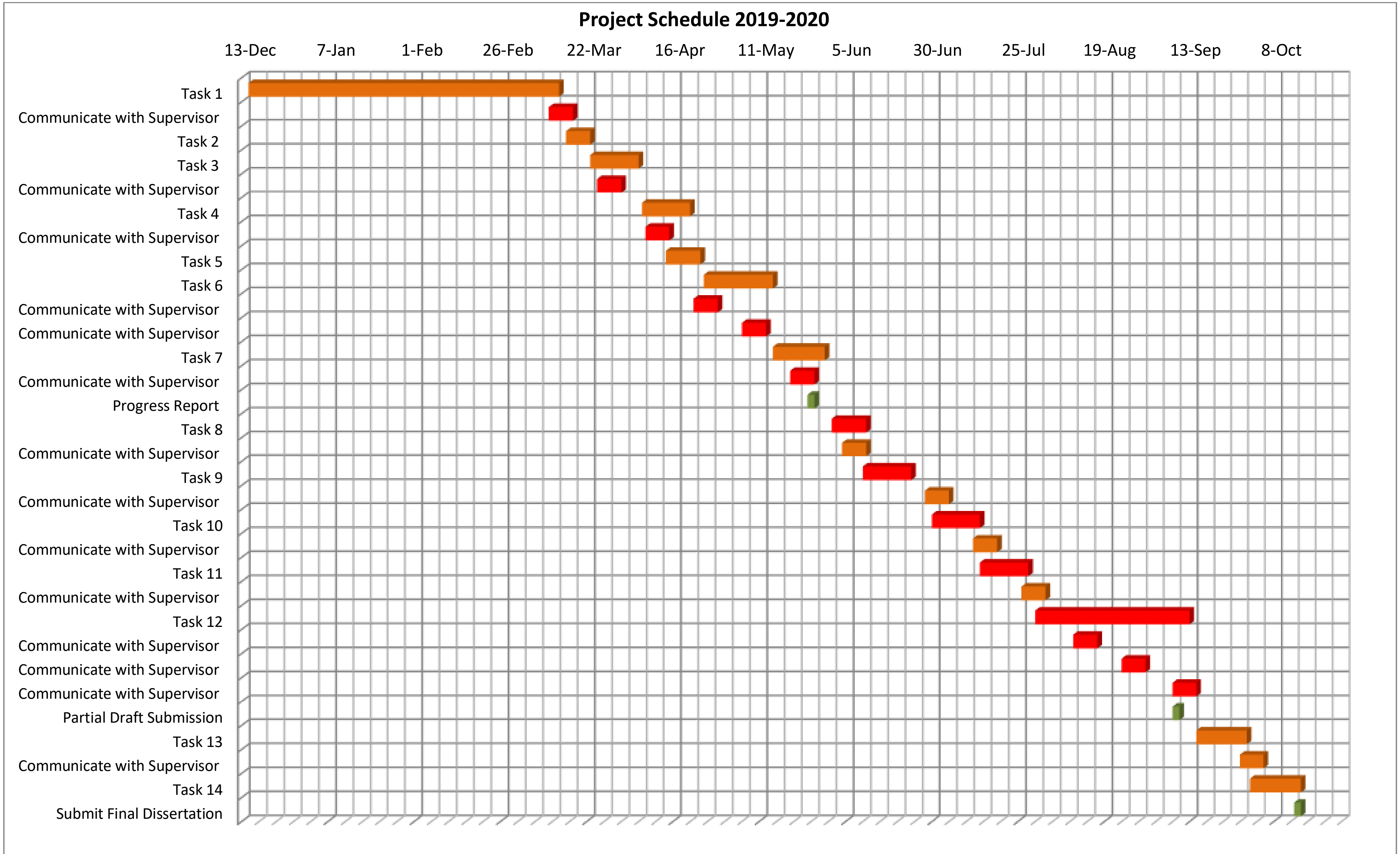
APPENDIX B

Project Plan

- **Task 1:** Review all relevant literature and understand how specific weather events damage pavements
- **Task 2:** Consult with GCCC and USQ project supervisor to confirm the selected experimental testing and/or case study procedures are correct and confirm USQ has the materials and facilities required for laboratory testing if required.
- **Task 3:** Consult with GCCC and find suitable road pavement locations where flooding events occurred
- **Task 4:** Obtain relevant data from GCCC for selected pavement sites
- **Task 5:** Collect BOM for before, after and during weather event at location of case study sites
- **Task 6:** Analyse data for selected pavement locations and form case studies
- **Task 7:** Identify type of pavement failure from the case studies
- **Task 8:** Compare types of pavement failure evident for each case study and attempt to identify similarities for each weather event
- **Task 9:** Compare case study pavement data collected from GCCC and compare with data collected from literature, essentially a comparison of the types of failures that are evident in both sets of data.
- **Task 10:** Develop discussion and conclusion on whether extreme weather events have any impact on pavement and what types of failure they cause.
- **Task 11:** Perform a cost analysis to identify the annual cost extreme weather events have on GCCC roads.
- **Task 12:** Prepare draft dissertation
- **Task 13:** Present dissertation findings at Professional Practice 2
- **Task 14:** Finalise dissertation and submit final copy

Gantt chart below displays an approximation of when each task is to be completed.

All Blocks displayed in red below in the Gantt chart are regarding communication with Dr Andreas and have been allocated 7-day duration to allow for correspondents between myself and Dr Andreas. Furthermore, Communication will be in the form of emails, fortnightly.


Project Schedule 2019-2020
13-Dec
7-Jan
1-Feb
26-Feb
22-Mar
16-Apr
11-May
5-Jun
30-Jun
25-Jul
19-Aug
13-Sep
8-Oct
Task 1
Communicate with Supervisor
Task 2
Task 3
Communicate with Supervisor
Task 4
Communicate with Supervisor
Task 5
Task 6
Communicate with Supervisor
Communicate with Supervisor
Task 7
Communicate with Supervisor
Progress Report
Task 8
Communicate with Supervisor
Task 9
Communicate with Supervisor
Task 10
Communicate with Supervisor
Task 11
Communicate with Supervisor
Task 12
Communicate with Supervisor
Communicate with Supervisor
Communicate with Supervisor
Partial Draft Submission
Task 13
Communicate with Supervisor
Task 14
Submit Final Dissertation

APPENDIX C

SMEC PMS Data (Raw)

Name	Suburb	Road No.	Section	Identifer	Chainage	Between	Length	Width	Surface Age	Pavement Age	Hierarchy	Surface Type	Surface Code	Roughness	Rutting	Ravel/ Strip %	All Crack %	Wide Crack	Potholes %	PCI
SOMERSET DRIVE	MUDGEERABA	142,191.00000	1.6000	142191_1.6	350 to 523	CHN 350 to BRIDGE NORTH ABUT	173	9.60	10	10	COLLECTOR	Asphalt	AC40	93.5	11.1	0.0	0.0	0.0	0.0	7.84
SOMERSET DRIVE	MUDGEERABA	142,191.00000	1.3000	142191_1.3	175 to 350	CHN 175 to CHN 350	175	9.60	10	10	COLLECTOR	Asphalt	AC40	78.1	7.1	0.0	0.0	0.0	0.0	8.90
VINCE HINDE DRIVE	WORONGARY	147,650.00000	6.0000	147650_6	898 to 1001	END MAJOR CULVERT to HARRY MILLS	103	7.60	29	29	RESIDENTIAL ACCESS	Asphalt	AC25	756	96.8	2.0	0.0	0.4	0.0	0.0
VINCE HINDE DRIVE	WORONGARY	147,650.00000	3.0000	147650_3	545 to 765	CHARLES KURZ (STH) to CHARLES KURZ (NTH)	220	7.60	29	29	RESIDENTIAL ACCESS	Asphalt	AC25	756	77.4	2.0	0.0	0.4	0.0	0.0
SIGANTO DRIVE	HELENSVALE	141,850.00000	2.0000	141850_2	124 to 396	END MEDIAN to START CULVERT	272	10.00	12	22	MINOR COLLECTOR	Asphalt	AC50	5,759	82.3	6.0	2.2	11.7	0.0	0.0
SIGANTO DRIVE	HELENSVALE	141,850.00000	5.0000	141850_5	614 to 888	GREY GUM ST to CHN 888-CARAVAN PARK	274	8.25	12	28	MINOR COLLECTOR	Asphalt	AC50	5,759	60.1	5.0	2.1	0.0	0.0	0.0
HIGHFIELD DRIVE	MERRIMAC	121,060.00000	8.5000	121060_8.5	1465 to 1736	CHN 1465 to BRIDGE ABUT NORTH	271	11.50	15	31	RESID. COLLECTOR	Seal	PMBR	2,934	60.5	0.00	0.0	1.3	0.0	0.0
HIGHFIELD DRIVE	MERRIMAC	121,060.00000	10.0000	121060_10	1779 to 1870	BRIDGE ABUT SOUTH to SEAL CHANGE/T-SIGN	91	11.50	15	31	RESID. COLLECTOR	Seal	PMBR	2,934	63.1	0.00	0.0	3.8	0.0	0.0

APPENDIX D

List of Flooded roads from CoGC

NATURAL DISASTER FLOOD STORM AFFECTED AREAS

AREA	ROAD	ID	MAP REF.	ASSET
MUDGEERABA	Berrigans Road	ID 132	Map 57, K5	Culvert
	Hardys Road	ID 423	Map 58, C16	Culvert
	Hardys Road	ID 25	Map 57, P4	Footbridge
	Somerset Drive	ID 717	Map 58, C4	Footbridge
	Gunsynd Drive	ID 422	Map 58, B10	Bridge
AUSTINVILLE	Austinville Road	ID 570	Map 57, A18	Bridge
	Austinville Road	ID 124	Map 67, A7	Culvert
	Austinville Road	ID 816	Map 66, R5	Up-grade culvert
	Staghorn Drive	ID 485	Map 66, R2	Culvert
WORONGARY	Vince Hinde Drive	ID 293	Map 47, H9	Culvert
MERRIMAC	Highfield Drive, No. 1	ID 430	Map 48, B16	Culvert
	Highfield Drive, No. 2	ID 431	Map 48, B15	Culvert
TALLEBUDGERA VALLEY	Syndicate Road	ID 268	Map 69, A20	Culvert
	Syndicate Road	ID 269	Map 79, A3	Culvert
	Dalton Road	ID 400	Map 78, C5	Culvert
	Luxton Court	ID 719	Map 78, H1	Culvert
	Petsch Creek Road	ID 468	Map 78, G11	Culvert
	Petsch Creek Road	ID 469	Map 78, F12	Culvert
	Petsch Creek Road	ID 470	Map 78, G13	Culvert
	Araluen Road	ID 1039	Map 77, P8	Culvert
	Mt Cougal	n/a	Map 77, M15	Causeway
	Len Dickfos Road	ID 1221	Map 77, F29	Bridge
	Tallebudgera Valley	n/a	Limit of Maps	3 x floodways
	Bramely Drive	ID 371	Map 78, J6	Culvert
CURRUMBIN VALLEY	Bains Road	ID 9	Map 79, A17	Traffic Bridge
	Boyds Bridge	ID 22	Map 78, M21	Traffic Bridge
	Fordyce Close	ID 413	Map 79, F11	Culvert
	Doloans Crossing, #1481	ID 164	n/a	Causeway
	Mt Cougall Crossing NP	ID 701	n/a	Causeway
CLAGIRABA	Clagiraba Road (little Clagi Creek)	ID 357	Map 35, K5	Culvert
	Clagiraba Road (Coomera River)	ID 154	Map 35, D1	Culvert
MT NATHAN	Heritage Drive, Coomera River	ID 587	Map 25, G14	Traffic Bridge
	Heritage Drive	ID 429	Map 25, E12	Culvert
MAUDSLAND	Guanaba Creek Road, (Coomera River)	ID 24	Map 25, N4	~~Timber Traffic~~ Bridge
GUANABA	Birds Road (Coomera River)	ID 136	Map 15, M18	Culvert Crossing
	Tarata Road	ID 274	Map 15, H19	Culvert
	Guanaba Creek Road (Hollindale Park)	ID 1111	Map 15, A19	Culvert
HELENSVALE	Siganto Drive	ID 543	Map 17, A4	Culvert
WONGAWALLAN	Lanes Road	ID 218	Map 5, B12	Culvert
	Upper Coomera Road	ID 714	Map 4, M8	Culvert
WILLOW VALE	Hotham Creek Road	ID 434	Map 325, Q13	Culvert
	Hotham Creek Road	ID 211	Map 325, N13	Culvert
	Hotham Creek Road	ID 212	Map 325, L5	Culvert
	Hotham Creek Road	ID 210	Map 325, A9	Culvert
CEDAR CREEK	Shaws Pocket Road	ID 259	Map 304, G11	Culvert Box
	Chardons Bridge Road	ID 11	Map 304, G15	Traffic Bridge
	Cedar Creek Road	ID 1217	Map 304, H19	Traffic Bridge

UPPER COOMERA [illegible]

APPENDIX E

Risk Assessment

Risk assessment is vital for any project. It allows for possible risks to be identified and a mitigation strategy to be put in place before the initiation of the project. To analyse the possible risks involved, a risk assessment matrix will be used as shown in Figure E1. This will ensure any possible hazards are mitigated to a reasonable amount. Table E1 lists all possible personal risks involved and the allocated procedures assigned to it to ensure hazards are mitigated.

Furthermore, there are other types of risks that are associated with the project itself, these are considered project risks and are listed below in Table E2. These risks are more likely to occur and therefore must be give more importance.

		Consequences				
		Insignificant (1) No injuries / minimal financial loss	**Minor (2)** First aid treatment / medium financial loss	**Moderate (3)** Medical treatment / high financial loss	**Major (4)** Hospitable / large financial loss	**Catastrophic (5)** Death / massive financial loss
Likelihood	**Almost Certain (5)** Often occurs / once a week	Moderate (5)	High (10)	High (15)	Catastrophic (20)	Catastrophic (25)
	Likely (4) Could easily happen / once a month	Moderate (4)	Moderate (8)	High (12)	Catastrophic (16)	Catastrophic (20)
	Possible (3) Could happen or known it to happen / once a year	Low (3)	Moderate (6)	Moderate (9)	High (12)	High (15)
	Unlikely (2) Hasn't happened yet but could / once every 10 years	Low (2)	Moderate (4)	Moderate (6)	Moderate (8)	High (10)
	Rare (1) Conceivable but only on extreme circumstances / once in 100 years	Low (1)	Low (2)	Low (3)	Moderate (4)	Moderate (5)

Figure E1: Risk Assessment Matrix

Identified Risk	Likelihood	Consequences	Risk Level Before	Mitigation Measures	Risk Level After
Contract COVID-19 while collecting data at CoGC	Possible (3)	Catastrophic (5)	High (15)	- Maintain social distancing at all times - Work from home when possible	Low (3)
Getting sore eyes while analysing data	Likely (4)	Minor (2)	Moderate (8)	- Take breaks every 2 hours -Reduce screen brightness	Low (3)
Getting a sore back/neck	Likely (4)	Moderate (3)	High (12)	- Take regular breaks and use an ergonomic chair	Low (3)
Getting a migraine/headache	Possible (3)	Minor (2)	Moderate (6)	- Stay hydrated and have regular breaks - Measure blood sugar levels regularly (As I'm a Type 1 diabetic)	Low (3)

Table E1: Personal risks

Hazard	Likelihood	Risk Level	Mitigation
Unable to obtain data from CoGC/TMR	Possible	High	Attempt to get data as early as possible, if not possible attempt to get data from other transport and road authorities in a different state
Unable to obtain list of flood affected roads from Council	Unlikely	Medium	Attempt to get list of flood prone/affected roads as soon as possible and also have a contingency plan for an alternative location
Unable to access USQ laboratory equipment	Unlikely	Low	Book required lab usage time early, alternative arrange for TMR lab access.
Loss of data or results	Possible	High	Back up data on a regular basis and store data on multiple locations

Table E2: Project risks

APPENDIX F

Data from CoGC Disaster Management Unit

OBJECTID	Street Name	Suburb	Location	Road Authority	Condition	Catchment	City Floodway	Typical Closure	LAST EDITED DATE	x	y
56	Somerset Drive	Mudgeeraba	between North of Bonogin Rd and Gold Coast-Springbrook Rd (Franklin Dr)	Council	Road subject to flooding	Nerang	Yes	Gold Coast-Springbrook Rd (Franklin Dr) to Bonogin Rd	December 21, 2018	535638.5	6893287
100	Siganto Drive	Helensvale	between Helensvale Rd and Grey Gum St	Council	Road subject to flooding	Coomera	Yes	between Helensvale Rd and Grey Gum St		531175.4	6913417
127	Siganto Drive	Helensvale	c.20m north of Trade Winds Drive	Council	Normal conditions	Coomera	Yes			530997.8	6914654
150	Siganto Drive	Helensvale	causeway c400m south of Saltwater Avenue	Council	Normal conditions	Coomera	Yes			531023.8	6914008
192	Highfield Drive	Merrimac	210m north of Breakwater Road	Council	Normal conditions	Nerang	Yes	between Breakwater Rd and All Saints School		535571.2	6895384
196	Somerset Drive	Mudgeeraba	1450m from Gold Coast-Springbrook Rd (Franklin Dr)	Council	Normal conditions	Nerang	No		December 21, 2018	536290	6892621
205	Vince Hinde Drive	Worongary	between Charles Kurz Drive and Harry Mills Drive	Council	Normal conditions	Nerang	Yes	between Charles Kurz Drive and Harry Mills Drive	December 21, 2018	533078.5	6896953