WATER USAGE AND WATER AVAILABILITY UNDER CHANGING LAND USE AND CLIMATE WITHIN TOWOOMBA REGION, QUEENSLAND, AUSTRALIA

A Thesis submitted by
Luningning Maranan Dalayon
BSF
MF

For the award of
Doctor of Philosophy
2021

ABSTRACT

This study aimed to quantify the water usage of eight sectors of users in the Toowoomba Region and to identify the significant factors affecting their consumption. The sectors are residential, agriculture, livestock, mining, industrial, commercial, institutional, parks, and gardens. Land Change Modeler (LCM) in TerrSet was employed to analyze land use change and predict the future "business as usual" scenarios for 2038 and 2058. The data used in the analysis were land-use, socio-economic, and geophysical data of 1999, 2010, and 2018. Land Change Modeler (LCM) in TerrSet was employed to analyze land use change and predict the future "business as usual" scenarios for 2038 and 2058. Future land use changes were simulated using the Multi-Layer Perceptron Neural Network and Markov chain model, considering various influencing factors, such as distance from roads and anthropogenic disturbances, elevation, slope, rainfall, and temperature. Using the land prediction output, the demand and water supply were simulated for years 2038 and 2058 using the Water Evaluation and Planning (WEAP) System to determine future unmet water demands of the different water user sectors, including the Environmental Flow as an additional sector. The area of each sector was expressed in hectares. Water usage of each sector used in WEAP was based on the 2018 Toowoomba Region's land-use map. The water use coefficient of each sector per hectare was quantified to determine the current water consumption, which was subsequently inputted in WEAP as the demand side.

Agriculture, residential, commercial, and industrial sectors were the top four major water users in the Region with annual average water usage of 39 million kl, 5.3 million kl, 930 thousand kl, and 550 thousand kl, respectively. Mining with 76 thousand kl and electricity generation with 380 kl were the least at 7th and 8th place, respectively. Regression analysis showed that the different sectors have varying significant factors affecting water usage. For the residential sector, it was observed that surface water and annual access charge were the dominant factors with R^2 = 79.5%. Surface water was the only dominant factor in the commercial sector with R^2 = 83%. On the other hand, Agriculture, Livestock, and Mining were significantly influenced by Tier 1 and December temperature with R^2 = 96.7%, access charge and annual rainfall with R^2 = 86.7%, and Toowoomba population and December temperature with R^2 = 89.6%,

respectively. Moreover, the sole sector affected by Toowoomba bores was the institutional sector with R^2 = 85.1%. In terms of parks-gardens and energy generation, these sectors were significantly affected by surface water supply and temperature with R^2 = 93%, respectively.

Land use change projection showed an expansion of farmlands and mining area by 2038 and 2058, followed by a reduction in the area for livestock production for the base scenario (1999-2018). On the contrary, the first alternative scenario (1999-2010), which simulates the "Big Dry" period, showed a steady increase in the area for livestock production and a gradual decrease in mining area while farmlands may increase until 2058. Meanwhile, the second alternative scenario (2010-2018) predicted a general decline and/or stable expansion in farmland and mining areas until 2058. There was no difference in the water usage projection under land use and climate change scenarios. The overall comparison of the long-term annual average unmet water demands for 2038 and 2058 revealed no difference in values under normal years and very dry water years. Simulations of unmet water demand under climate trends 2038 and 2058 for very dry water years revealed that there would be a total water deficit of approximately 590 million cubic meters in both years. Conversely, in a very wet water year, there would be a total deficit of 462 million cubic meters and 525 million cubic meters in 2038 and 2058, respectively.

There were limited studies that have been conducted about the nexus between water consumption and land-use change under different climate scenarios. The implications of these studies, as mentioned, extend to addressing this significant issue by identifying the various sectors affecting water consumption. This study found that land use and its future changes are good factors to consider in managing the current and future water demands either in wet or dry climate conditions. This is especially important in a society, such as Toowoomba, because it is an example of a vastly growing regional city in Australia, where sustainable water management is one of its primary concerns. This study generated information and knowledge to help in addressing the region’s current and water consumption issues, with wider applications not only to other regions in the country but also worldwide.

CERTIFICATION OF THESIS

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this thesis are entirely my own efforts, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

______________________________ ___________________________

Signature of Student Date

ENDORSEMENT

Principal Supervisor: Armando Apan

Associate Supervisor: Tek Maraseni

Associate Supervisor: Steven Goudie

Date: ____________________________

Student and supervisors' signatures of endorsement are held at the University.

ACKNOWLEDGEMENT

The author is profoundly grateful to the Australian Government through its Australia Awards Scholarship for the opportunity to study in one of the prestigious universities, which helped enhance my technical capabilities.

The Department of Environment and Natural Resources honed me to be a better individual—my training ground in developing excellence, nobility, discipline, and responsibility. I owe you a lot.

Dr. Armando Apan and Dr. Tek Maraseni, for the untiring support and guidance every step of the way throughout this entire journey. Thank you for sharing your expertise and wisdom, which helped me a lot to get this humble piece of work through. Thank you for not giving up on me when times got rough and challenges were unbearable.

Mr. Steve Goudie, who shared his insights and guided me in establishing networks with institutions concerned and to individuals who, in one way or another, extended their assistance by providing data/information for this research.

Toowoomba Regional Council, specifically Wendy Brunchorst, Bruce Gaydon, David Frizzel, and Joel Altwood for the significant data they provided.

Assistant Regional Director of DENR XI, Ma'am Marcia G. Isip, for painstakingly reviewing my proposal, not to mention the constant encouragement and belief that I can complete this thesis.

Dr. Rudolf Espada, Ms. Gracee Daquiado, and Mr. Paul Oñez for the technical assistance. Your help is highly appreciated and will always be treasured.

To my forever sissy, Sis Marylou Espada, and Brod Dolf Espada, and daughter Trish, you are my family and my home away from home. I really thank God for your lives. Your love and friendship are incomparable.

To my Toowoomba friends, Ate Zeny and Kuya Jun Garcia, Sheena, Ate Hope and Brod Arman, Sis Myra, Ate Peachy and Mae, Melvin and Nice, thank you for the friendship.

To my spiritual family, The New Castle Foursquare Gospel Church of Bago Oshiro, Mintal, Philippines. My prayer warriors, and my comfort zone, thank you so much. I am extremely excited to serve the Lord with you.

To Rev. Daniel Suboan and his wife, Ate Glo, and to Ptr. Yoy Italio and his wife, Sister Jenny, thank you for always being there for me and my family. To Rev. Isidro Gubal and Rev. Leah Gubal, love you still.

To my sister and brother in Christ, Lea and Zabdiel Zacarrias, I cannot thank you enough for all your prayers, love, and support. Truly, I've found true and faithful friends in you.

To my BFFs, For. Eve M. Mallari and Sisterete Romela Macahilig, thank you for everything.

To my Ninong Germs and Ninang Nic Urbiztondo, my spiritual parents, my supporters, thank you so much.

To Mae and Onel, my secret keepers and my shoulders to cry on, I am blessed to have you. To Mark and Nene, thank you for everything.

To my sisters and brothers, thank you for the prayers and love. To Ate Loida, this is it. Without your support and love, I would not be where I am right now.

To Mr. Marianito, Sr., and Mrs. Emma Dalayon, my beloved and my supportive and kind-hearted in-laws. Thank you, Ma and Pa, for everything.

To my three wonderful children, Kiel, Bless, and AJ, you are my treasures from heaven. Thank you for your patience during all those months that I was away just to complete this piece of work. Your love and support keep me going.

And to my husband Jun, my loved ones, thank you so much for your untiring support spiritually, financially, and emotionally. Thank you for believing in me to complete this journey.

Above all else, to my God Almighty who is the Author and Finisher of my faith, my faithful and amazing Father, my source of wisdom, my everything. WITHOUT YOU LORD, I AM NOTHING. This humble piece of work is for you, with this, your NAME will be GLORIFIED.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABS	Australian Bureau of Statistics
ALUM	Australian Land Use Map
ANCOLD	Australian National Commission on Large Dam
BOM	Bureau of Meteorology
CSIRO	Commonwealth Science & Industrial Research Organization
DERM	Department of Environment and Resources Management
DEWS	Department of Energy and Water Supply
DNRM	Department of Natural Resources and Mines
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
MDB	Murray-Darling Basin
MDBA	Murray-Darling Basin Authority
NLWRA	National Land & Water Resources Audit
NWC	National Water Commission
SEQ	South East Queensland
TRC	Toowoomba Regional Council
QGIS	Queensland Government Information Service
QSO	Queensland Statistics Office
UN	United Nations

GLOSSARY OF TERMS

Term	**Definition**
Aridity	refers to regions of low rainfall and is a permanent feature of their climate.
Bale	refers to a package of compressed cotton lint after ginning tied with wire or metal bands and wrapped in cotton jute. This is the basic tradable unit of lint (ginned cotton). Bales vary in weight in different countries but the universal density bale weights 218 to 225 kg.
Catchment	refers to an area of land surrounded by natural high features such as hills or mountains, down which water flows to a stream, river or sea.
Climate change	the longer-term change in average conditions over several decades to centuries.
Climate change adaptation	refers to initiatives and measures to reduce the vulnerability of natural and human systems against actual and expected climate change effects.
Climate variability	is the year to year and decade to decade noise or variability around the average climate.
Coal Seam Gas	referred to as coal seam methane or coal bed methane. It is an unconventional form of natural gas that occurs naturally within the pores or fractures of coal seams.
Dam	a structure that is made from earth, rocks and concrete materials constructed on rivers to control and store water during times of excess flow. The water from this reservoir can be released during times that natural flows are inadequate to meet the needs of the water users.

Distributed water	is water supplied to a user, often through a non-natural network (piped or open channel), and where an economic transaction has occurred for the exchange of this water. Water supplied by the irrigation water providers through natural waterways and bores falls under the definition of distributed water.
Drought	is a typical deficiency of precipitation, including rainfall, snow, hail and sleet, over an extended period of time, usually a season or more, which result in a water shortage for some activity, group, or environmental sector.
Efficient use	refers to a pattern of use that maximises the benefits arising from the exploitation of water resources.
Environmental flow	is defined as the streamflow necessary to sustain habitats, encourage spawning and the migration of fauna species to previously unpopulated habitats, enable the process upon which succession and biodiversity depend, and maintain the desired nutrient structure within lakes, streams, wetlands and riparian areas.
Land use	for the purpose of this research, it is the alteration of the land surface as well as the changes in the human use of the land.
Reuse water	refers to wastewater that may have been treated to some extent, and then used again without first being discharged to the environment. It excludes water that is reused onsite, (e.g. on-farm water reuse or water being constantly recycled within a manufacturing plant.
Return Flow (RF)	generally, refers to any volume of water made available for re-allocation to downstream users within the greater catchment system. It also refers to the flows generated from other land use activities. For the purpose of this research, RF will be the flows generated from irrigation, residential and commercial/industrial.
Statistical Significance	is a term which is used to assess the degree to which a researcher can rule out chance as the explanation for any relationship

found.

Surface water/stream flow	is the volume of water passing a fixed point over a unit of time. For the purpose of this research, this is the available surface water less the environmental flow.
Water usage	for the purpose of this research, this will mean the total amount of water used by all identified sectors.
Water availability	in this research, this will be the volume of available surface water + return flow + coal seam water output. It can also be defined as the total potential water available for withdrawal from the catchment.
Water Yield Stress Index	the ratio between water usage and water availability. It is also known as relative magnitude in water usage and available water.

CHAPTER 1

INTRODUCTION

1.1 Background

Water is widely regarded as one of the most essential natural resources, as it supports human life and culture, ecological functions, and socio-economic development, and it is easily vulnerable to and susceptible to successive uses (Durán-Sánchez et al., 2018; Fuentes et al., 2020; Mehran et al., 2017). However, for many hundreds of years, humans' impacts on water resources have been insignificant due to their outstanding properties of natural renovation and self-purification during the water cycle. These gave rise to an illusion and preconception of its immutability and inexhaustibility, which led to a careless attitude toward the use of water resources. The massive influence of anthropogenic activities in the hydrological cycle significantly affects the quality of water resources (Khatri & Tyagi, 2015). In the last century, the need and use of water have been growing at more than twice the rate of population growth (Wada et al., 2016).

Today, water scarcity has already affected every continent (UN, 2018) with approximately 2.7 billion people suffering from water shortage at least once a month per year (World Wildlife Fund, 2012). The situation could potentially worsen when considering the basic hygiene and livelihood demands of people and the natural climate variability with the presumed changes in water availability brought by global warming (Kattel, 2019; Mehran et al., 2017).

In Australia, availability and access to water are also critical issues. The country is marked by recurrent droughts and extreme floods, leading to river flow and forcing groundwater recharge to become very low and variable (Acworth et al., 2021; Hughes, 2011). Fuentes et al. (2020) mentioned that the major reason for rising water demand in this country is due to the increasing population and the increase in people's living standards. Aside from the expanding population, Koech & Langat (2018) mentioned irrigation, industrial use, and environmental allocations as contributors to the pressures.

With the pressing issues on global and regional water resources, various studies have been conducted to estimate both water usage and water yield. One of these significant studies was conducted in the southeastern part of the United States. Qin et al. (2019) studied the flexibility and intensity of global water use, which quantified the annual water availability for water supply and demand using the "Water Supply Stress Index" and "Water Supply Index Ratio." Noticeably, this study disregarded other water users such as vegetation, recreational areas, and wildlife. It also overlooked mining and thermoelectric water as possible sources of water supply. However, the authors recommended including environmental flows in future studies. Another study was on the Mara River Basin in Eastern Africa, which mapped and analyzed the catchment's water availability, demand, and usage (Hoffman et al., 2011). While it looked at several consumptive water-use factors, the study disregarded water usage from non-irrigated, commercial, and other industrial areas.

In Australia, two national surveys conducted in 1977 and 1983/84 provided data on water consumption encompassing irrigation, urban, rural, and industrial water uses, but there was little information on in-stream, non-consumptive water use such as for hydro-electricity generation, recreation, and aesthetic purposes (Crabb, 1997). While several water-related studies have been published with significant results (Coombes et al., 2002; Loh & Coghlan, 2003; Roberts, 2005), they only offered piecemeal information on water use and water availability. The Commonwealth Scientific and Industrial Research Organization (CSIRO, 2008a) rigorously attempted to estimate the worldwide impacts of catchment development, changing groundwater extraction, climate variability, and anticipated climate change on water resources at a basin scale. In one of their project areas where the Condamine-Balonne catchment was included, the study undertook the most comprehensive hydrologic form of modeling using examples from rainfall-runoff, groundwater recharge, river system, and groundwater models. While this study identified the current and future water availability, it failed to identify the particular water users or sectors that would possibly be impacted from future decreases or increases in water resources. Moreover, it did not consider the impacts of possible future land use/cover (LULC) change and population change on future water availability. On the other hand, a recent study conducted by Zhang et al. (2019) in the Manning River catchment in Eastern Australia evaluated the impacts of climate change on water resource availability.

Therefore, it is necessary to conduct a comprehensive study on historical and current water usage, taking into consideration sectoral water users along with groundwater and surface water availability/yield. Likewise, it is equally important to determine future water usage and yield under the projected effects of climate change, LULC change, and population change. The proposed research project is challenged to go in this direction.

1.2 Statement of the Problem

One of the important issues faced by mankind today is the availability of freshwater resources (FAO, 2019). Access to freshwater resources is likely to become increasingly scarce globally (Koutroulis et al., 2019). The challenge for the 21st century will be to manage these resources in order to balance the needs of both people and the ecosystems. Consequently, ecosystems should be able to continue to provide other services essential to human well-being (Kattel, 2019). Pressure on water resources intensifies whenever allocation of groundwater and surface water is increased due to a variety of reasons such as domestic, agriculture and industrial. This can lead to tension and conflict between users, and potentially exert further excessive pressure on the environment (Durán-Sánchez et al., 2018). With the possible impacts of future climate change, the problem associated with water availability and allocation could be more severe. It has been reported by the Intergovernmental Panel on Climate Change (IPCC) (2007) in their Fourth Assessment Report that climate change impact will most likely be felt in several global sectors such as water.

Water is extracted from rivers, lakes and groundwater. At present, it is evident that there is an increase in the demand for water, and a decrease in the availability of water in certain parts of Australia (Crabb, 1997; Maduku, 2020; A. Turner et al., 2016). Water use is dominated by irrigated agriculture, industry and households. The National Centre for Groundwater Research and Training (NCGRT) reported that Australia will not have enough freshwater to meet the combined needs of a rapidly-growing population, expanding industries and conservation of native landscapes by the middle of the 21st century if it fails to articulate a national groundwater strategy for the future (Middlemis et al., 2019). As Professor Craig Simmons (2012), Australia's most eminent water scientist, said:

"When industries, communities and environment are competing for the same water resources – as is bound to happen increasingly from now on - we need better ways for allocating the water that meet social, economic and environmental needs" (pp2).

Several studies on competing water users, water supply, climate change and water availability relationship, and the effects of land use to groundwater recharge had been conducted. One of these was by the CSIRO (2008b) which quantified the projected water availability for the year 2030 under wet extreme and dry extreme climates (Grafton & Wheeler, 2018). While this study considered the current developments and the current water users in the analysis, the elements of domestic consumption, industrial water extraction (e.g. coal mining and coal methane production), livestock and wildlife water usages were neglected. Moreover, the scenario modelling for the future climate and development utilised the current development as the input rather than the reasonable consideration of the possible future LULC and population changes. Finally, the significant factors that could affect water availability such as the return flow and the environmental flow were not included in the analysis.

The study by Romano et al. (2016) explored factors affecting water consumption in major Italian towns. However, the study was limited up to the household level and considered only the tariffs, income per capita, weather conditions, geographical and population characteristics.

A recent water demand study by Nover et al. (2019) was conducted to mitigate increasing water demand in semi-arid regions of California. It focused on increasing reservoir storage but not on the factors why there was such an increase in water demand. Other authors focused on the evolution of water consumption per capita within the residential areas, but other users such as commercial and industrial sectors were not taken into consideration (Tortajada et al., 2019). A study by Zhang et al. (2019) tackled the comprehensive ecological water demands but mainly focused on the cascade hydropower plants operation.

But in order to reliably assess the future water usage and the future available water, it is also necessary to take into account the changes to land use and population which both cause the water stress problems (Li et al., 2017; Zhang et al., 2020).

Considering these gaps and issues, this research aims to comprehensively identify all the water user sectors, their corresponding water usage, and the available water resources.

1.3 Research Questions

The following research questions were addressed in this study:

1. What is the water usage of each significant water user in Toowoomba Region and the dominant driving forces influencing their consumption rates?

2. What are the projected land use changes in Toowoomba Region in the years 2038 and 2058?

3. What is the projected water demand of each sector under land use and climate changes in Toowoomba Region for the years 2038 and 2058?

1.4 Research Objectives

This study generally aimed at quantifying the sectoral water usage/demand under the influences of current and future changes in land uses and climates in Toowoomba Region. Specifically, this study aimed at:

1. estimating the water consumptions of the different sectors (e.g., residential, agriculture, livestock, mining, industrial, institutional, energy generation, parks and garden, and human population) in Toowoomba Region;

2. projecting the potential land use changes in Toowoomba Region for the year 2038 and 2058; and

3. estimating the future water demand in Toowoomba Region in relation to its land use under a range of climate change scenarios for the year 2038 and 2058.

1.5 Significance of the Study

Various issues and knowledge gaps on water users, the volume of water they use, and the factors affecting water availability were identified in the literature. For instance, the Australian Academy of Science (2011) reported that there was no comprehensive understanding of the historical volumes of groundwater extraction for farming and human use. In addition, Turner et al. (2016) mentioned that demand management used around Australia during drought is difficult to calculate retrospectively because of the following reasons: records are not publicly available, they are incomplete, and/or are difficult to compare due to the changing nature of the programs implemented. The NGCRT (2011) declared that the number of competing water users is increasing, and there is a need for a better strategy for water allocation. The IPCC (2007) 4th AR warned that climate change impact will most likely be felt by several sectors such as water. It was cited that population growth will also cause water stress problems as demands for agriculture, urban, industrial, and environmental sectors have been on the rise globally (Dahal et al., 2016). Moreover, it was further mentioned that the impact of LULC change on water may surpass the impact of recent climate change (Vörösmarty et al., 2004). Hence, understanding the impact of LULC change on the hydrologic cycle is needed for the optimal management of natural resources (Scanlon et al., 2005). Although land use changes are largely induced by the growing population, societies will be able to react and adapt to climate change if water resources are managed well (Mehran et al., 2017).

This research will significantly contribute to the body of knowledge by producing a scientifically publishable research paper with innovation in the field of water and land use management and allocation. The following information and innovation are expected to make a significant input in planning and management, decision-making, and policy formulation in the field of water and land use:

- Identified significant water users, quantified water demand per sector, and the major factors affecting water demand;
- Projected land use change for years 2038 and 2058; and
- Projected water demand for years 2038 and 2058 considering the land use and climate changes.

It is essential to mention that one of the very significant innovations in this research is the inclusion of the Mining Industry as a water user and the Environmental Flow, which also needs water allocation.

1.6 Scope and Limitation of the Study

Due to the limitation of time and resources, this research is confined only within the Toowoomba Region. This study focuses on the quantitative aspect of surface water and groundwater supply. The water user sectors considered in this research are residential, livestock, commercial, institutional, industrial, mining, parks and gardens, energy generation, and irrigated agriculture. For agriculture, only irrigated cotton was considered for the first technical chapter, while other irrigated and non-irrigated crops were included in the land use change analysis. Due to time constraints, datasets for other irrigated agricultural crops could not be collected and were therefore excluded from this study. Moreover, water usage in this study was not measured based on virtual water but on allocation and consumption, taking into consideration the water use coefficients from various literatures. Virtual water is the water used in the production process of an agricultural or industrial product (e.g., 32 kg of water is required to produce a 32-megabyte computer chip of 2 grams, 1 kg of cheese needs 5,000-5,500 kg of water, and the production of a cotton T-shirt weighing about 250 grams requires about 2.7 cubic meters of water) (Allan, 2020).

For the return flow, it will only cover flows from irrigation based on the flow coefficient from literature, while flows from residential and commercial/industrial will be included if there is available data on treated effluent from government institutions concerned.

1.7 The Structure of the Thesis

This thesis consists of seven chapters. The first three cover the Introduction, Literature Review, and Methodology. Chapter Four presents and discusses the water user sectors, the total water usage, as well as factors affecting water use for each sector. Chapter Five covers the land use change in the Toowoomba Region from 1999 to 2018 and the projected land use in the years 2038 and 2058. Chapter Six is a discussion on the future water demand of the Toowoomba Region by the year 2030 in relation to projected land use and climate changes. In the last and final chapter, Chapter Seven summarizes the key aspects of the research thesis and offers research contributions and recommendations for future water management in the Region and future research in the same field.

CHAPTER 2

A REVIEW OF WATER RESOURCES, WATER USER SECTORS, LAND USE AND CLIMATE CHANGE

2.1 Introduction

In the first chapter, the need for conducting this research and its significance to society and the environment were presented. This chapter critically reviewed literature on water usage and its relation to land use change and climate change, primarily focusing on water resources and water usage in the global and Australian context. Competing water user sectors, such as residential, agriculture, livestock, commercial, industrial, institutional, parks and gardens, and electricity generation, were examined. Specifically, factors affecting water usage were thoroughly presented, examined, and discussed. Moreover, climate change and its relation to water availability and water use were studied, with consideration given to land use change.

2.2 Water Resources from the Past into the Future

This section describes the history of water resources worldwide, with a particular focus on Australia. It examines the evolution of water resources from abundance to scarcity and explores the potential scenarios it may face. The following subsections elucidate the reasons behind conceptualizing and premeditating this research within the State of Queensland.

2.2.1 Global Water Distribution and Availability

According to the United States Geological Survey (USGS, 2019), seventy percent of the Earth's surface is covered with water. However, a surprising fact is that only 0.5% of the Earth's total water supply—comprising water found in aquifers, lakes, reservoirs, rivers, and rainfall—is actually accessible for human use (Baker et al., 2016). This scarcity is further explored in Table 2.1, entitled 'Major Stocks of Water on Earth,' which provides an in-depth analysis of various water reservoirs. The table not only details their distribution across oceans, glaciers, and groundwater but also quantifies each reservoir's volume along with its contribution to the total water and freshwater available on Earth. This data emphasizes the overwhelming predominance of oceanic water and underscores the relative rarity of freshwater resources. Examining this further, the Earth holds approximately 1.4 billion km³ of water in various forms, yet a staggering 97% of this is oceanic. Freshwater reserves, which total around 35 million km³, are predominantly locked away in glaciers, permanent snow cover, and deep groundwater, rendering them largely inaccessible to humans (du Plessis, 2019).

Table 2.1. Major Stocks of Water on Earth

	Distribution Area (10^3 km^2)	Volume (10^3 km^3)	Percent of Total Water (%)	Percent of Freshwater (%)
Total Water	510,000	1,386,000	100	
Total Freshwater	149,000	35,000	2.53	100
World Oceans	361,300	1,340,000	97	
Saline Groundwater		13,000	1	
Fresh Groundwater		10,500	0.76	30
Antarctic Glaciers	13,980	21,600	1.56	61.7
Greenland Glaciers	1,800	2,340	0.17	6.7
Arctic Islands	226	84	0.006	0.24
Mountain Glaciers	224	40.6	0.003	0.12
Ground Ice/Permafrost	21,000	300	0.022	0.86
Saline Lakes	822	85.4	0.006	
Freshwater Lakes	1,240	91	0.007	0.26
Wetlands	2,680	11.5	0.0008	0.03
Rivers (as Flow on Average)		2.12	0.0002	0.006
In Biological Matter		1.12	0.0001	0.0003
In the Atmosphere (on Average)		12.9	0.0001	0.04

Source: Shiklomanov (1993) as cited by Gleick (2009)

Given this huge volume of water on Earth, the probability of water scarcity in the global context is unlikely. Yet, due to widespread scarcity and pollution, including the depletion of freshwater resources, water has become unavailable; hence, becoming a major water-related environmental concern of the 21st century (Hogeboom, 2020). Rapid growth in population, income, and the demand for energy, food, and livestock feed has increased global freshwater withdrawal from ∼2,500 km^3 annually in 1970 to ∼4,000 km^3 in 2010 (Z. Huang et al., 2018). USGS (2019) further revealed that out of the 10.6 million km^3 liquid freshwater found, 93,113 km^3 of it is surface-water sourced from rivers and lakes.

Liu et al. (2017) and Hogeboom (2020) emphasized the growing recognition of water scarcity being a major challenge affecting every part of the world. This same concern was reiterated by then UN Secretary-General Ban Ki-Moon when he said that water is on the top of the list of the world's diminishing resources (World Economic Forum, 2011). In 1994, a comprehensive assessment of freshwater resources was done by the United Nations Commission for Sustainable Development in response to the rapidly growing demand for freshwater resources. As a consequence of the demand, water stress in several parts of the world has been on the rise since (Vanham et al., 2018). It was reported that many of the river basins nowadays are unable to meet all the water demand of the competing users (Kattel, 2019).

2.2.2 Trends of Water Use and Global Comparison of Resources

The global demand for water has undergone significant changes, leading to increased stress on water resources worldwide. A staggering 600% increase in global demand for water has been observed over the past century (Boretti & Rosa, 2019). The situation is exacerbated by the projection that approximately 6 billion people will be affected by water scarcity by 2050 (UN World Water Development Report, 2018 edition; Boretti & Rosa, 2019). This looming crisis is particularly pronounced in regions such as northern Africa, the Mediterranean, the Middle and Near East, southern Asia, northern China, the USA, Mexico, northeastern Brazil, the west coast of South America, and Australia, where an estimated 1.4-2.1 billion people will face severe water stress (du Plessis, 2019).

The increase in water demand is primarily attributed to population growth, economic development, and changing consumption patterns, leading to heightened competition over freshwater resources (Heinke et al., 2020). Vörösmarty et al. (2000) highlighted that severe water stress was already impacting around 450 million people worldwide as of 1995.

In contrast to localized studies, a global comparison reveals significant variations in water resources and usage across different regions. For example, Australia stands out for having the lowest proportion of rainfall that converts to runoff when compared with other major regions globally. It experiences an average annual rainfall of 417 mm, totaling 3,700,000 gigaliters (GL), yet only 350,000 GL (or 9% of this rainfall) results in runoff (Prosser, 2011). This low conversion rate, combined with Australia's sparse population density of 3.32 persons per square kilometer as of July 2019 (United Nations, Department of Economic and Social Affairs, 2019), leads to a relatively high per capita water availability. However, as highlighted in Table 2.2, titled 'Global Comparison of Water Resources and Use,' Australia's water availability per unit area is marginally lower than that of other regions. This table provides a comprehensive comparison of water availability, population density, water consumption, and the percentage of resources consumed in different regions around the world. By doing so, it underscores the stark contrasts in water resource distribution and usage, emphasizing the disparities between regions abundant in water and those facing scarcity.

Table 2.2. Global Comparison of Water Resources and Use

Region	Available Water per Area (ML/ha)	Population Density (people/km^2)	Available Water per Capita (ML/person/year)	Water Consumed (10^3 GL/year)	Consumption per Resource (%)
Australia	0.5	2.5	21.3	25	6
North America	2.8	20.7	13.4	603	9.9
Central America	11.2	115.7	9.6	23	2.9
Southern America	6.9	21.5	32.2	165	1.3
Western and Central Europe	4.3	107.1	4	265	12.6
Eastern Europe	2.5	11.5	21.4	110	2.5
Africa	1.3	32.7	4	215	5.5
Middle East	0.8	47.1	1.6	271	56
Central Asia	0.6	18.5	3	163	62
Southern and Eastern Asia	5.5	174.4	3.2	1,991	17.1
Oceania and Pacific	1.1	3.3	33	26	2.9
World	3.2	50.4	6.4	3832	8.9

Source: Prosser, 2011

This combination of global trends and a regional case study underscores the complexity of water resource management. It highlights the need for tailored strategies that consider both the global increase in demand and the unique circumstances of individual regions.

Building on this, a comparison of the trends from Tables 2.1 and 2.2 reveals the global distribution and availability of water resources and their correlation with regional consumption patterns. These figures, when analyzed together, reveal the interconnected and complex challenges of water management in Australia. This analysis, spanning different time periods, illustrates the changes in water supply and usage within the Australian economic context. Such a comparative approach is instrumental in uncovering trends in sustainability, efficiency, and the impact of policy changes over time.

2.2.3 Australia and its Water Resources

It is most certain that there are yearly changes to the demand and access to water, as well as the amount that can be extracted from the environment on a sustainable basis (Kattel, 2019; Young, 2014). For example, a total of 65,968 GL of water was self-extracted in 2018-19. Seventy-eight percent (51,368 GL) of this was primarily driven by the electricity and gas supply industry for hydroelectricity generation. Water supply, sewerage, and drainage services accounted for 9,936 GL, which was used to supply industries and households (ABS, 2020).

In 2011-2012, out of the total 74,925 GL of water that was taken out from the environment, 85% (63,674 GL) of which was extracted directly by water users for mostly hydroelectricity generation, while 15% (11,251 GL) was for the water providers. This amount of water extracted from the environment, together with the 227 GL of reuse water, comprises the 75,152 GL water use of all sectors. Of this amount, 16,019 GL was used for consumptive purposes, and 58,632 GL was for non-consumptive use (e.g., electricity and gas supply industry). On the other hand, 63,727 GL of water was returned back to the environment as regulated discharge, the majority of which was effluent from hydro-electricity generation.

In comparing the periods of 2004-2005 and 2011-2012, there was a noticeable decline in the volume of water extracted from the environment and used, with decreases of 6.09% (4,859 GL) and 14.64% (2,748 GL), respectively. Remarkably, the latter period's reduction occurred despite the alleviation of usage restrictions and a growing population, which typically drive higher consumption. This trend suggests a heightened public awareness and commitment to water conservation, potentially a consequence of the prolonged drought the country endured (Prosser, 2011). Figures 2.1 and 2.2

graphically represent these dynamics, detailing the flow and utilization of water within the Australian economy across the specified periods. Both diagrams delineate the roles of 'Water Providers' and 'Water Users', measuring water in gigaliters to elucidate the exchange and recycling processes. In the 2011-2012 timeframe, providers distributed 11,251 GL, while users self-extracted 63,674 GL, indicating a presence of unquantified sewage and wastewater. Conversely, for the period of 2004-2005, providers and users self-extracted 11,337 GL and 68,447 GL, respectively, against a backdrop of 242,779 GL of runoff from rainfall. Additionally, a significant 62,455 GL of regulated discharge was associated with hydro-electric generation. These figures underscore the importance of comprehensive water flow accounting in understanding the full scope of water usage within the economy, reflecting both the quantified and unquantified aspects.

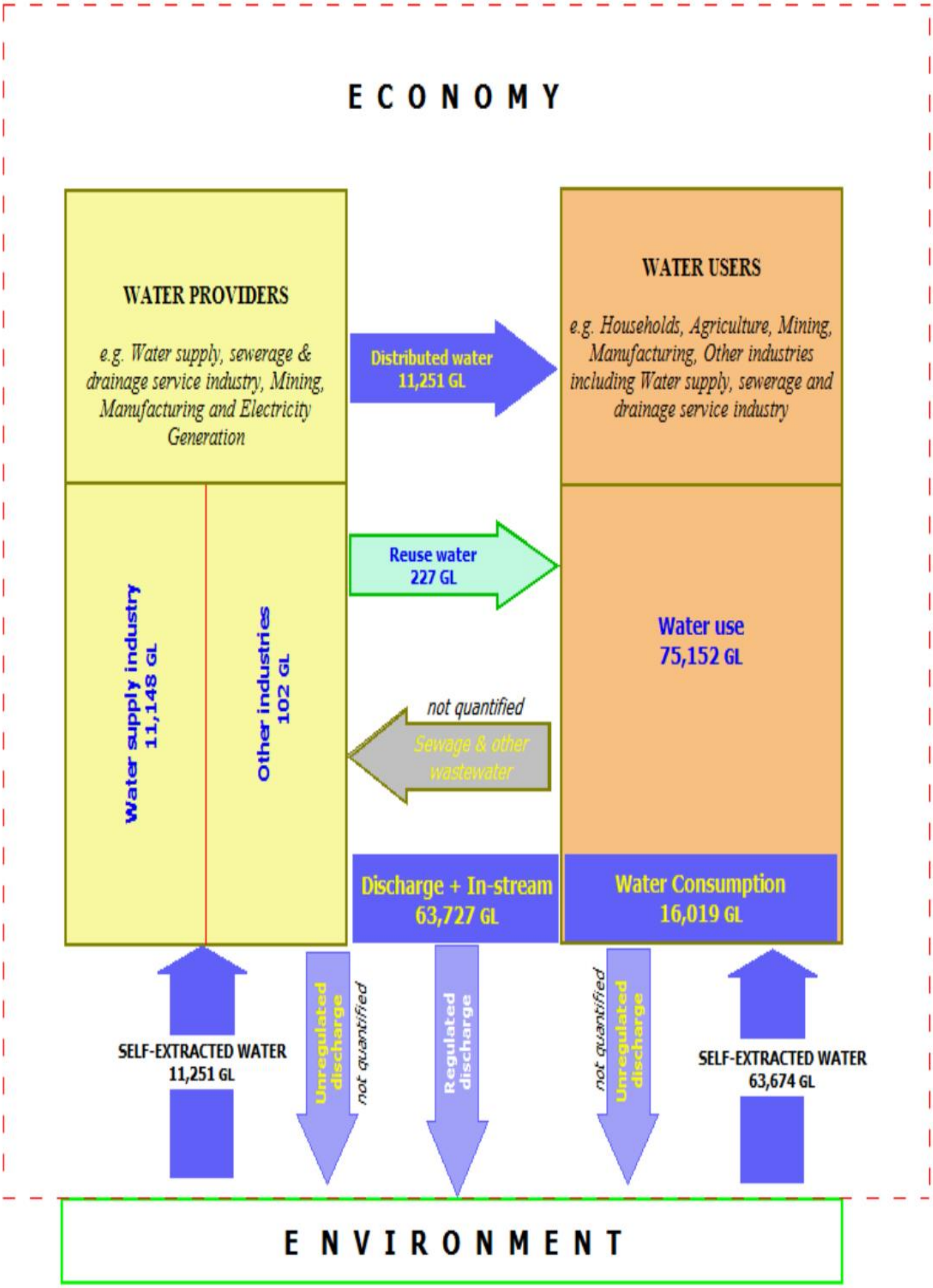


Figure 2.1. Water supply and use in the Australian economy, 2011-2012 (Source: ABS, 2012).

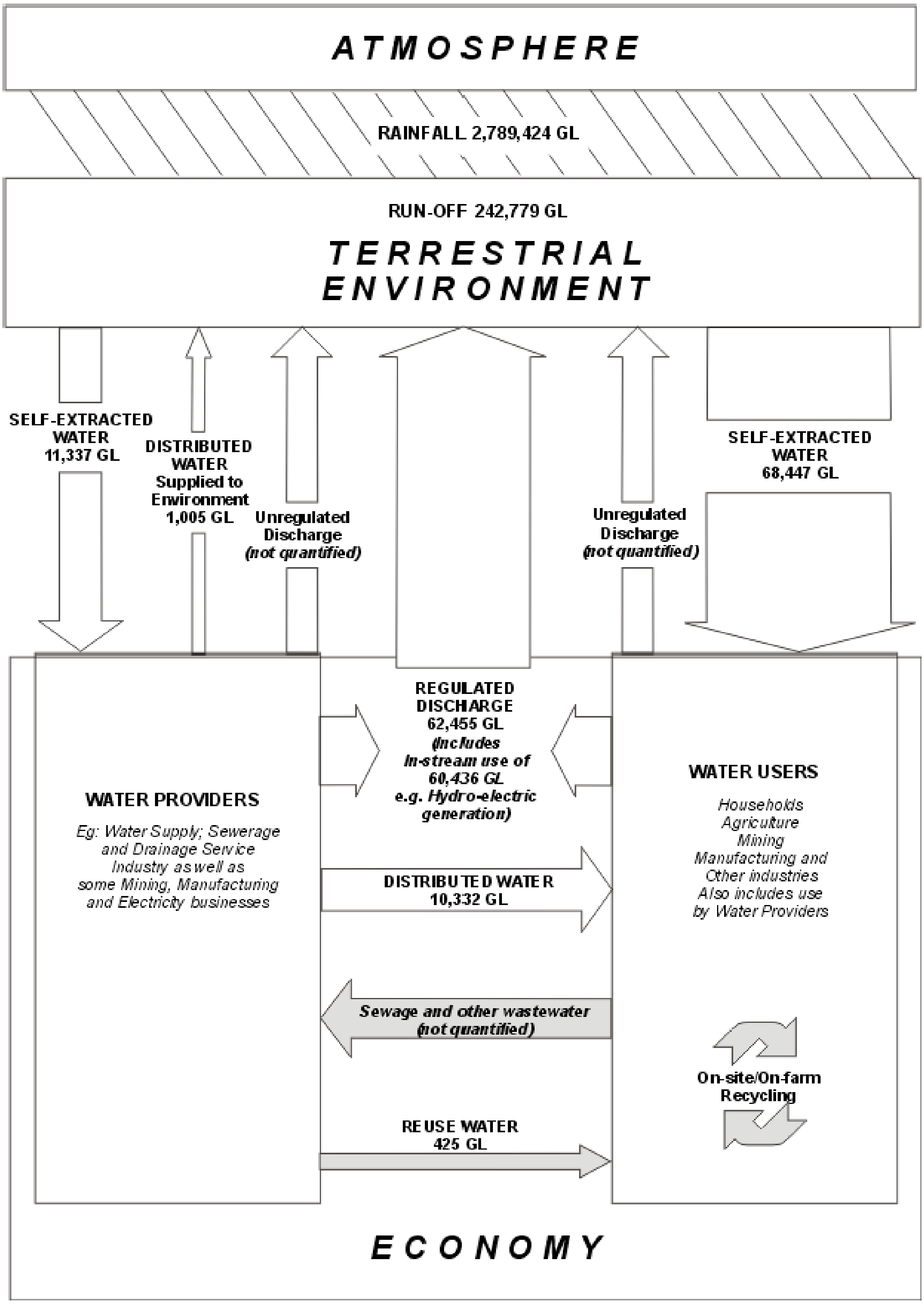


Figure 2.2. Water supply and use in the Australian economy, 2004-2005 (Source: ABS, 2005).

2.2.4 Trends and Characteristics of Water Consumption in Australia

Globally, freshwater consumption is primarily dominated by agriculture, which uses approximately 70% of supplies to irrigate crops, contributing to 45% of the world's food provision. In contrast, the domestic and industrial sectors consume about 10% and 20%, respectively (Koech & Langat, 2018; Boretti & Rosa, 2019). Within Australia, similar patterns are observed, with the agricultural sector accounting for an average of 59% of total water consumption, a statistic depicted in Figure 2.3. This figure charts sector-specific water usage over 11 water years, demonstrating significant variability. Consumption reached its zenith in the 2000-01 period at roughly 24,500 GL, with notable reductions in 2004-05 and 2008-09 corresponding to periods of drought, and a subsequent increase in 2011-2012. Figure 2.3 extends this analysis to 2017, highlighting the trends and fluctuations in water usage both in total and within specific sectors, such as agriculture, forestry, fishing, mining, manufacturing, electricity and gas, water supply, and households. Agriculture consistently emerges as the predominant consumer, followed by the water supply and household sectors. The graph reveals shifts in consumption over time, reflecting the interplay of industrial evolution, policy reforms, and climatic variations on Australia's water resource management.

The pressing controversies surrounding water revolve around its scarcity and the competition between sectors (Arbués et al., 2003; du Plessis, 2019). Water's inclusion in the policy agenda is driven by concerns over scarcity and access inequalities exacerbated by population growth and climate change. Traditional economic policies face challenges, highlighting the necessity of coordinated management across all sectors to ensure sustainable water resource use (Garrick et al., 2020; Lake and Bond, 2007). The growing water demands of the agricultural, industrial, and urban sectors pose risks to freshwater ecosystems, pointing to the need for balancing these demands with ecological sustainability (Campbell et al., 2017; FAO, 2019; Lake and Bond, 2007).

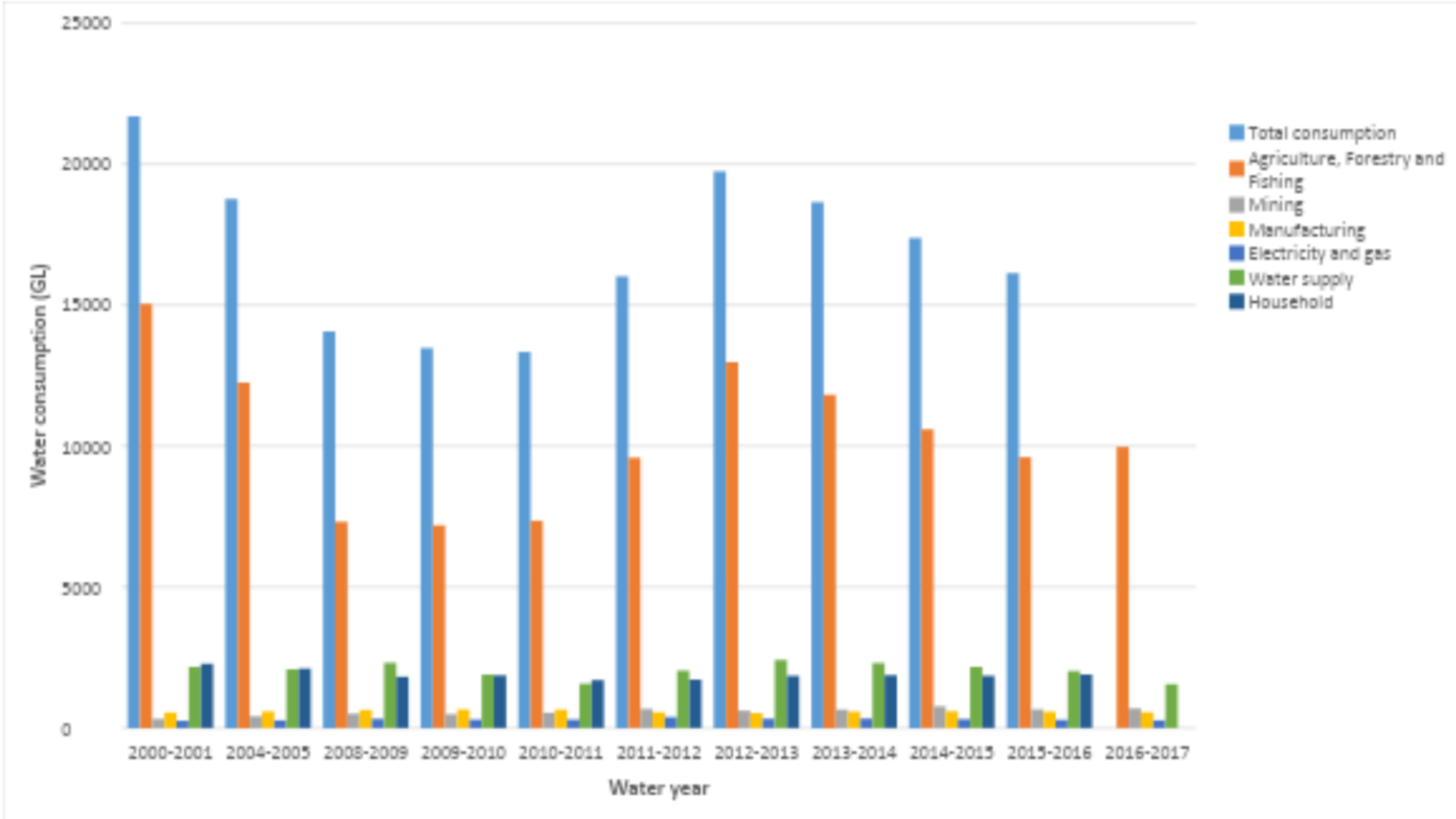


Figure 2.3. Water consumption by different sectors of the economy over a span of six water years (Source: ABS, 2020b).

2.2.5 Dynamics of Water Demand Among Competing User Sectors

In many areas, water has become the root of increasing controversy considering supplies failed to meet the demand, and conflicts over this resource always involve competition among alternative uses (Arbués et al., 2003; du Plessis, 2019). Water is rising on the policy agenda as population growth and climate change intensify scarcity, shocks, and access inequalities. Conventional economic policy recommendations—privatization, pricing, and property rights—have struggled due to a failure to adequately account for the politics of water and the associated distributional conflicts (Garrick et al., 2020). As Lake and Bond (2007) stated, to achieve ecologically sustainable management of water resources, it will be necessary for management to be coordinated across all sectors and possible uses, from the capture of water to its ultimate disposal. Demands for water resources have been explored in a different context. It has been reported that agricultural, industrial, and urban sectors' growing demand for water are ecologically unsustainable and are considered to be the great contributors to the serious damage of most freshwater ecosystems (Campbell et al., 2017; FAO, 2019; Lake and Bond, 2007).

This section presents and discusses various water user sectors and the determinants of water demand for each sector.

2.2.5.1 Residential Sector

In 2014, it was estimated that close to 3.9 billion people lived in cities (Arfanuzzaman & Atiq Rahman, 2017). By 2050, two-thirds of the entire population is projected to be living in cities, generating an additional 80% water demand (Flörke et al., 2018). Water demand management, ensuring minimum water for daily consumption, water resource planning, and groundwater depletion are common concerns faced by rapidly urbanized mega-cities around the world. The challenge to address and mitigate such primary water problems is much higher in developing countries (Arfanuzzaman & Atiq Rahman, 2017).

Water demand has been extensively studied since the 1960s with emphasis on municipal and residential demand. Water management during extreme climate conditions such as drought will improve by understanding the factors affecting residential water demand (Ghimire et al., 2016). According to Liu et al. (2017), population increase, economic growth, and western lifestyles are the main factors why demand for water is continuously increasing. A case study by Jayarathna et al. (2017) found that residential water demand is determined by factors such as age, household size, income, average water price, and the presence of facilities such as dishwashers, pools, and toilets. Citizenship, whether born in Australia or otherwise, also plays a role. However, studies from the experiences of Australia during the Millennium Drought and the behavioral studies that were focused on customer engagement proved that social and behavioral factors can play a significant role in increasing public awareness of water scarcity when drought is brought to the forefront of the public agenda (Gonzales & Ajami, 2017). Sahin et al. (2017) elaborated on sustainable and responsive water management policies that are essential to provide high-quality and reasonably-priced drinking water to consumers, while simultaneously ensuring a profit for the water utility. Although residential use of water is relatively small in comparison to other users, it has become imperative to ascertain its adequacy for human use (Maduku, 2020).

2.2.5.2 Irrigated Agriculture

Water shortage has become a serious problem for the sustainable development of irrigated agriculture in arid regions. In these areas, the scale and planting structure of agriculture suitable for local water resources are particularly important. Irrigation water demand is a crucial indicator of water requirement in irrigation districts (Jingsi Li et al., 2020). In arid regions like Australia, there are policies to estimate the joint effects on agricultural water demand. This is critical to effectively guide irrigation districts, manage water resources, and plan agricultural production (Grafton & Wheeler, 2018; A. Turner et al., 2016). Irrigated agriculture accounts for 75% of 24,000 GL (Grafton & Wheeler, 2018). Two-thirds of irrigation occurs in the Murray-Darling Basin (MDB) (Grafton, 2017), and about 2 million of the 106 million hectares of agricultural land in the Basin are irrigated (Koech & Langat, 2018). Major users of irrigated water include cotton, hay and silage production, perennial and annual horticultural crops, and rice (Mallawaarachchi et al., 2020).

Irrigation technology and management have played a great role in addressing issues of both supply and demand (Mallawaarachchi et al., 2020). In MDB, less water could be available for use in the future because of a return of some environmental values and because of lower river flows as a result of climate change, bushfires, and changing land use (Hart et al., 2021). River flows in the Basin are projected to decline by 11% (2,500 GL/year) under a mid-range projection of climate change by 2030, with further reductions in later decades or under conditions of more severe climate change (Kirby, 2011).

2.2.5.3 Water Conservation Efforts

Mandatory water restrictions have been implemented in some parts of Australia in response to drought conditions. For instance, in 2002, water authorities in Melbourne were forced to impose voluntary per capita water use targets as part of strenuous water restrictions after 20 years of unrestricted water supply (Khastagir & Jayasuriya, 2010). This restriction was implemented while Melbourne was experiencing severe drought and having its 12th consecutive below-average rainfall (Khastagir & Jayasuriya, 2010). During the Millennium Drought, water restrictions were in place in most capital cities and many regional towns all over Australia. However, most of these restrictions were not applied for several decades (Turner et al., 2016).

Currently, to promote efficient use of water and to reduce its demand, a range of permanent water-saving measures were adopted and have since remained in place. Among these measures are improved water use efficiency, new supplies, and streamlined institutional arrangements (State of Queensland, 2010). For instance, the government further stretched the target of reducing at least 15% per capita consumption in Melbourne by 2010 to 25% and 30% in 2015 until 2020, respectively (Khastagir & Jayasuriya, 2010).

2.2.5.4 Water Resources Management Strategies

MDB supports around 90% of Australia's total irrigated area and contributes almost 40% to the country’s national gross value of agricultural production (Grafton & Wheeler, 2018). Often referred to as Australia’s food basket, MDB is the source of tangible materials for most of the economic activity across and outside the region. MDB predominantly supports dryland sheep and cattle production, dairy, crops production such as cereals (wheat, barley, and rice), oilseed, cotton and a variety of horticultural crops (CSIRO, 2008a; Grafton & Wheeler, 2018; Hart et al., 2021; T. D. Pearce et al., 2018).

MDB is managed by the MDBA under four priorities: tackling climate change, supporting healthy rivers, using water wisely, and securing the region's water supply. Initiatives in the MDB since 1994 are summarized in Table 2.3.

Table 2.3. Water Management Initiatives in the Murray-Darling Basin

Year	Initiatives
1994	The Council of Australian Governments (COAG) developed a nationwide reform framework to improve water management. Changes included a reduction in price subsidies and the separation of the regulatory and supply functions of water management agencies.
1995	A cap on surface water extractions was established. The cap limited entitlement holders' access to water, forcing them to meet any increases in demand through trade in water entitlements.
1990s	Interstate water trading commenced. A significant increase in the volume of trading occurred after the introduction of the cap because there was little incentive to trade prior to the cap. Carryover, capacity sharing, and continuous accounting started to be implemented at pilot sites. Carryover provides farmers with flexibility in managing water supply between seasons. Capacity sharing is a system of property rights to water from shared storages. Continuous accounting is a form of carryover where users' accounts are updated on a frequent time scale.
2000	The first water account was published. This was the first time that there was comprehensive data on water supply and use in Australia. Water accounting has increased the precision of the identification of where, when, and how much water is available or lost.
2001	The National Action Plan for Salinity and Water Quality was funded to further implement the MDB Salinity and Drainage Strategy (1989). A number of salt interception schemes were put in place to pump out saline water and evaporate it, and also catchment strategies to change land use to reduce salinity.

2002	The Living Murray initiative was established to address the declining health of the Murray-Darling River system. The initiative's first step focused on recovering 500 gigalitres of water from the river Murray specifically for improving the environment at six iconic sites from 2004–2009.
2004	The National Water Initiative was built on the earlier COAG reforms in expanding the use of the water market as the key mechanism for handling re-allocation of water between consumptive users, and in defining a system of water planning and access entitlements to establish sustainable levels of use and allocate the resource for the environment.
2006/ 2007	The CSIRO was commissioned by the Prime Minister and MDB state Premiers to report on sustainable yields of surface and groundwater systems of 18 regions within the Basin. Prime Minister Howard proposed a $12.9 billion National Plan for Water Security (10-point plan) to improve water efficiency and address over-allocation of water by modernizing irrigation infrastructure in rural Australia.
2007	The Prime Minister announced a $10 billion plan to reform rural water management (Connel, 2007). Australian Water Act 2007, as amended, makes provision for the management of water resources of the MDB and is an amendment to the previous MDB Act. It includes the MDB Plan; water charging, water market, and water trading rules; environmental water; and new investments in water information.
2008	The Murray Darling Basin Authority (MDBA) was formed. MDBA is an Australian Government statutory agency responsible for planning the integrated management of the water resources of the Murray-Darling Basin. The Rudd Government adopted, in practice, the National Plan for Water Security Program, seeking to purchase $3.1 billion worth of water to protect or restore environmental assets; the $5.8 billion Sustainable Rural Water Use and Infrastructure program to save water by upgrading outdated irrigation systems; the $450 million Improving Water Information Program to improve the accuracy of monitoring, assessing, and forecasting water resources.
2009/ 2010	In preparation for the first MDBA plan, the Murray Darling Basin Authority, directly arising from the Water Act (2007), issued its Guide to the Proposed Basin Plan (MDBA, 2010) in October 2010. The proposed plan aims to reduce volumes of water that can be taken for consumptive use (expressed as long-term average 'sustainable diversion limits') for both surface water and groundwater. The reduction is estimated to bring about specified improvements to ecosystems. The Basin Plan (a legislative instrument) is scheduled to be delivered in 2011 following widespread consultations.

	However, current proposals to significantly reduce water available for irrigation have faced strong opposition from basin communities and are currently undergoing discussions and negotiations.

Based on (Wei et al., 2011).

2.3 Factors Affecting Water Resources

2.3.1 Drought

Vulnerability to drought has increased globally. Australia, being a dryland continent and one of the driest in the world, is at high risk of such a phenomenon. In all regions, droughts have been considered a normal part of climate variability. They can have severe impacts on natural resources, economic and social activities, damage biodiversity, and threaten human health. Plans need to be in place for timely and systematic action when there is a prolonged water shortage (Berbel & Esteban, 2019; Y. Yang et al., 2017). Various efforts have been made to fully understand drought. Prediction of drought was first attempted in 1967 (Yevjevich, 1969). Şen (1976, 1977) introduced the use of run theory in drought forecasting. The occurrence of drought events was modeled using renewal processes (Loaiciga & Leipnik, 1996). In characterizing the stochastic behavior of drought, the Palmer drought severity index (PDSI) was used in a non-homogeneous Markov Chain model (Lohani & Loganathan, 1997). The probability of drought occurrence was estimated using low-order discrete autoregressive moving average models (Chung & Salas, 2000). Furthermore, to forecast the standardized precipitation index (SPI), an applied seasonal autoregressive integrated moving average model was also used (Mishra and Desai, 2005). Today, among developed nations, the United States has the most developed and sophisticated drought monitoring system worldwide, while Australia is the sole country with a risk management-based national drought policy (Botterill & Hayes, 2012; Turner et al., 2016).

In Australia, since the arrival of Europeans, drought was considered an irregularity in climate and treated as one of the natural disasters in its onset. Severe droughts were experienced in Australia as early as the 1840s. There was the Federation Drought (1897–1903), 1911–1916 Drought, 1925–1929 Drought, World War II

Drought (1937–1945), and Millennium Drought (2002–2010) (Botterill, 2005; Deo et al., 2017). From 1997 to 2009, large areas of southern Australia, particularly the southern MDB, Victoria, southwest Australia, and southeast Queensland, experienced a prolonged drought, often referred to as the Millennium Drought or "Big Dry" (Wei et al., 2011; Y. Yang et al., 2017). The government considered drought the same way it was recognized by the Europeans. In fact, in the 1980s, the government treated drought similar to cyclones, earthquakes, or floods, as evidenced in their response through Commonwealth-State natural disaster relief arrangements (Y. Yang et al., 2017). Though considered a natural hazard, it differs in several ways as it has a slow onset, evolves over months or years, and could affect a large spatial region (Berbel & Esteban, 2019; Modarres, 2007; Wilhite et al., 2000). However, during the late 1980s, drought was removed from the national disaster relief arrangements and scientifically questioned based on its characteristic being an unmanageable natural disaster (Kiem, 2013). Subsequently, a collaboration between State and Commonwealth Governments ensued that led to the creation of the National Drought Policy (NDP) in 1992.

Drought has a substantial impact on economic, environmental, and social aspects (Turner et al., 2016). For instance, during the Millennium Drought in 2006-2007, farm gross cash income for irrigated broadacre farms averaged around $62,690, with an average farm business loss of around $36,390. On the other hand, farm cash income for irrigated dairy farms averaged around $33,640 in 2006-2007, with an average farm business loss of around $55,170 (Ashton et al., 2009). Milk production by the dairy industry of northern Victoria was low when water allocations were very low during 1996-1997 and 2008-2009; rice production decreased from 1.6 million tonnes in 2000 to 18,000 tonnes in 2008 (Wei et al., 2011).

Aside from drought, there are issues associated with the present pressing problem of limited water resources. Among them are growing population and land-use change, lack of commitment to water and poverty, targeted investment, insufficient human capacity, ineffective institutions, and poor governance. Clear, credible communication about the drought situation and response is paramount to public participation and support. Hence, good data and robust monitoring and evaluation are critical (Maduku, 2020; Turner et al., 2016). Practical drought hazard mapping remains challenging due to the possible exclusion of the most pertinent drought drivers and the use of inadequate predictive models that cannot adequately describe drought (Rahmati et al., 2020).

2.3.2 Land Use Change

The alteration of natural land cover due to human land uses is a major element of environmental change (Findell et al., 2017; Riebsame et al., 1994; Schneider & Pontius, 2001). Human activities and natural processes that drive changes in land use and land cover can have profound biophysical, ecological, economic, political, and social consequences (Riebsame et al., 1994; Vitousek et al., 1997). LULC change intensely affects the configuration and operation of ecosystems (Shiferaw et al., 2019; Vitousek et al., 1997). For instance, land conversion according to Hopkinson & Vallino (1995), is the most important factor influencing both water quantity and quality. Moreover, Meyer & Turner (1992) reported that land cover changes like deforestation affected water quantity and flow while irrigation, the largest element of global withdrawal from the hydrologic cycle, deplete downstream rivers and water bodies.

LULC changes have become a subject of various global and local studies (Aldwaik & Pontius, 2012) in relation to a variety of fields. Impacts of LULC change on the atmospheric component of the hydrologic cycle (regional and global climate) are increasingly recognized (Yang et al., 2017). Similarly, there have been a number of earlier papers designed to assess the impacts of land use on the subsurface and surface components of the hydrologic cycle. These include impacts of land use on stream flow (Cho et al., 2009); groundwater levels and recharge (Cho et al., 2009; Harbor, 1994; Huang et al., 2018; Scanlon et al., 2005), wetland hydrology (Giri et al., 2018; Huang et al., 2018), and surface runoff (Harbor, 1994; Wang et al., 2017). Moreover, the relationship between land use change and population density by Shoshany & Goldshleger (2012) has been considered in previous studies. However, impacts of land use change on the volume of water usage specifically those from surface water are less well recognized. It is therefore necessary to understand how land use change affects the amount of water usage more specifically in the future for ideal management of both land and surface water (Gashaw et al., 2018; Owuor et al., 2016).

2.3.3 Climate Change

Pre-industrial levels of global warming ranged between 0.8 °C to 1.2 °C. It is estimated that anthropogenic activities have caused an approximate 1 °C increase. In 2030 and 2052, global warming is predicted to reach 1.5 °C if the current increase rate will not be changed (IPCC, 2018). Global warming of 1.5 °C is projected to increase the amount of damage to many ecosystems, such as reducing the productivity of fisheries and aquaculture, as well as increasing climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth (IPCC, 2018). Half of the insect habitat might be lost at a 2 °C increase in temperature, which will affect the pollination of crops, while 99% of corals would be lost. However, there will be more than a 10% chance of surviving if the lower target of 1.5 °C is reached. A half-degree extra warming will lead to a 10 cm sea-level rise that would affect 10 million more people by 2100. Marine fisheries would lose 3m tonnes at 2 °C because of elevated acidity and lower levels of oxygen (Hoegh-Guldberg et al., 2018). There is now strong evidence of global warming (IPCC, 2007; Rea et al., 2011). Global warming due to the enhanced greenhouse effect is likely to have significant implications for the hydrological cycle (Inglezakis et al., 2016; IPCC, 1996), which will amplify runoff in arid and semi-arid areas (Mehran et al., 2017; Sankarasubramanian et al., 2001; Wigley & Jones, 1985; Wu et al., 2020). The hydrological cycle will be intensified, and there will be more evaporation and more precipitation, which is unequally distributed around the globe (Arnell, 1999; Tabari, 2020). On the other hand, CSIRO (2012) reported that climate change projections show a wide range of possible and plausible impacts. Thus, there is a high degree of uncertainty about future rainfall and streamflow scenarios. For example, Arnell (2004) described that climate change increases water resources stresses and decreases runoff in some parts of the world, including the Mediterranean, in parts of Europe, central and southern America, and southern Africa.

The rate at which greenhouse gas emissions are rising is exceeding the worst-case scenario. Thus, for the last few years, the scientific consensus on prospects for global warming has become more cynical, and the latest projections of some reputable climate scientists' border on apocalyptic (Krugman, 2009). Recently, the British government's Chief Scientific Adviser John Beddington gave a terrifying speech where he said, "By 2030, the world will be facing a perfect storm of food, energy, and water shortages caused by population growth and exacerbated by climate change" (Perlmutter & Rothstein, 2010). This is parallel to what Rosegrant et al. (2002) reported that by 2025 demand for water by competing user sectors is projected to rise to about 50%. Moreover, it is estimated that out of a total population of 8 billion, around 5 billion will be living in countries experiencing water stress during that same year (Arnell, 1999). Furthermore, scientist James Lovelock predicts that by the end of the century, global warming will wipe out 80% of humankind.

Future scenarios using Global Climate Models (GCM) experiments indicate global warming of 1.4 to 5.8 °C by the year 2100, relative to 1990 (IPCC, 2001). This warming is likely to be associated with changes in weather patterns, sea-level rise, and impacts on ecosystems, agriculture, forests, fisheries, industries, settlements, energy, tourism, health, and water resources (Hoegh-Guldberg et al., 2018).

Recently, the IPCC Sixth Assessment Report incorporates new evidence from climate science. Based on the report, the global surface temperature in 2001-2020 was 0.9 °C, which was higher than the period from 1850-1900, and it is indisputable that humans contribute to the warming of the atmosphere, ocean, and land (IPCC, 2021). Further, it was reported that CO2, CH4, and N2O were higher in 2019 compared to their values 2 million years and 800,000 years ago (IPCC, 2021). In Australia, a warming between 0.4 and 0.7 °C has been experienced for almost six decades, with more rain in the northwest, less rain in the southern and eastern regions along with the increasing intensity of drought (Thom et al., 2010). This country also experienced increasing stresses on water supply and is expected to face more severe extreme events with more intense and frequent heat waves, fires, floods, and storm surges (Rahman & Zafarullah, 2020; Suppiah et al., 2007; Zeppel, 2011). For example, research conducted by the South Eastern Australian Climate Initiative (SEACI) showed that MDB, an agricultural crop-producing region, is not exempted from the effects of climate variability. This region had a 13% reduction in rainfall over the period of 1997-2006, and this led to a stream flow decrease of 44%, which is 3.4 times the percentage reduction in rainfall (CSIRO, 2010). This is similar to the report of ABS (2008) that the MDB in 2001-2002 had reduced rainfall in the basin which led to lower inflows to the river system. This reduction in rainfall and streamflow might continue in the future specifically in the southern parts of Australia. Chiew & Prosser (2011) reported that for the moderate climate change projected to occur by 2030, the worst consequences are likely to be more intense droughts and less frequent but more intense floods.

Table 2.4 reflects Australia's climate projections, which were derived by combining the output from global climate models developed specifically for Australia from around the world (Keenan & Cleugh, 2011). This table describes that in a projected moderate emission by 2030, the annual temperature of eight major cities in Australia will increase in a range of 0.6 to 1 °C based on the average annual temperature from 1971 to 2000 in which Brisbane and Darwin will have the highest temperature. For a low emission scenario by 2070, an increase of 1.1-1.6 °C is projected wherein Sydney and Brisbane will have the highest annual temperature. On the other hand, for a high emission scenario, the annual temperature of Darwin is projected to increase by 3.2 °C while other cities' temperature will increase in a range of 2.1-3.1 °C. Among these cities, Hobart is the sole city with a low temperature increase of 2.1°C.

The table also shows that for all scenarios, Darwin will experience the greatest number of days where the temperature will be over 35 °C specifically in a high emission scenario in which 62% of the days in the year 2070 are hot.

Annual rainfall in all major cities of Australia is projected to decrease in all scenarios. It is notable that among these cities, Brisbane's annual rainfall will be reduced significantly for 2030's mild emission and 2070's low emission. On the other hand, Perth's annual rainfall will be lessened significantly in the 2070 high emission scenario.

Table 2.4. Regional Climate Change Projections Under Low, Mild, and High Emission Scenarios for 2030 and 2070.

		Sydney	Melbourne	Brisbane	Adelaide	Perth	Cairns	Hobart	Darwin
Present Average (1971-2000)									
	Annual Temperature (ºC)	18.3	15.7	20.5	16.5	18.5	24.9	13	27.8
	No. of Days Over 35 (ºC)	3.5	9.1	1	17	28	3.8	1.4	11
	Annual Rainfall (mm)	1277	654	1192	463	747	2112	576	1847
2030 Average (Mild Emissions)									
	Annual Temperature (ºC)	19.2	16.6	21.5	17.4	19.3	25.8	13.6	28.8
	No. of Days Over 35 (ºC)	4.4	11.4	2	23	35	6.6	1.7	44
	Annual Rainfall (mm)	1238	628	1109	444	702	2112	571	1847
2070 Average (Low Emissions)									
	Annual Temperature (ºC)	19.9	17.1	22.1	18	19.9	26.4	14.1	29.5
	No. of Days Over 35 (ºC)	5.3	14	3	26	41	12	1.8	89
	Annual Rainfall (mm)	1225	615	1133	430	665	2091	559	1829
2070 Average (High Emissions)									
	Annual Temperature (ºC)	21.3	18.5	23.6	19.3	21.2	27.8	15.1	31
	No. of Days Over 35 (ºC)	8.2	20	7.6	35	54	44	2.4	227
	Annual Rainfall (mm)	1174	582	1085	403	605	2091	542	1829

Source: Whetton et al. in (Keenan & Cleugh, 2011) (eds)

CHAPTER 3

METHODOLOGY

3.1 Overview of the Study Area

Situated in the southeast of Queensland, the Toowoomba Region is approximately 100 kilometers west of Brisbane. This region has a land area of approximately 1,297,337 hectares with a population density of 0.12 persons per hectare. It is bounded in the north by Somerset, the Lockyer Valley Regions in the east, the Southern Downs and the Goondiwindi Regions in the south, and the Dalby region in the west (TRC, 2011). Figure 3.1 provides a detailed map of the Toowoomba Region, illustrating these geographical details and boundaries. Next to Canberra, Toowoomba is considered Australia’s second-largest inland city and is situated 700 meters above sea level (Peng, 2003).

Prior to the 1940s, Toowoomba's bulk water source was the underlying basalt aquifer, supplemented by the construction of three (3) dams: Cooby in the 1940s, Perseverance in the 1960s, and Cressbrook in the 1980s (Mead & Aravinthan, 2009), supporting the demand of more than 80,000 people. Over time, as the population continued to expand, bores were installed to support the dwindling surface water supply (Mead & Aravinthan, 2009).

In addition to the region, Toowoomba's bulk water supply serves surrounding towns, including Oakey, Jondaryan, Kingsthorpe, Westbrook, Highfields, and Goombungee. However, there are areas within the region that are not connected to the Toowoomba bulk water supply. These areas are referred to as Toowoomba Region’s suburbs for the purpose of this research. The Region’s suburbs include Clifton, Pittsworth, Millmerran, Greenmount, and Yarraman. These suburbs source their water underground, serviced by bores (personal interview with David Frizzel, Coordinator of Water Operations Toowoomba). Other water sources include small dams and weirs, such as Ted Pukallus weir for Yarraman, Goombungee Dam for Goombungee, and Condamine River for Cecil Plains.

Approximately 70% of the water supply for the region comes from dams (Hurlimann & Dolnicar, 2010), and around 30% is extracted from bores. Out of the 70% surface water supply, 60% comes from Lakes Perseverance and Cressbrook, while 30% comes from Cooby (personal interview with David Frizzel).

Figure 3.1. Map of Toowoomba Region.

3.2 Toowoomba Region's Climate and Climate Change Effects

Toowoomba's climate is classified as warm and temperate. The Toowoomba Region has experienced declining rainfall over the years. For the last 12 years from the period 2001 to 2012, the least amount of rainfall occurred in July with an average of 23 mm, while most of the precipitation falls in December with an average of 108 mm. The temperatures are highest on average in January, at around 23.3 degrees Celsius. July has the lowest average temperature of the year.

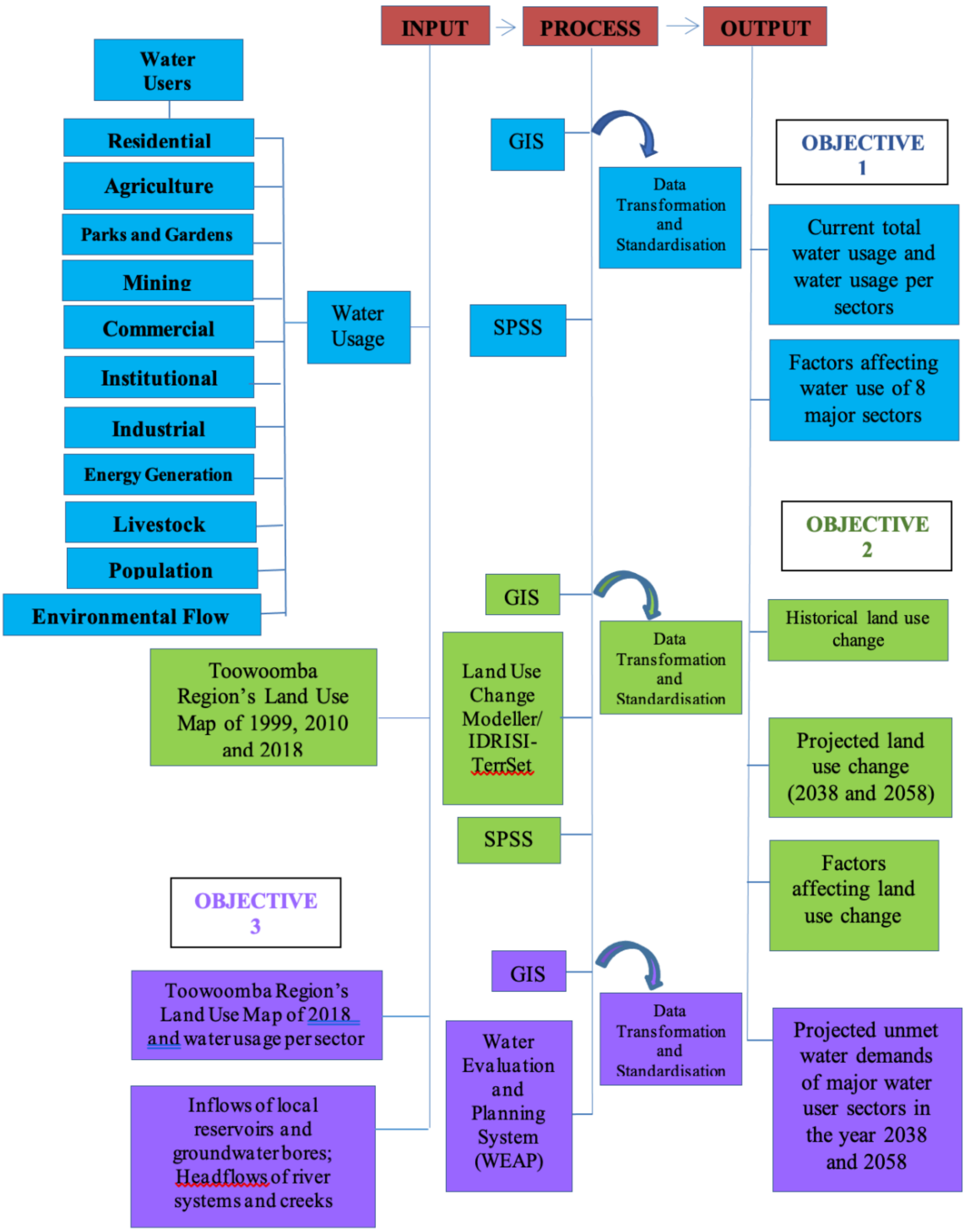
In the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), it was identified that South Eastern Queensland, to which Toowoomba belongs, was one of the most vulnerable areas to climate change in Australia. The report made it clear that existing severe weather events and natural hazards are impacts of climate change (IPCC, 2007). For instance, severe drought was experienced by SEQ from 2001 to 2009 (BOM, 2010), and the significant decline in rainfall frequency and volume led to restrictions on water consumption (TRC, 2010). Among the climate change-induced incidents occurring in the SEQ region were not just droughts but also floods.

Long ago, in February 1893, Toowoomba suffered the greatest flood where every bridge in the district was seriously damaged, the railways were destroyed, and cattle were carried down the stream (Trove, 1893). The town was again hit by floods in 1906 and 1915. After a century, in January 2011, an extreme flash flooding was experienced in Toowoomba due to an exceptional and tragic rain event over southeast Queensland. Records from the Bureau of Meteorology show that SEQ had the highest rainfall for the month of December 2010, aggravated by continuous rainfall in the first week of January that saturated the catchment area. This situation resulted in rapid creek rises and extreme flash flooding in Toowoomba and the Lockyer Valley.

3.3 Research Flowchart

The research process is broken down into three parts, corresponding to the three objectives of this study. Figure 3.2 summarizes the process flow of the study.

Figure 3.2. Input-Process-Output Model



For the 1st Objective, the water usage of the identified nine (9) major water user sectors was quantified. For water usage that is not readily available, Toowoomba Region's land use map was transformed, standardized, and analyzed using Geographic Information System (GIS). The socio-economic and climatic factors (independent variables) were identified. To determine the significant drivers of the water usage of each sector, the Statistical Package for the Social Sciences (SPSS) was used in the analysis.

For the 2nd Objective, three-time frames of Toowoomba Region's Land Use Maps (1999, 2010, and 2018) were analyzed using the Land Use Change Modeller of IDRISI-TerrSet Software. Geographic Information System and modeling techniques were employed in this chapter to determine the dynamics in Toowoomba Region Land Use Land Cover (LULC). Map images were used to analyze the LULC change, model the transitional potential, and project the future LULC pattern under three different scenarios. The future land use scenarios of Toowoomba Region were predicted for 2038 and 2058 using the historical land use data between 1999 and 2018. To carry out this analysis, the combination of Multi-Layer Perceptron and Markov Chain Analysis was applied.

The last part of the Input-Process-Output Model depicts the 3rd Objective. The TRC Land Use Map of 2018 was used to determine the area in hectares of the identified water user sectors. The water use coefficient per hectare of each water user was determined using existing literature, and the water usage was quantified. Inflows of local reservoirs and groundwater bores, as well as the headflows of river systems and creeks, were determined. These water demand and water supply data were used as input in the Water Evaluation and Planning System (WEAP) to determine the projected unmet water demands of major water user sectors in the year 2038 and 2058.

3.3.1 The Water Evaluation and Planning System (WEAP)

Water Evaluation and Planning System (WEAP) was developed by the Stockholm Environment Institute (SEI, 2015). It is an Integrated Watershed Resource Management model that focuses on water management and catchment hydrology. The model considers biological and physical factors that influence the river system and the socio-economic factors that affect the level of water demand of domestic, industries, and agriculture (Höllermann et al., 2010; Yates et al., 2005). The factors related to the biophysical system are climate, topography, land cover, surface water hydrology, groundwater hydrology, soils, water quality, and ecosystems. These factors shape the availability of water and its movement within the catchment. On the other hand, socio-economic factors, driven largely by human demand for water, dictate how available water is stored, allocated, and delivered within or across the catchment.

This model is applicable at various scales such as municipal and agricultural systems, single catchments, or complex transboundary river systems (Arranz, 2006; Droogers et al., 2012; Leong & Lai, 2017; Tena et al., 2019). It calculates a water balance for every node in the system. Water is allocated to meet in-stream and consumptive requirements, taking into account demand priorities, supply preferences, mass balance, and other constraints (Yates et al., 2005).

Studies that have applied WEAP in other contexts and river basins showed highly satisfactory performance and usability (Höllermann et al., 2010). Droogers et al. (2012) mentioned that this supply and demand model is very well-established, and the modeling framework is well-tested.

WEAP is also used for various scenario analyses, such as changes in land use and changing water demands of different water user sectors (Harma et al., 2012; Yates et al., 2005); climate change (Donley et al., 2012; Harma et al., 2012) and various management practices (SEI, 2015). It was also used to evaluate alternative water supply options (Alfarra et al., 2012) and to analyze the vulnerability of the future public water supply (Hall & Murphy, 2010). Moreover, the WEAP model has been successfully employed in Western Algeria to evaluate and analyze the existing balance and future water resources management scenarios by taking into account the various operating policies and factors that may affect demand for 2030 (Hamlat et al., 2013).

One of the unique characteristics of WEAP is its capability to integrate hydrologic processes into a water resources systems modeling framework such that climatic inputs can be used directly to run the model (Yates et al., 2009). Thus, the hydrologic implications of a climate change scenario as well as the water management ramification of this hydrologic change can be assessed within a single software package. Understanding its concept and applicability, the WEAP model will be used to achieve Objective 3 of this study. The 3rd objective of this study is to project the water demand in Toowoomba Region in relation to its land use under a range of climate change scenarios for 2038 and 2058. Water demand projection was set for 2038, considering that the Toowoomba Region set its Bold Ambitions in 2038 (TRC, 2018). Further, another projection was set for 2058, 20 years after the initial projection. This was based on existing literature that climate-related projections were being set on an average of 20 to 30 years.

CHAPTER 4

TOTAL WATER USAGE OF TOOWOOMBA REGION AND THE FACTORS AFFECTING WATER USE

4.1 Introduction

This chapter addresses the first objective, which is to identify the water user sectors within the Toowoomba Region and quantify their water usage. Likewise, it outlines the socio-economic and climatic factors that significantly affect the consumption of each sector. Outcomes in this chapter were subsequently utilized in the analysis of the two remaining technical chapters; thus, it is necessary to begin by first outlining current patterns of water use by sector within the Toowoomba Region and the availability of surface and groundwater in the context of the Toowoomba Region landscape.

The nine water user sectors considered in this chapter are residential, agriculture, mining, livestock, industrial, commercial, institutional, parks and gardens, and electricity generation.

This chapter is composed of five sections. The first section expands on Australia's water resources, highlighting this country's water use and water availability and addressing water-related studies on the country in general and on the Toowoomba Region in particular. The second section presents the methodology implemented in this research. The third section discusses the water usage of each sector per year within the Toowoomba Region. The socio-economic and climatic factors that significantly and insignificantly affect water usage were analyzed and discussed.

4.2 Toowoomba's Water Resources and Their Use

4.2.1 Toowoomba and Toowoomba Region's Suburbs Water Consumption per Sector

Based on the recommendation of the Local Government Review Commission Report of 2007 and an amendment to the Local Government Act 1993, Toowoomba Regional Council was created by the amalgamation of eight councils on 15 March 2008. These councils are Cambooya, Clifton, Crows Nests, Jondaryan, Millmerran, Pittsworth, Rosalie, and Toowoomba. Prior to the amalgamation, the Toowoomba City Council (TCC) had already been recording the water consumption per land use codes, while there is no record available for the other seven councils. Due to differences in the timeframe of the available datasets, there is a need to analyze the water consumption of the entire Toowoomba Region separately. The analysis covers the entire Toowoomba alone with a 10-year dataset available.

A ten-year (2004 to 2013) water consumption dataset per land use code collected from Toowoomba Regional Council was categorized into nine sectors. These are Agriculture, Residential, Commercial, Institutional, Industry, Livestock, Mining, Parks and Gardens, and Electricity Generation. The coverage of each sector is presented in the Appendices. Appendix Table A.1 defines what covers the Residential sector, while Appendix Table A.2 describes what belongs to the Commercial Sector. On the other hand, Appendix Tables A.3 and A.4 outline what consists of the Institution and Industrial sectors, respectively. Moreover, Appendix Tables A.5 and A.6 provide what includes the Livestock and Mining, respectively. Finally, Appendix Table A.7 identifies what covers the Parks and Gardens category.

4.2.2 Irrigated Cotton Water Consumption within Toowoomba Region

The Darling Downs Region is one of the most important agricultural assets of Queensland. A significant portion of the state's agricultural production comes from this region (Department of Agriculture, Water and the Environment, 2020). Darling Downs covers 77,389 km^2 and includes six local government areas, namely: Balonne Shire, Goondiwindi, Maranoa, Southern Downs, Western Downs, and Toowoomba Region.

These are managed under two Natural Resources Management bodies: the Border Rivers Maranoa-Balonne and the Condamine Catchment. Out of the total area of Darling Downs, 17% is Toowoomba Region, which is under the Condamine Catchment.

For the agriculture sector, this research focused on irrigated cotton plantations. Due to the unavailability of yearly irrigated cotton plantation datasets within the Toowoomba Region, three strategies were applied to successfully identify the extent of the area planted and subsequently quantify irrigated cotton water use. For all these three strategies explored, datasets on irrigated cotton available within Darling Downs Region play a vital role. These datasets provided the basis for all the assumptions.

- The first strategy utilized data from various sources, including the Australian Land Use Map of 2006, National Land Use Maps of 2005 and 2010, and TRC's Agriculture Sector Profile Report of 2013, to identify irrigated cotton areas in the Toowoomba Region. These datasets were compared to the actual irrigated cotton areas in Darling Downs, as reported annually in Cotton Yearbooks. However, inconsistencies were noted in the datasets, particularly for a specific year. Figure 4.1 illustrates the irrigated cotton area in the Toowoomba region and Darling Downs from 2004 to 2013, using data from the Australian Land Use Map, National Land Use Map, and TRC's Agriculture Sector Profile Report. It demonstrates the relative stability of irrigated cotton cultivation in the Toowoomba region, fluctuating between approximately 20,000 and 30,000 hectares over the past decade. In contrast, the Darling Downs experienced a significant decline, with irrigated cotton cultivation decreasing from over 50,000 hectares in 2004 to less than 10,000 hectares in 2013.

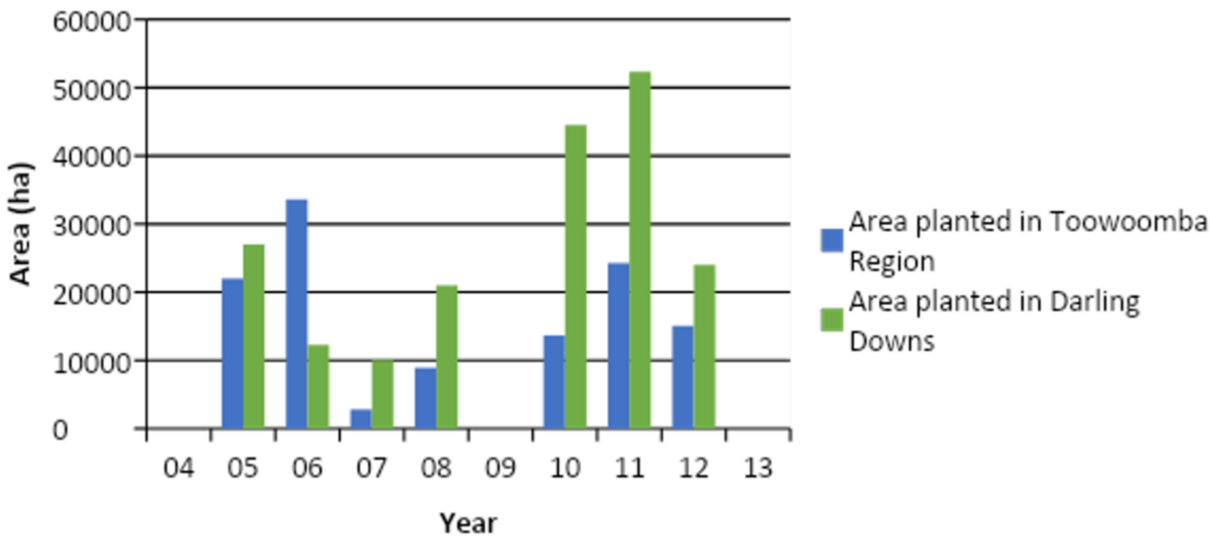


Figure 4.1. Irrigated cotton plantation planted in Toowoomba Region and Darling Downs. (This is based on the Australian Land Use Map, National Land Use Map, and TRC's Agriculture Sector Profile Report).

- The second strategy focused on the ratio of the area of the Darling Downs to the area of the Toowoomba Region. Darling Downs covers 77,389 km2, 17.16% of which is Toowoomba Region. In this strategy, it is assumed that the 17.16% of irrigated cotton planted in the Darling Downs, as reported in the Cotton Yearbook, is more or less equal to the plantation across the Toowoomba Region. Figure 4.2 illustrates the changing area of land dedicated to irrigated cotton cultivation in the Toowoomba region from 2004 to 2013. The graph reveals a fluctuating pattern with a noticeable decline until 2007, followed by a rise with a peak in 2012, maintaining a similar level in 2013. The data reflects a ratio of the area planted in the Darling Downs to the total Toowoomba region, suggesting a focus on comparative regional productivity. It is believed that through this strategy, a more or less realistic dataset will be captured to ensure that the area planted with cotton across the region will not be overestimated. Although this strategy is more reliable compared to the first method, a major downside is that the disparity between the estimated cotton planted specifically in 2011 and the actual area planted in the region for that same year, as reported in the TRC Agriculture Profile, is 37%. This outcome challenged an attempt at another strategy to be able to finally quantify the irrigated cotton areas planted within the region yearly from 2004 to 2013. The summary of this data is shown in Table 4.1.

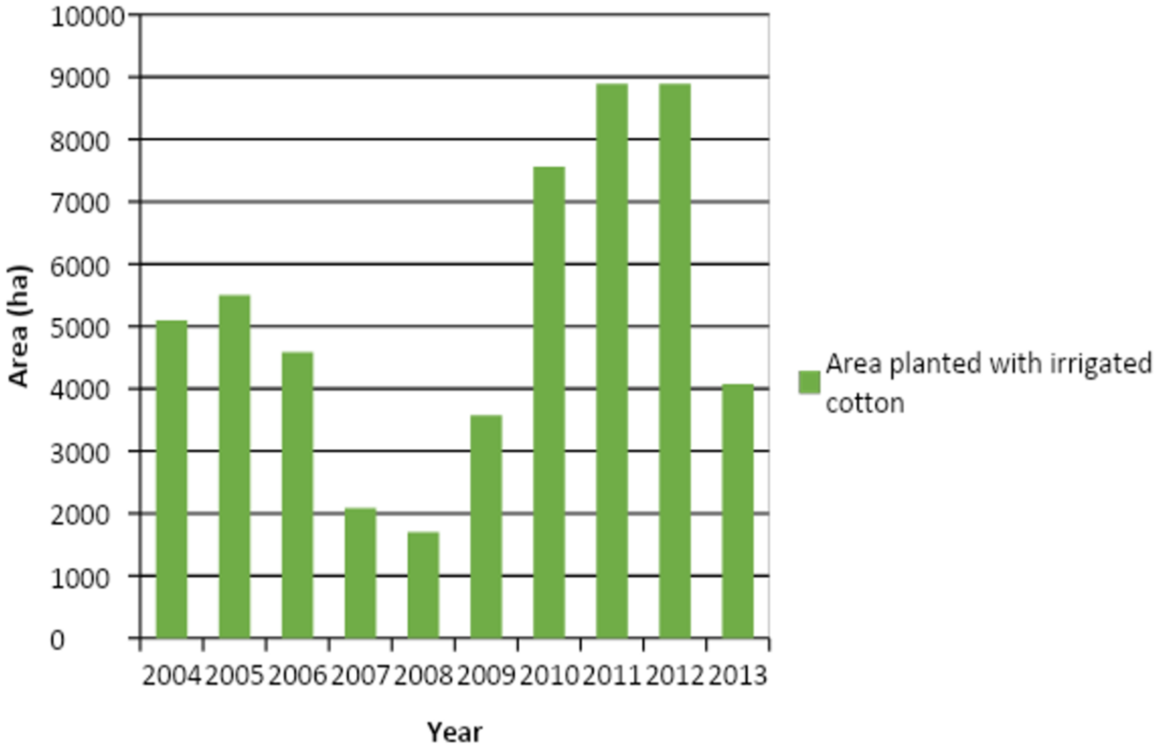


Figure 4.2. Irrigated cotton planted in Toowoomba Region. (This is based on the ratio of the area of irrigated cotton planted in Darling Downs to the total area of Toowoomba Region).

Table 4.1. Area of Irrigated Cotton Plantations in Darling Downs and Toowoomba Regions from Cotton Year 2003/2004 to 2012/2013.

Cotton Year	Area Planted (ha)	
	Darling Downs Region	Toowoomba Region
2003/2004	30,000	6,300
2004/2005	32,000	6,720
2005/2006	27,000	5,670
2006/2007	12,270	2,576
2007/2008	10,000	2,100
2008/2009	21,000	4,410
2009/2010	24,000	5,040
2010/2011	44,500	9,345
2011/2012	52,300	10,983
2012/2013	24,000	5,040

- The third strategy analyzed the 2006 Australian Land Use Maps (ALUM) for the Border Rivers Maranoa-Balonne and the Condamine Catchment, which together constitute the Darling Downs Region. Using ArcGIS, the area of irrigated cotton plantations was determined to be 209,192 hectares across the region. Further analysis of the Toowoomba Region land use codes map from the Toowoomba Regional Council-GIS Office identified irrigated cotton zones within Toowoomba, totaling 42,982.7 hectares. Figure 4.3 depicts these areas with irrigated cotton fields in yellow, set against the Toowoomba Region in pink, the Border River Maranoa-Balonne in red, and the Condamine Catchment in blue. The calculated ratio of irrigated cotton zones within the Toowoomba Region to the entire Darling Downs plantation area was found to be 21%. To assess the extent of the irrigated cotton plantation in the Toowoomba Region from 2004 to 2013, 21% of the annual plantation figures reported in the Cotton Yearbook were used, as shown in Table 4.1.

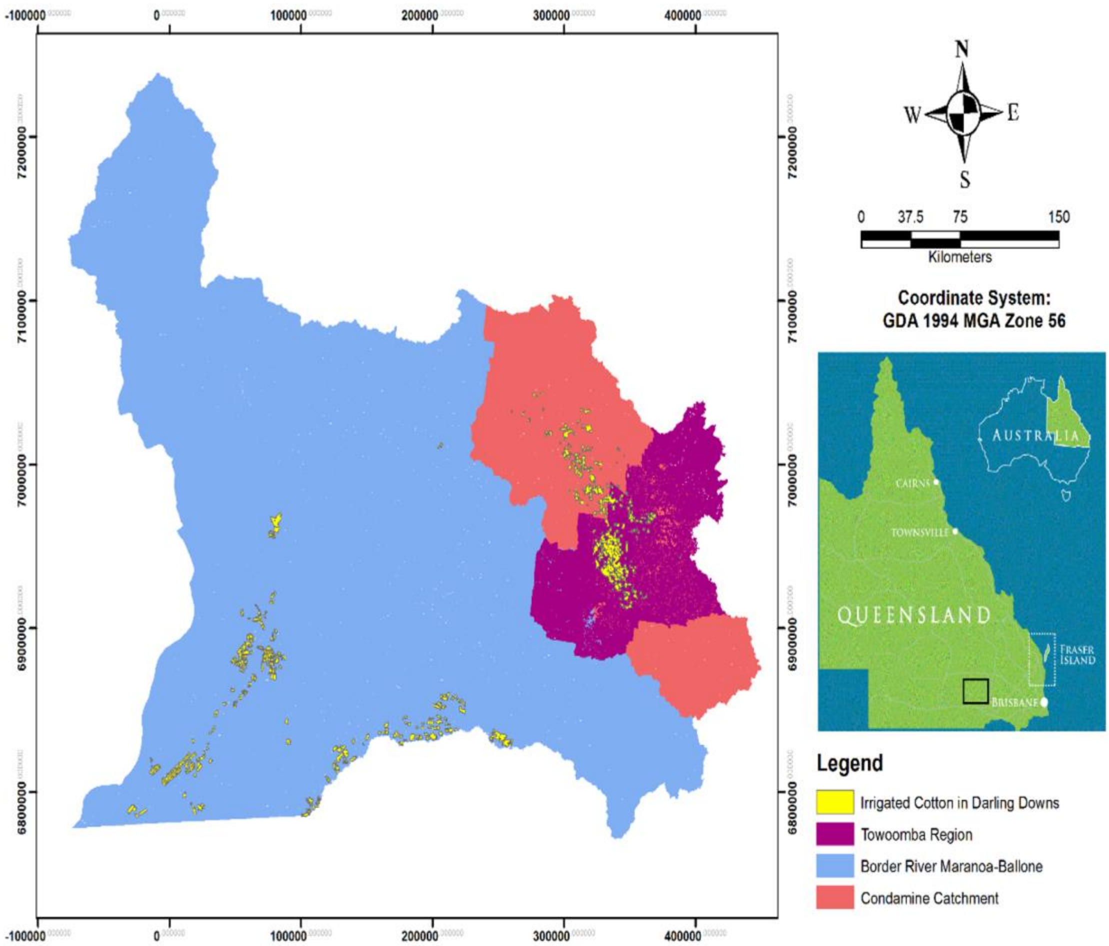


Figure 4.3. Irrigated cotton areas (yellow) in Darling Downs.

4.3 Per Capita Water Consumption

In Toowoomba City, not all people are connected to the Toowoomba Bulk Water Supply System. To determine how many people are supplied by this system, the number of water-metered connections was obtained from the TRC-Water Sector Office. From the data collected, it was assumed that one residential connection is equivalent to one household. A summary of the census provided in QuickStats of the Australian Bureau of Statistics (ABS) website was explored to define the average number of households in the city. Results of the 2001, 2006, and 2011 census revealed that the average number of households in Toowoomba City was 3. The average household is multiplied by the number of residential connections to quantify how many people are supplied by the Toowoomba Bulk Water Supply System.

The human population was included among the major users due to possible inconsistencies in residential water consumption. Residential water consumption is calculated on a per hectare/year basis, while population consumption is measured per person/year. Traditional Land Use Land Cover (LULC) datasets primarily focus on the physical characteristics of the land surface. Although these datasets may categorize areas as 'residential' based on built infrastructure, they do not directly measure the human population; hence, the author decided to include human population data.

It is important to note that the provided datasets from the Toowoomba Regional Council likely don't directly incorporate population data. However, the author's approach addresses this gap by employing complementary strategies cited above. To reinforce the independent population data, the author enhanced the analysis by including actual human population figures for Toowoomba, obtained from the latest population survey. This ensures that the analysis accurately reflects the actual human population size, separate from the 'residential' land use category. Furthermore, the author demonstrates foresight by incorporating population projections from the Australian Bureau of Statistics. This forward-looking perspective allows for insights into how future population changes might impact future water demand within Toowoomba, hence included in the analysis in Chapter 6.

Furthermore, environmental flow consumption is included as a sector of water use. Traditionally overlooked as a significant water user, environmental flow has recently been recognized for its critical role in sustaining freshwater ecosystems, prompting its inclusion in water management considerations (Arthington, 2019). Disrupting this vital flow can trigger a cascade of ecological consequences, as evidenced by research highlighting the potential for downstream biodiversity loss and habitat degradation (Hermoso, 2022; Brauman, 2019). Recognizing the inherent link between environmental flow and ecosystem health underscores the urgency of incorporating environmental water demand into allocation planning to ensure adequate reserves for Towoomba's freshwater ecosystems.

4.4 Data Collection

Samples of consumption datasets used in this particular study were obtained from Toowoomba Regional Council - Water and Waste Services Group through the assistance of Ms. Wendy Brunckhorst, Coordinator of Water and Waste Reporting. Surface water supply, groundwater supply, and dam levels at the beginning and at the end of the year were acquired from Mt. Kynoch Water Treatment Plant with the support of David Frizzel, Coordinator of Water Operations.

Water-related data, such as water price, water restrictions, water meter connections, and water access charge, were also obtained from the Water and Waste Services Group, while socio-economic data, such as population, number of households, and average annual income per household, were collected from ABS.

Moreover, the map of Toowoomba Region land use zones was requested from Toowoomba Regional Council's Spatial Services through the assistance of their GIS Team Leader, Joel Attwood. Australian Land Use Maps of the Border Rivers Maranoa-Balonne and the Condamine Catchment were downloaded from the Department of Agriculture, Forestry, and Fishery website.

Climatic data, such as rainfall and temperature data, were obtained from the Bureau of Meteorology website. For a detailed overview of the data requirements and the sources used in this study, refer to Table 4.2.

Table 4.2. Summary of data requirements and data sources.

Datasets	Description	Data Sources
Population		Queensland Statistics Office
Annual Individual Income		ABS
Sector's Water Consumption (residential, livestock, commercial, institutional, industrial, mining, parks and gardens, electricity generation)	**Toowoomba:** Annual Water Consumption of Each Sector from Water Year 2004-2013 **Toowoomba Region suburbs:** Annual Water Consumption of Each Sector from Water Year Water Year 2008-2013	Toowoomba Regional Council - Water and Waste Services Group/Toowoomba Service Centre
Border Rivers Maranoa-Balonne (ALUM)	Land Use Map of 2006	QGIS
Condamine Catchment Maps (ALUM)	Land Use Map of 2006	QGIS
Toowoomba Region Irrigated Cotton Zone	Map of Land Use Zones	Toowoomba Regional Council
Irrigated Cotton Areas	Darling Downs's cotton production estimates covering number of hectares, number of yields per hectare, and total number of bales.	Cotton Yearbook 2003/2004 to 2012/2013
Cotton Prices	Australian base price for raw cotton (Ac/kg) from Cotton Year 2003-04 to 2004-05.	ABARES
Water Use Coefficient/ha		ABS

Groundwater Water Supply	**Toowoomba:** Volume of groundwater pump per year and monthly average pumped per year from Toowoomba Bores from Water Year 2004-2013 **Toowoomba Region suburbs:** Annual volume of water pumped in Clifton, Millmerran, Brookstead, Greenmount, Cambooya, Valeview, Wyreema, Hodson, and Cecil Plains bores from Water Year 2008-2013.	Water Services - Mt Kynoch Water Treatment Plant
Surface Water Supply	**Toowoomba:** Monthly average and annual volume of water in Condamine River, Cooby, Cressbrook, and Perseverance.	Water Services - Mt Kynoch Water Treatment Plant
Dam Levels	Levels at the beginning and the end of year.	Water Services - Mt Kynoch Water Treatment Plant
Rainfall	Annual average rainfall reading from rain gauges of Crows Nest, Cambooya, Clifton Post Office, Jondaryan Post Office, Oakey Aero, Westbrook, Toowoomba, Goombungee Post Office, Greenmount Post Office, Pittsworth, Millmerran, and Cecil Plains Homestead.	BOM
Temperature	Annual mean maximum temperature records in Oakey Aero and Toowoomba Airport.	BOM

4.5 Data Analysis

Data analysis was meticulously conducted using the Statistical Package for the Social Sciences Statistics 22 (SPSS 22). The study focused on the annual consumption data of various sectors in Toowoomba and its suburbs, including residential, livestock, mining, commercial, industrial, institutional, parks and gardens, electricity generation, and irrigated cotton, treated as dependent variables.

A comprehensive range of independent variables was considered, encompassing climatic factors like average annual rainfall, summer rainfall, average annual maximum temperature, and summer temperature, as well as socio-economic factors such as population, average annual individual income, first and second-tier water pricing, water restriction policies, and access charges (annual and bi-annual). Additionally, water supply data (surface, groundwater, and treated water) were also examined.

The initial phase of the analysis employed Spearman’s correlation analysis, as delineated by Gogtay & Thatte (2017), to explore the relationships between the nine water user sectors and the independent variables. Subsequently, a regression analysis using the forward selection method in SPSS 22 was undertaken. This method, by sequentially adding variables based on their statistical significance, refined the model to identify the most significant predictors of water consumption for each sector.

4.6 Results and Discussions

The results are presented in three parts. The first part details the annual water consumption by sector. The second part examines the percentage change in Toowoomba's water consumption. The third part integrates the outcomes of the Spearman correlation analysis with the regression analysis, using the forward selection method. This method, as applied in SPSS 22, systematically built a model to identify key socio-economic and climatic variables impacting water use across sectors. The use of the forward selection method, consistent with the approach recommended by Gogtay and Thatte (2017), enhanced the robustness of our findings, isolating the most impactful variables and providing a comprehensive understanding of the determinants of water consumption in Toowoomba.

4.6.1 Annual Water Consumption in Toowoomba per Sector

Water consumption discussed in this section refers to all water used by different sectors in the Toowoomba Region. The eight (8) major water user sectors in Toowoomba from 2004-2013 were residential, livestock, mining, commercial, industrial, institutional, parks and gardens, and electricity generation. The large volume of water was mainly consumed by the residential sector from 2004-2013, followed by commercial, industrial, and institutional sectors. Consumption by all sectors spiked during the normal years (2004 and 2005) then sharply declined from 2006 to 2009 due to drought (Figure 4.4).

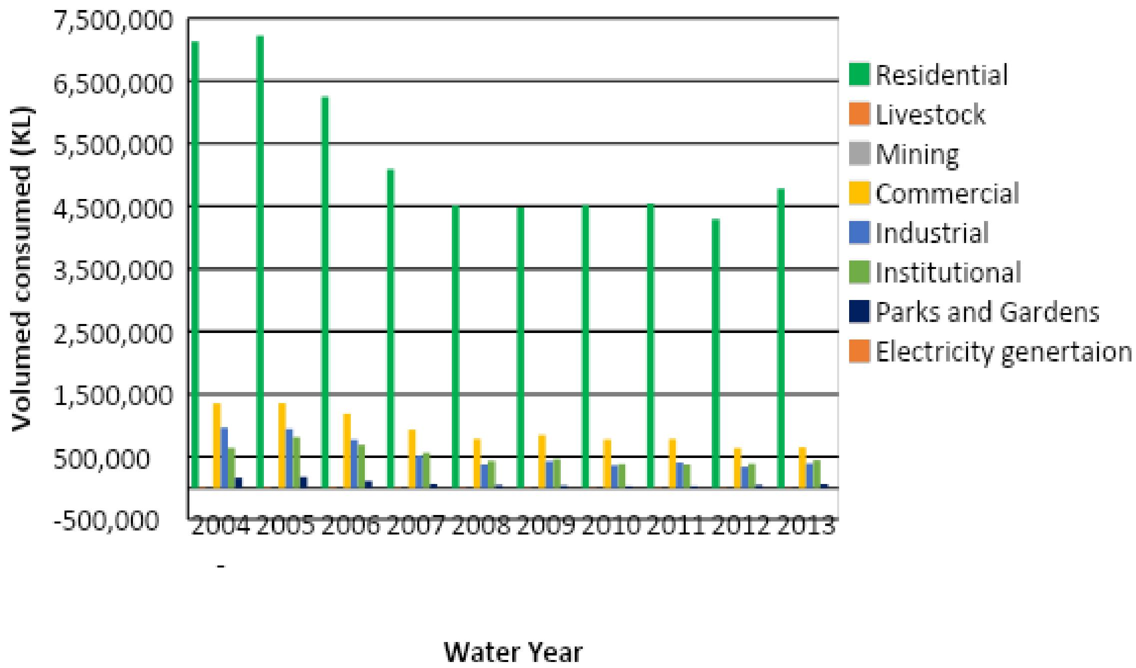


Figure 4.4. A 10-Year Summary of Toowoomba's Water Consumption in Kilolitres (2004-2013) Per Sector.

An analysis of average annual water demand in the Toowoomba Region, as illustrated in Figure 4.4, reveals that the residential, commercial, industrial, and institutional sectors are the major water consumers. These sectors consume 5.3 million kiloliters, 930 thousand kiloliters, 550 thousand kiloliters, and 519 thousand kiloliters of water per year, respectively. Following them, the parks and gardens, livestock, and electricity generation sectors have significantly lower demands, with annual water consumption of 76 thousand, 12 thousand, and 384 kiloliters, respectively.

Interestingly, there was a dramatic drop in water consumption across all sectors during the extremely dry years of 2006-2007. Residential consumption plummeted to 978,236 kL, while commercial, industrial, and institutional sectors also saw significant reductions, consuming 168,131 kL, 171,778 kL, and 124,217 kL, respectively. In contrast, during the extremely wet year of 2010-2011, there was only a slight increase in consumption across most sectors. Residential usage rose to 21,374 kL, and commercial and institutional sectors experienced modest increases to 6,512 kL and 6,127 kL, respectively. Notably, the industrial sector was an exception during this period, showing a considerable increase in water consumption of 47,830 kL.

Generally, the increasing trend of water consumption per sector in Toowoomba cannot be compared with other water consumption studies because of dissimilarities in the categorization of the sectors. For instance, Saidan (2020) quantified the industrial water demand by considering annual production capacities. Annual production capacities are considered as virtual water use, which is one of the limitations of this study. Furthermore, the ABS, in their Water Account reports, classified the sectors as agriculture, household, water supply, other industries, manufacturing, mining, electricity and gas, forestry, and fishing.

On the other hand, parallel to Toowoomba's water consumption, the ABS report on Australia's water use revealed that water consumption significantly decreased from water years 2004-05 to 2008-09.

This decrease in water demand can be associated with the water restrictions implemented in various parts of Australia in response to drought. For instance, Stage One water restriction was implemented in Melbourne from 2002 to July 2003 due to the depletion of water stored brought about by drought (Edwards, 2008). In this restriction stage, the use of water outside the house for watering gardens and lawns (using a hose), and washing paths, patios, and cars were banned. This was subsequently followed by the implementation of Stage Two water restriction from August 2003 to February 2005, in which watering of lawns, even by using a manual watering system and water toys using water from a hose, were also banned. From March 2005, permanent water-saving rules replaced the Stage Two restriction. From September 2006 to September 2010, water restrictions kept on changing from Stage Two and Stage Three depending on the amount of water being held in Melbourne's water storage (Edwards, 2008).

In the case of Toowoomba, the Regional Council started to impose residential water restrictions as early as September 1993 due to the weather condition, also in support of the "Waterwise Education" program, which aims to educate consumers about the importance of water conservation (Mead & Aravinthan, 2009). From September 1993 to July 2003, Toowoomba residents were restricted in the use of sprinklers. The council set the days and times the sprinklers were allowed to be used.

In the preceding decade, the Toowoomba City Council faced several water management challenges, including operational issues at Mt. Kynoch, algal blooms in Lake Cressbrook, and extreme heat events. These issues necessitated policy adjustments, leading to sprinkler use restrictions while allowing handheld hoses and micro-spray systems. In August 2003, the Council implemented a formal water restrictions policy based on dam storage levels, detailed in Table 4.3.

Table 4.3 presents the Toowoomba Bulk Water Supply Area Water Restriction Framework from 2010. It specifies residential water use targets: 140 liters per person per day under Extreme Level, 170 liters at High Level, and 200 liters for both Medium Level and Permanent Conservation. The framework sets thresholds for easing or tightening restrictions in response to reservoir levels, with less than 15% increase allowing easing at Extreme Level, and over 30% decrease necessitating tightening at Permanent Conservation. This policy is instrumental for sustainable water management in varying conditions.

Table 4.3. Toowoomba Bulk Water Supply Area Water Restriction Framework (2010).

Restriction Level	Extreme Level	High level	Medium Level	Permanent Conservation
Residential Use Target (l/p/day)	140	170	200	200
Ease Restrictions: Levels Rising	< 15%	15%	25%	35%
Tighten Restrictions: Levels Falling	10%	20%	30%	> 30%

A year after the restriction policy was implemented, Toowoomba residents were placed under Level 3 water restriction, and it was subsequently raised to Level 4 the following year due to the low dam capacity of 40% and 30%, respectively. Figure 4.4 reveals that between 2004 and 2005, though residential use was limited from 190 l/p/d to 210 l/p/d, there were no changes in water consumption. However, when the dam capacity reached below 20%, and Level 5 restriction was in place from September 2006 to November 2009, residential water use shrank significantly. Every year, consumption lessened by 978,236 kL, 1,156,490 kL, and 578,727 kL. Before the end of 2009, the new water restrictions framework based on the Queensland Water Commission (QWC) was introduced (Table 4.4), and the Wivenhoe Pipeline was operational.

Table 4.4 presents the water restrictions framework introduced for the Toowoomba Bulk Water Supply (TBS) by the Queensland Water Commission (QWC) before the end of 2009. This framework, based on the supply from dams and basalt bores, played a crucial role in managing water resources. The table outlines the specific restriction regime for TBS, coinciding with the operational commencement of the Wivenhoe Pipeline.

Table 4.4. Restriction regime for Toowoomba Bulk Water Supply (TBS) based on the supply from dams and basalt bores.

Restriction Level	Level 5	Level 4	Level 3	Level 2	Level 1
Residential Use: Target (l/p/day)	150	190	210	240	280
Ease Restrictions: Rising Dam Level	< 30%	30%	40%	60%	90%
Tighten Restriction: Decreasing Dam Level	20%	30%	50%	80%	> 80%

At the onset of 2010, the dam capacity reached 7.8%, and the Toowoomba Bulk moved to Extreme Level. However, it was moved to High Level in March and April of the same year. At the end of 2010, the dam level reached 35%, and the TBS was set down to Permanent Conservation.

From January 2011, the Perseverance, Cooby, and Cressbrook Dams were overflowing, and until 2013, dam levels remained above 90%. Table 4.4 shows that even after the drought period, water consumption remained low. Residents' consciousness of water conservation could be a possible explanation for this trend.

4.6.2 Water Consumption Trends and 10-Year Population Overview in Toowoomba

The table below (Table 4.5) shows the percent change in Toowoomba’s water consumption per sector from 2004-2013. This also covers a 10-year summary of Toowoomba’s population. It can be noted that Toowoomba’s population is slightly increasing, at about 1.1%, from 2004-2013. However, despite the slight increase, there is a downward trend in water consumption usage in residential areas, which is about -4.3%. Statistically, however, these two variables had a very weak correlation at -0.261 (Table 4.6). The decrease in water consumption in the residential area is largely attributed to the decreasing supply of surface water, as indicated by a high correlation coefficient of 0.721. The decreasing supply of surface water also affects the water consumption of these sectors: 1) Parks and gardens with the highest correlation coefficient of 0.927; the commercial sector at 0.903; and 3) the industrial sector at 0.867.

From 2004-2013, the mining sector also showed a remarkable decrease in water usage of almost 19%. This was followed by a significant decrease in water consumption by parks and gardens by almost 11%, industrial areas by 9.5%, and the commercial areas by 7.8 percent. The water price in Tier 1 and Tier 2 does not seem to significantly contribute to the reduction in water consumption—except for the livestock and electricity sectors, which showed a slight significant correlation with water price at 0.661 and 0.636, respectively.

Normally, rainfall is another strong variable for reduced water consumption. The lesser the rainfall, the lesser is the surface water supply; therefore, reduced water consumption. However, at a -1.4% reduction of average annual rainfall from 2004-2013, the sectors that have only been affected include institutions at -0.661.

Table 4.5. A 10-year summary of Toowoomba's population and water consumption in million litres from 2004-2013.

Year	**Population ('000)**	**Residential**	**Livestock**	**Mining**	**Commercial**	**Industrial**	**Institutional**	**Parks and Gardens**	**Electricity Generation**
2004	144.7	7,134	182.3	3210	1,352	963.186	640.147	162.997	459
2005	148.31	7,225	167.18	564	1,355	943.634	811.456	175.382	230
2006	151.3	6,247	153.9	399	1,187	771.856	687.239	113.352	113
2007	151.97	5,090	137.04	851	933	516.981	563.886	61.802	265
2008	152.93	4,512	125.42	985	784	377.422	433.572	44.413	291
2009	154.26	4,480	114.14	719	846	428.515	460.442	37.319	141
2010	154.92	4,522	103.47	222	776	361.964	383.202	28.713	916
2011	154.93	4,544	102.7	757	782	409.794	377.075	28.84	734
2012	157.02	4,293	91.65	399	638	338.044	387.411	45.389	519
2013	160.25	4,783	88.01	488	651	391.558	442.603	59.171	175
% Rate of Change in 10 years	**1.10%**	**-4.30%**	**-7.80%**	**-18.90%**	**-7.80%**	**-9.50%**	**-4.00%**	**-10.60%**	**1.10%**

4.6.3 Statistical Analysis on the Relationship Between Water User Sectors and Socio-Economic and Climatic Factors

In this research, the impact of several socio-economic and climatic determinants on the water consumption of residential, commercial, institutional, industrial, livestock, irrigated agriculture, mining, parks and gardens, and energy generation within the Toowoomba Region was statistically analyzed. Besides population, water price, water restrictions, access charge, and annual individual income, the effects of annual average rainfall, summer rainfall, average temperature, and December temperature were also considered. Additionally, the effects of surface water and groundwater supply, treated water supply, and dam levels at the beginning and end of the year were explored.

4.6.3.1 Correlation Analysis between Water User Sectors and Socio-Economic as well as Climatic Factors

The Spearman rank-order correlation, commonly known as Spearman's correlation, was used in this research to determine whether there is an association between the consumption of each water user sector and the socio-economic and climatic factors. Spearman calculates a coefficient, r_s or p. This is a measure of the strength and direction of the association between either two continuous variables, two ordinal variables, or one ordinal and one continuous variable. Correlation coefficients range from -1 to +1, where r = 0 indicates no significant relationship between the variables while a value approaching +/-1 denotes a strong relationship (Kerr et al., 2002). A positive and negative correlation indicates that the two variables covary in the same and opposite directions, respectively (Kerr et al., 2002).

Table 4.6 presents the correlation analysis of the water user sectors' consumption and the variables considered. The result of this analysis is discussed in two different categories. The first is focused on the relationship between variables, classified into positive and negative, while the second is the statistical significance. The guidelines set by Cohen (1988) were used in interpreting the magnitude of the correlation coefficient in this study. It was reported that Cohen's guidelines are the most widely known and more realistic in interpreting the magnitude of correlation coefficients (Hemphill, 2003). According to Cohen, correlation coefficients of 0.10, 0.30, and 0.50 are considered small (weak), medium (moderate), and large (strong) correlation, respectively.

Livestock consumption showed to be strongly and positively correlated with population, water price (1^{st} & 2^{nd} tier), annual average rainfall, summer rainfall, and access charge. There is also a strong positive correlation between livestock consumption and groundwater supply, while electricity generation was observed to have a strong and positive correlation with average annual individual income. On the other hand, commercial, industrial, institution, and parks & gardens consumption revealed a strong and positive correlation with average temperature, surface water supply, and treated water supply. However, only commercial parks and gardens had a strong positive correlation with water restriction. Moreover, residential consumption had a strong, positive correlation with surface water supply and treated water. Aside from livestock and electricity generation, industrial consumption also showed to be strongly and positively correlated with population. These results suggest a direct relationship between the sectors' water consumption and the socio-economic and climatic factors and vice versa, where an increase in one variable also causes an increase in another variable.

On the other hand, industrial and institution consumption showed a strong negative correlation with water price (1^{st} tier), average annual income, groundwater supply, and access charge. This same relationship was also observed for livestock consumption with average temperature and treated water supply; commercial consumption with access charge; industrial consumption with temperature (December); institution's consumption with annual average rainfall and summer rainfall; parks and gardens with access charge; and electricity generation with average temperature. These findings indicate an inverse relationship between the consumption of these water user sectors and socio-economic and climatic factors and vice versa, where an increase in one variable leads to the decrease of another variable.

Table 4.6. Correlation Matrix between Water User Sectors and Socio-Economic and Climatic Variables within Toowoomba.

Sectors	Population	Water Price		Ave. Annual Individual Income	Annual Ave. Rainfall	Summer Rainfall	Ave. Temp.	Temp. (December)	Surface Water Supply	Ground Water Supply	Treated Water Supply	Water Restriction	Access Charge
		1st Tier	2nd Tier										
Residential													
Correlation Coefficient	-0.261	-0.239	-0.222	-0.261	0.139	0.212	0.395	0.042	0.721*	-0.442	0.523	0.465	-0.261
Sig. (2 tailed)	0.467	0.507	0.537	0.467	0.701	0.556	0.258	0.915	0.019	0.2	0.121	0.175	0.467
Livestock													
Correlation Coefficient	0.636*	0.661*	0.611		0.539	0.733*	-0.557	-0.259	0.479	0.673*	-0.687*	0.059	0.813
Sig. (2 tailed)	0.048	0.038	0.06		0.108	0.016	0.095	0.5	0.162	0.033	0.028	0.871	0.004
Commercial													
Correlation Coefficient	-0.37	-0.318	-0.272	-0.37	-0.139	-0.03	0.517	0.259	0.903**	-0.455	0.790**	0.597	-0.532
Sig. (2 tailed)	0.293	0.37	0.448	0.293	0.701	0.934	0.126	0.5	0	0.187	0.007	0.069	0.114
Industrial													
Correlation Coefficient	0.576	-0.557	-0.488	-0.576	-0.103	-0.152	0.511	-0.075	0.867**	-0.6	0.778**	0.387	-0.657*
Sig. (2 tailed)	0.082	0.095	0.153	0.082	0.777	0.676	0.132	0.847	0.001	0.067	0.008	0.269	0.039

Table 4.6. Correlation Matrix between Water User Sectors and Socio-Economic and Climatic Variables within Toowoomba. (*cont.*)

Institution													
Correlation Coefficient	-0.648*	-0.624	-0.549	-0.648*	-0.661*	-0.636*	0.845**	0.427	0.685*	-0.515	0.681*	0.046	-0.563
Sig. (2 tailed)	0.043	0.054	0.1	0.043	0.038	0.048	0.002	0.252	0.029	0.128	0.03	0.9	0.09
Parks and Gardens													
Correlation Coefficient	-0.394	-0.355	-0.315	-0.394	-0.333	-0.248	0.681*	0.469	0.927**	-0.37	0.924**	0.597	-0.657*
Sig. (2 tailed)	0.26	0.314	0.376	0.26	0.347	0.489	0.03	0.203	0	0.293	0	0.069	0.039

4.6.3.2 Determinants of Water Usage per Sector

Table 4.7 shows a summary of the results of the regression analysis done using continuous 10 years' water usage of eight (8) water user sectors of Toowoomba Region as dependent variables. Ten (10) year values of independent socio-economic variables and climatic variables have been analyzed. Among the socio-economic variables were the Annual Water Price (1^{st} Tier and 2^{nd} Tier), number of populations, average annual income, access charge, and water restrictions within the Region. Moreover, among independent climatic variables were surface water pump annually from three dams, annual groundwater pump from bores, average summer rainfall, annual average rainfall, and average temperature. Looking at the table, it can be noticed that significant factors affecting the water usage of each sector vary. For the residential sector, it was observed that surface water and annual access charge were the dominant factors, with R^2 = 79.5%. Surface water was the only dominant factor in the commercial sector with R^2 = 83%. On the other hand, agriculture, livestock, and mining were significantly influenced by Tier 1 and December temperature with R^2 = 96.7%, access charge and annual rainfall with R^2 = 86.7%, and Toowoomba population and December temperature with R^2 = 89.6%, respectively. Moreover, the sole sector affected by Toowoomba bores was the institutional sector with R^2 = 85.1%. As for the parks and gardens and energy generation, these were significantly affected by surface water supply and temperature with R^2 = 93%, respectively.

Despite the high computational effort needed due to the huge volume of data utilized, the results are very good and beneficial. The regression analysis method is suitable for identifying the mathematical relationships between large data that change over time. The table above was generated by applying Forward Selection Regression. This type of stepwise regression approach begins with an empty model and adds in variables one by one. In each forward step, one variable that gives the single best improvement to the model was being added. Below is the detailed discussion of each water user sector. The interpretation of the model, the significance of the regression models derived from the regression analysis, and the clear explanation of the significance values of R^2 for each water user are presented below.

Table 4.7. Significant Determinants of Sectoral Water Consumption Based on Regression Analysis

	R-squared	Adjusted R-squared	Std. Error	The Model
Residential	79.50%	73.70%	342,997.52	**Residential** = 3,033,480.165 + 3.533 * Surface Water Supply + 2,305.255 * Annual Access Charge
Agriculture	96.70%	95.70%	2,540.03	**Agriculture** = -27,568.026 + 20,474.529 * Tier 1A Water Consumption Charge + 557.808 * December Temperature
Livestock	86.70%	82.90%	4,108.14	**Livestock** = -3,057 + 45.528 * Annual Access Charge + 91.038 * Rainfall
Mining	89.60%	86.60%	4,271.58	**Mining** = -253,726.806 + 2.837 * Toowoomba Population - 551.271 * December Temperature
Commercial	83%	80.80%	73,331.89	**Commercial** = 621,918.92 + 0.763 * Surface Water
Industrial	99.99%	99.99%	398.985	**Industrial** = 427,684.1 + 5.954 * Surface Water Supply (sw supply) – 3,264.9 * Water Restriction – 0.424 * Surface Water Toowoomba – 1,096.7 * Rainfall + 111.461 Average Rainfall – 49.6 * Bi-annual Access Charge
Institutional	85.10%	80.90%	43,651.20	**Institutional** = -496,685.9 – 0.11 * Toowoomba Bores + 55,511.53 * Temperature
Parks and Gardens	93%	92.10%	12,277	**Parks and Gardens** = -33,978.54 + 0.195 * Surface Water Supply (sw supply)
Electricity Generation	82%	76.90%	156	**Electricity Generation** = 6,831.512 – 297.45 * Temperature = 0.001 Total Water Supply (tw supply)

Residential Sector

$$\text{Residential Water Consumption } (y_1) = 3{,}033{,}480.165 + 3.533 * \text{Surface Water Supply} + 2{,}305.255 * \text{Annual Access Charge}$$

Analysis of the Residential Water Consumption Model

This model, derived from regression analysis, uses surface water supply and annual access charge to predict residential water consumption. It reveals a statistically significant direct relationship between both independent variables and the dependent variable.

The coefficient of 3.533 for surface water signifies that with all other factors held constant, a one unit increase in surface water supply leads to a 3.533 unit increase in residential water consumption. This suggests that readily available surface water appears to encourage, on average, higher water usage within the residential sector.

The positive coefficient of 2,305.255 for the annual access charge indicates that, again holding other factors constant, a one unit increase in the annual access charge corresponds to a 2,305.255 unit increase in residential water consumption. This may seem counterintuitive, but it could potentially reflect affordability, with higher access charges potentially leading to consumers feeling less constrained in their water usage.

The model's high coefficient of determination (R^2) of 0.795 implies that nearly 80% of the variability in residential water consumption is explained by the variations in surface water and annual access charge. This highlights the model's effectiveness in capturing the relationship between these key factors and residential water usage.

Agriculture Sector

$$\text{Agriculture Water Consumption } (y_2) = -27{,}568.026 + 20{,}474.529 * \text{Tier 1A Water Consumption Charge} + 557.808 * \text{December Temperature}$$

Analysis of the Agriculture Water Consumption Model

This model, based on regression analysis for irrigated cotton, uses Tier 1A water consumption charge and December temperature to predict agricultural water consumption. It reveals statistically significant relationships between both independent variables and the dependent variable.

The positive coefficient of 20,474.529 for Tier 1A signifies that, with all other factors held constant, a one-unit increase in this charge leads to a 20,474.529 unit increase in agricultural water consumption. This suggests that a higher financial incentive for water conservation could potentially motivate increased consumption, possibly due to factors like increased affordability of irrigation technology or changes in cropping patterns.

The positive coefficient of 557.808 for December temperature indicates that, again holding other factors constant, a one-unit increase in temperature in December leads to a 557.808 unit increase in water consumption. This aligns with expectations, as higher temperatures increase evapotranspiration and crop water demand, particularly for water-intensive crops like cotton.

The model's exceptionally high coefficient of determination (R^2) of 0.967 implies that nearly 97% of the variability in agricultural water consumption can be explained by the variations in Tier 1A charge and December temperature. This highlights the model's strong ability to capture the relationship between these key factors and water usage in irrigated cotton agriculture.

Livestock Sector

$$\text{Livestock Water Consumption } (y_3) = -3{,}057 + 45.528 * \text{Annual Access Charge} + 91.038 * \text{Rainfall}$$

Analysis of the Livestock Water Consumption Model

This model, based on regression analysis, uses the annual access charge and rainfall data to predict water consumption in the Livestock Sector. It reveals statistically significant relationships between both independent variables and water consumption (y_3).

The positive coefficient of 45.528 for the annual access charge suggests that with all other factors held constant, a one-unit increase in the charge leads to a 45.528 unit increase in livestock water consumption. This may seem counterintuitive, but it could be driven by factors like increased farm income influencing investment in water-intensive livestock practices. Further research would be needed to understand the underlying mechanisms.

The positive coefficient of 91.038 for rainfall aligns with expectations, indicating that a one-unit increase in rainfall is associated with a 91.038 unit increase in water consumption, assuming other factors remain constant. This likely reflects reduced reliance on supplementary water sources due to increased natural water availability.

The model boasts a strong coefficient of determination (R^2) of 0.867, meaning that nearly 87% of the variability in livestock water consumption is explained by the variations in the annual access charge and rainfall. This highlights the model's effectiveness in capturing the relationship between these key factors and water usage in the livestock sector.

Mining Sector

$$\text{Mining Sector Water Consumption } (y_4) = -253{,}726.806 + 2.837 * \text{Toowoomba Population} - 551.271 * \text{December Temperature}$$

Analysis of the Mining Sector Water Consumption Model

This model, built using regression analysis, sheds light on the factors influencing water consumption in the Mining Sector. It focuses on the Toowoomba population and December temperature as key variables.

The positive coefficient of 2.837 for the Toowoomba population signifies that, with all other factors held constant, a one-unit increase in the population leads to a 2.837 unit increase in mining water consumption (y_4). This suggests a potential link between increased population growth and expanded mining activities, which could drive higher water demand.

The negative coefficient of -551.271 for December temperature aligns with expectations, indicating that a one-unit increase in December temperature leads to a 551.271 unit decrease in water consumption (y_4), assuming other factors remain unchanged. This likely reflects reduced water usage for cooling processes under warmer conditions.

The model boasts a high coefficient of determination (R^2) of 0.896, meaning that nearly 90% of the variability in mining water consumption is explained by the variations in the Toowoomba population and December temperature. This highlights the model's strong ability to capture the relationship between these key factors and water usage in the Mining Sector.

Commercial Sector

Commercial Sector Water Consumption (y_5) = 621,918.92 + 0.763 * Surface Water

Analysis of the Commercial Sector Water Consumption Model

This model, built using regression analysis, sheds light on a key factor influencing water usage in the commercial sector: surface water availability. It reveals a statistically significant direct relationship between readily available surface water and increased commercial water consumption.

The key finding is the positive coefficient of 0.763 for surface water. This signifies that, with all other factors held constant, a one-unit increase in surface water supply corresponds to a 0.763 unit increase in commercial water consumption (y_5). In simpler terms, easier access to sources like rivers or lakes appears to encourage higher water usage in commercial establishments like hotels, restaurants, and office buildings.

The model boasts a high coefficient of determination (R^2) of 0.830, meaning that nearly 83% of the variations in commercial water consumption can be explained by fluctuations in surface water availability. This highlights the model's strong ability to capture the relationship between these variables.

Several factors contribute to the positive correlation observed in the model. Firstly, reduced treatment costs play a role, as surface water may be more cost-effective to treat than groundwater, rendering it economically advantageous for commercial users. Additionally, businesses with abundant surface water resources tend to incorporate more water-intensive elements, such as fountains or landscaping, leading to an overall higher water consumption. Furthermore, shifting customer preferences contribute to this correlation, as customers are often attracted to commercially appealing amenities that utilize water features. This attraction can potentially influence business decisions and resource utilization, emphasizing the multifaceted nature of the relationship between surface water availability and commercial water consumption.

Industrial Sector

Industrial Sector Water Consumption (y_6) = 427,684.1 + 5.954 * Surface Water Supply (sw supply) – 3,264.9 * Water Restriction – 0.424 * Surface Water Toowoomba – 1,096.7 * Rainfall + 111.461 Average Rainfall – 49.6 * Bi-annual Access Charge

Analysis of the Industrial Sector Water Consumption Model

This analysis digs into the key factors influencing water consumption in the industrial sector by dissecting a regression model. It reveals a significant interaction between various independent variables and industrial water consumption (y_6).

Two significant drivers impact industrial water use, as revealed by the coefficients in the regression model. Firstly, surface water supply (sw supply) plays a crucial role with a positive coefficient of 5.954. This implies that readily available surface water acts as a direct catalyst for industrial water consumption. In practical terms, for every unit increase in sw supply, there is an anticipated corresponding 5.954 unit increase in y_6, assuming other factors remain unchanged. This underscores the importance of easy access to surface water, making it both convenient and potentially cost-effective for industries to utilize, consequently leading to higher consumption.

Similarly, average rainfall emerges as another influential factor with a positive coefficient of 111.461. This indicates a direct relationship between average rainfall and industrial water use. In simpler terms, a one-unit increase in average rainfall results in a substantial 111.461 unit increase in y_6. This association may be attributed to various factors, such as heightened industrial activity during wetter periods or a reliance on rainfall for specific industrial processes. The positive coefficients for both sw supply and average rainfall emphasize their roles as driving forces behind the demand for water in industrial operations.

In the industrial sector, various counterbalancing forces, evident through their negative coefficients in the regression model, play a crucial role in moderating water demand. Notably, stringent water restrictions exhibit a substantial inverse relationship, marked by a negative coefficient of -3264.9, leading to a significant reduction of 3264.9 units in y_6. The availability of surface water in Toowoomba, denoted by a negative coefficient of -0.424, also contributes to decreased industrial water consumption, potentially due to local sourcing or alternative water management practices. Moreover, overall rainfall, with a negative coefficient of -1,096.7, indicates reduced reliance on alternative sources during wetter periods. Lastly, the bi-annual access charge, carrying a negative coefficient of -49.6, serves as a financial incentive for conservation efforts, resulting in a decrease of 49.6 units in y_6. These findings illuminate the intricate dynamics between driving forces and constraints, providing valuable insights into factors influencing industrial water consumption.

The model demonstrates an exceptionally high coefficient of determination (R^2) at 0.9999, signifying that almost 100% of the variations in industrial water consumption are accounted for by the identified independent variables. This underscores the model's remarkable capability in capturing the intricate relationships governing water usage within the industrial sector. However, caution is warranted due to the risk of overfitting, where the model may be excessively tailored to the specific dataset and might lack generalizability to other situations.

Institutional Sector

Institutional Sector Water Consumption (y_7) = -496,685.9 – 0.11 * Toowoomba Bores + 55,511.53 * Temperature

Analysis of the Institutional Sector Water Consumption Model

The analysis sheds light on the factors influencing water consumption in the institutional sector, encompassing schools, hospitals, and government offices. It utilizes a regression model to show the relationship between water sources and temperature.

With a positive coefficient of 55,511.53, temperature plays a direct role in driving water use within institutions. For every one-degree increase in temperature, a corresponding increase of 55,511.53 units in institutional water consumption (y_7) can be expected, assuming other factors remain unchanged. This could be attributed to increased usage of air conditioning, irrigation, or a higher demand for drinking water during hotter periods.

The coefficient of -0.11 for Toowoomba bores suggests an inverse relationship with institutional water consumption. Increased reliance on water from Toowoomba bores leads to a slight decrease (0.11 units) in overall institutional water use, with other factors held constant. This might be because pumping from bores is often more energy-intensive and costly, encouraging institutions to conserve water.

The model boasts a relatively high coefficient of determination (R^2) of 0.851, indicating that over 85% of the variations in institutional water consumption can be explained by the identified independent variables: temperature and Toowoomba bores. This highlights the model's remarkable ability to capture the complex relationships between these factors and water usage within the institutional sector.

Parks and Gardens

Parks and Gardens Water Consumption (y_8) = -33,978.54 + 0.195 * Surface Water Supply (sw supply)

Analysis of the Parks and Gardens Water Consumption Model

This analysis delves into the water needs of the parks and gardens sector, showing a direct relationship between water consumption and readily available surface water supplies (sw supply).

With a positive coefficient of 0.195, increased surface water supply directly fuels higher water consumption in parks and gardens (y_8). This means that for every one unit increase in sw supply, there is a corresponding 0.195 unit increase in water use, assuming other factors remain constant. This suggests that easier access to surface water, like lakes or rivers, makes it more convenient and likely for these spaces to tap into this resource, leading to higher consumption.

This regression model sheds light on the crucial role of surface water in predicting park and garden water consumption. With a remarkably high coefficient of determination (R^2) of 0.930, the model indicates that nearly 93% of the variations in water usage can be explained simply by the availability of surface water. This highlights the model's exceptional ability to capture the influence of this key factor on water needs within parks and gardens.

Electricity Generation

$$\text{Electricity Generation Consumption } (y_9) = 6{,}831.512 - 297.45 * \text{Temperature} = 0.001 \text{ Total Water Supply (tw supply)}$$

Analysis of the Electricity Generation Consumption Model

This analysis delves into the water demands of electricity generation, showing the relationship between temperature and water supply. It uses a regression model to reveal how these factors influence the sector's water consumption.

With a negative coefficient of -297.45, temperature acts as a potent dampener on electricity generation (y_9). This means that for every one-degree increase in temperature, there is an expected corresponding decrease of 297.45 units in water consumption, assuming other factors remain constant. This could be due to reduced efficiency of power plants in warmer conditions, leading to lower water demand for cooling processes.

In contrast, the total water supply (tw supply), encompassing both surface water and bores, boasts a positive coefficient of 0.001. This suggests a direct, though limited, relationship with electricity generation, implying that for every one-unit increase in tw supply, there is a 0.001 unit increase in water consumption. This reinforces the crucial role of water in electricity generation, even if the impact is smaller compared to temperature.

This model boasts a relatively high coefficient of determination (R^2) of 0.820, indicating that over 82% of the variations in electricity generation water consumption can be explained by the identified independent variables: temperature and total water supply. This highlights the model's ability to capture the complex relationships between these factors and water usage within the electricity generation sector.

CHAPTER 5

LAND USE CHANGE ANALYSIS AND PREDICTION IN THE TOOWOOMBA REGION

5. 1 Introduction

On par with water, land is as indispensable as water as a natural resource and is heavily relied upon by terrestrial ecosystems and humanity for preservation and survival (Jazouli et al., 2019). Over the years, a complex and dynamic interplay of climate and land use and cover changes, mainly driven by anthropogenic influences, has left a deep imprint on the available resources. Rapid human population growth, along with its corresponding needs, coupled with the impacts of climate change resulting from land conversion, has placed intense and progressive pressure on land resources (Dissanayake et al., 2017). In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (2014), the agriculture, forestry, and other land use (AFOLU) sectors accounted for almost a quarter of global anthropogenic emissions. In turn, these changes can accelerate the depletion of water resources (Kaushal et al., 2017), thereby disrupting hydrological processes that support economic and human social activities and regulate life systems as a whole (Gibson et al., 2018; Liu et al., 2014).

Land use science sheds light on the complexity linking land use with environmental and ecological processes and socio-economics (Müller, 2016). Earlier studies in the 1970s were primarily concerned with the physical aspect of the change (Parveen et al., 2018). It was only in the early 1990s that global-scale research on the monitoring and simulation of the dynamic land change process, with an emphasis on human-nature interaction, gained momentum (Jiyuan Liu et al., 2014). The advancement of geospatial techniques, such as the integration of remote sensing with geographic information systems and modeling tools, has proven that land use analysis is a reliable instrument in supporting planning and management strategies. Several land use studies have served as tools to support and facilitate land use planning and policy design. Among them are the conservation model by Soares-Filho et al. (2006) for the Amazon Basin in Brazil and the spatio-temporal analysis by Parsa et al. (2016) of the

Arasbaran Biosphere Reserve in Iran. Thus, an in-depth understanding of the drivers, dynamics, and mechanisms of these land use changes, as well as how these changes will occur in the future, is key to making more informed, science-based decisions for land use challenges and steering.

This chapter deals with the second objective, which is to project the potential land use changes in the Toowoomba Region for 2038 and 2058 and identify the forces driving the change. The resulting projections were used to estimate the future water usage of the identified water user sectors in the region. Ultimately, the findings will aid the Council in planning and managing the region's land use and water resources.

5. 2 Study Area

Toowoomba Region is endowed with some of Queensland's most fertile and resource-rich terrain (State of Queensland, 2013) (Figure 5.1). Agricultural land predominates the region, occupying 96.4% of the area (TRC, 2016), of which grazing native vegetation and cropland are the most common agricultural land uses, both covering 34%. Located about 300 km west of Toowoomba is Surat Basin, a 30-million-hectare thermal coal and gas energy reserve; it is Queensland's largest coal seam gas (CSG) production area (Figure 5.2). Serving as the gateway to this area, the region dominates the eastern part of the Surat Basin, along with Maranoa and Western Downs local government areas in the western end and central section, respectively. These three regions comprise the Surat Cumulative Management Area (CMA) (State of Queensland, 2011; Windle & Rolfe, 2014). Exon (1976) reported that the basin held an estimated 51 billion cubic meters of gas and 31 million cubic meters of oil in 1974. As of June 2009, it was estimated to contain more than six billion tons of proven thermal coal reserves and 18,249 petajoules of CSG reserves (State of Queensland, 2011).

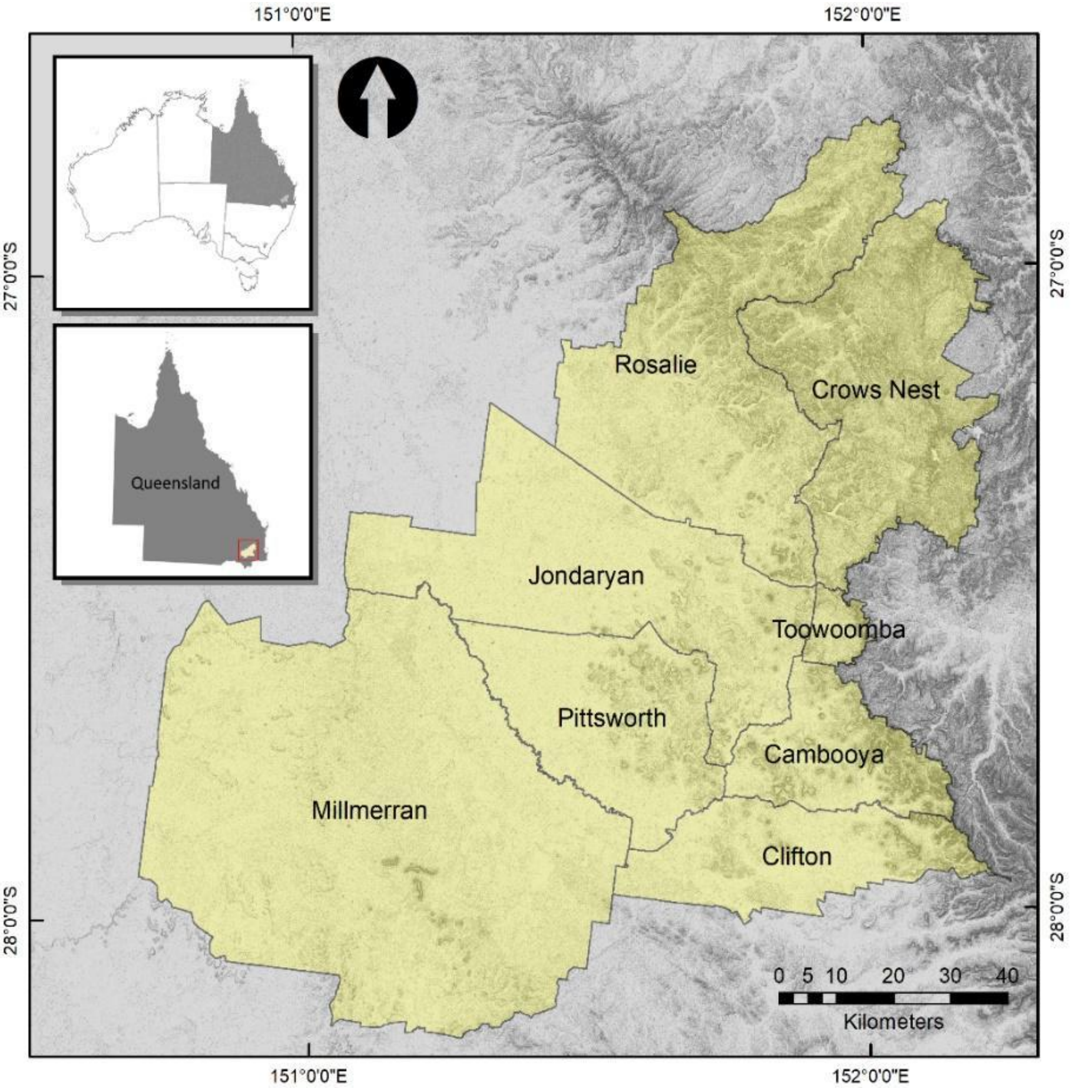


Figure 5.1. Location map of the study area.

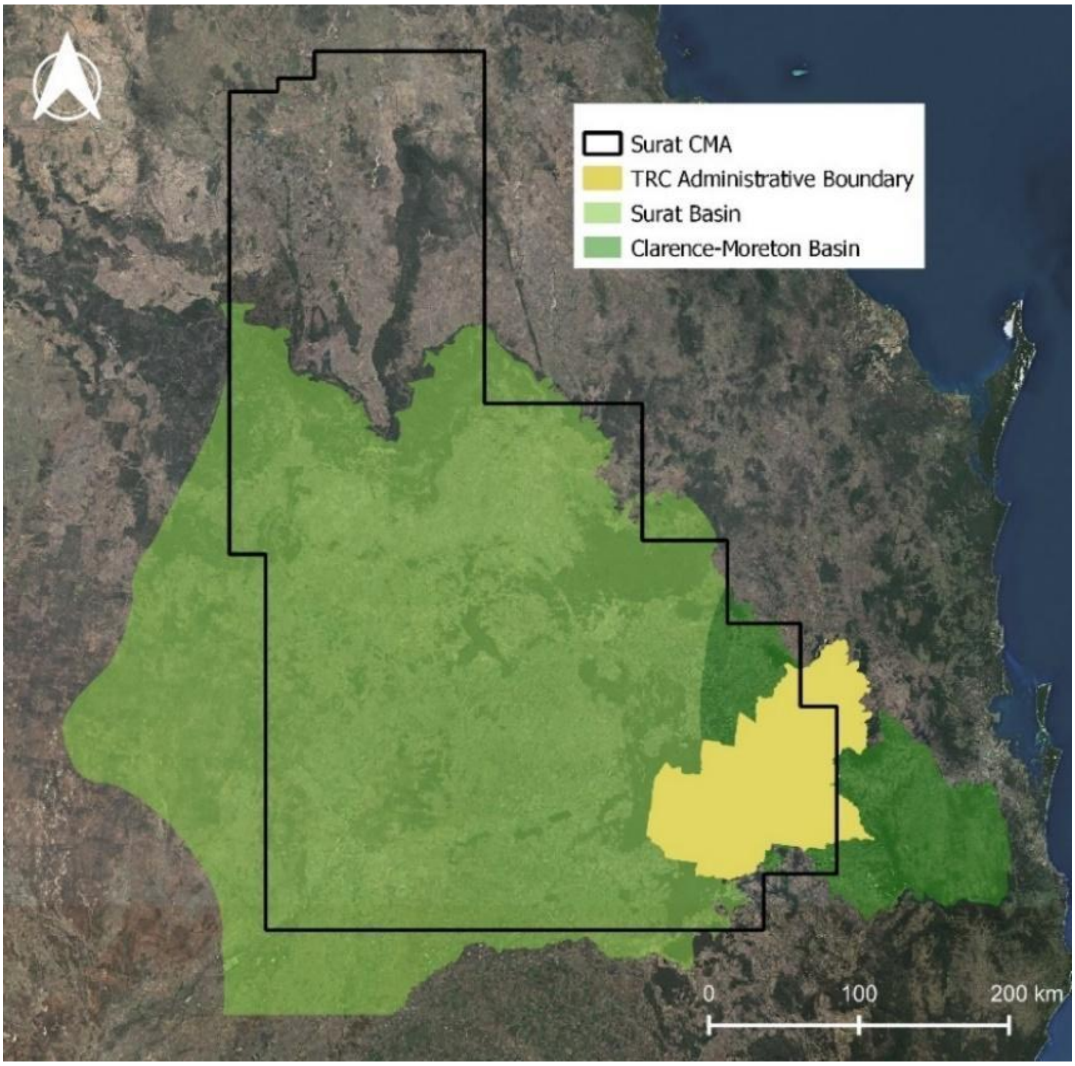


Figure 5.2. Relative location of Toowoomba Region within the Surat Cumulative Management Area.

Toowoomba Region belongs to Climate Zone 5, which is classified as warm temperate (Australian Building Codes Board, 2015). It is further characterized by hot summers and cool winters (State of Queensland, 2019). The long-term average annual temperature is recorded at 19 °C, while the average annual rainfall is 614 mm.

The dynamic region of Toowoomba boasts of being one of Australia's most diverse economies (TRC, 2017a, 2019). As of 2018, it is home to an estimated 167,567 people (ABS, 2019) and is projected to grow to around 235,851 by 2051, based on the 2016 census (TRC, 2019). The region plays an important economic role in Darling

Downs as an agricultural and food hub, a pivotal freight and logistics junction, and a major center for commerce, education, health, defense, and construction services (TRC, 2017b, 2018). From its agricultural roots, which remain a mainstay, pouring $728 million from grain, poultry, cotton, and livestock, it has diversified into other industries, including mining (coal), food product manufacturing, construction, education, and health (TRC, 2019). Development programs and infrastructure projects are already in the pipeline to concretize its bold ambition for 2038, which is to become 'an internationally competitive, vibrant, diverse, and inclusive economy that provides opportunities for employment, business, and investment…' (TRC, 2018). Given the course that the region is embarking on and the anticipated population growth this entails, assessing land use changes and their impact on water availability is imperative to improve resource utilization and promote sustainable development.

5.3 Data and Methods

5.3.1 Datasets

LULC shapefiles of the Toowoomba Region for 1999, 2010, and 2018, following the Australian Land Use and Management (ALUM) Classification Version 8, were obtained from the Spatial Services Unit of the Toowoomba Regional Council with the assistance of GIS Team Leader Joel Attwood. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was obtained from the United States Geological Survey (USGS) website for the elevation and slope dataset. The road network, classified as 'Main roads,' was downloaded from OpenStreetMap. Lastly, annual average mean temperature and annual average rainfall data covering the periods from 1996 to 2019 were obtained from the Australian Bureau of Meteorology website.

5.3.2 Pre-processing of Datasets in ArcGIS

In this chapter, the primary attribution level of the ALUM classification (Version 8, October 2016) was used mainly to reduce the number of categories to be considered for modeling. Existing LULC datasets for the Toowoomba Region in 1999, 2010, and 2018 were identified and assessed. Similar and related classes were aggregated and reassigned with new class types, hence the identification of the following 15 categories: commercial and public services, dryland agriculture and plantations, electricity generation, industrial, institution, irrigated agriculture and plantations, livestock, mining, nature conservation, other minimal use, production from relatively natural environments, residential, transport and communication, waste treatment, and disposal, and waterbodies and facilities. However, only eight of these (in bold) were highlighted in the discussion for the purpose of harmonizing the results with the water user sectors considered in this study. A description of each class is summarized in Table 5.1.

Table 5.1. Land-use/cover classification scheme based on the existing land-use/cover in the Toowoomba Region from 1999 to 2018.

ID	LULC Types*	Code	Description
1	**Commercial and Public Services**	**CPS**	Commercial and public services and recreation and culture.
2	Dryland Agriculture and Plantations	DAP	Plantation forests include hardwood plantation forestry, grazing modified pastures, cropping including cotton, perennial horticulture and land in transition.
3	**Electricity Generation**	**EG**	Fuel powered, hydro-, wind and solar electricity generation, electricity substations and transmissions and water extraction and transmission.
4	**Industrial**	**Ind**	Manufacturing and industrial and abattoirs.
5	**Institution**	**Ins**	Defence facilities (urban) and research facilities.
6	**Irrigated Agriculture and Plantations**	**IAP**	Irrigated cropping including irrigated hay and silage, irrigated cotton, irrigated perennial and irrigated seasonal horticulture and irrigated seasonal vegetable and herbs.
7	**Livestock**	**L**	Intensive animal production, dairy sheds and yards, feedlots, poultry farms, piggeries, aquaculture, horse studs and abandoned intensive animal production.
8	**Mining**	**M**	Mines, quarries, tailings and extractive industry not in use.
9	Nature Conservation	NC	National Park, other conserved areas and managed

			resource protection areas.
10	Other Minimal Use	OMU	Defence land (natural areas) and residual native cover.
11	Production from Relatively Natural Environments	RNE	Grazing native vegetation, producing native forests.
12	**Residential**	**R**	Urban residential, rural residential with and without agriculture, farm building/infrastructure.
13	Transport and Communication	TC	Airports/aerodromes, roads, railways, ports and water transport and navigation and communication.
14	Waste Treatment and Disposal	WTD	Landfill, solid garbage and sewage/sewerage.
15	Water Bodies and Facilities	WF	Lake, reservoir/dam including water storage for intensive use/farm dams, river, channel/aqueduct, marsh/wetland, estuary/coastal waters.

***Bold class types** denote the key water user sectors highlighted in this study.

The resulting cleaned shapefiles were converted to raster as Tagged Image File Format (.tiff). These were then resampled to 30-meter resolution and were adjusted to have the same extents and spatial characteristics to ensure that the requirements for performing change analysis and prediction were satisfied. The derivation of elevation and slope from SRTM DEM, interpolation (Kriging) of climatic data were all executed in ArcGIS, while the generation of a Euclidean map of main road networks and anthropogenic disturbances was processed in TerrSet. As with the shapefiles, these variables were also converted to raster and set to the proper extents and characteristics as the LULC maps (Figure 5.3).

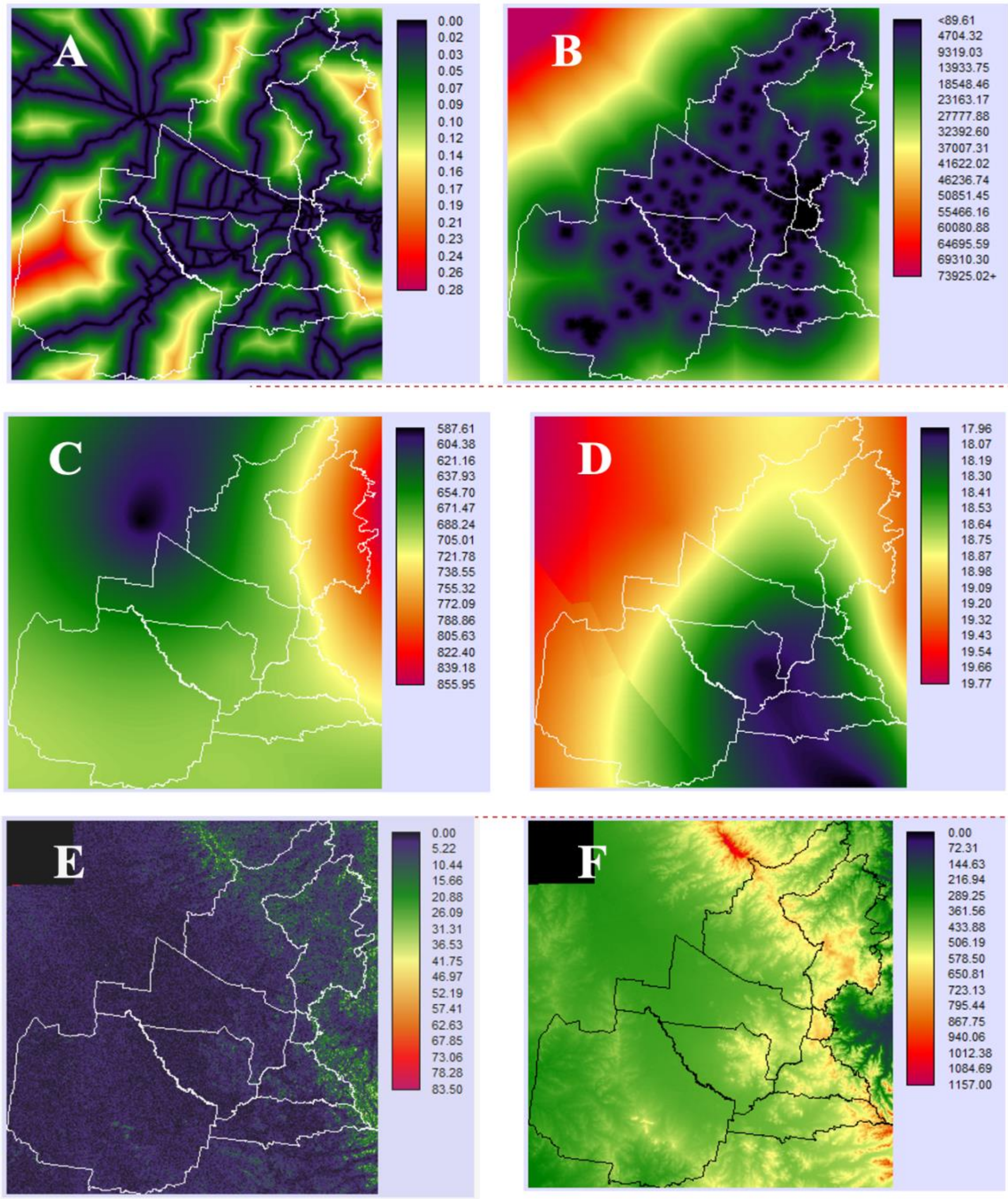


Figure 5.3. Variables used in the MLP Transition Potentials processing: distance to road network (A), distance to anthropogenic disturbances (B), average mean rainfall (C), average mean temperature (D), slope (E) and elevation (F).

5.3.3 Processing of Datasets in TerrSet (IDRISI Selva)

TerrSet Geospatial Monitoring and Modeling Software (formerly IDRISI Selva), developed by Clark Labs of Clark University, Worcester, MA, USA, was used to analyze the land changes in the Toowoomba Region and their dynamics. Reference system and unit of the imported LULC and variable images were set to World Geodetic System (WGS) 1984 Universal Transverse Mercator (UTM) 56S and in meters, respectively.

5.3.4 Land Change Modeler

Land Change Modeler (LCM) is one of the vertical applications—a software designed for a specific purpose—integrated in TerrSet and is among the frequently used LULC change modelers. It allows for rapid analysis of historical land cover changes and empirical modeling of the relationship between the transitions and explanatory variables to project future land change scenarios for land planning. LCM also provides special tools to support Reducing Emissions from Deforestation and Forest Degradation (REDD) climate projects and strategies by assessing a project's potential for carbon sequestration given the land change prediction results (Eastman, 2016a). The entire land use modeling process in LCM is summarized in Figure 5.4.

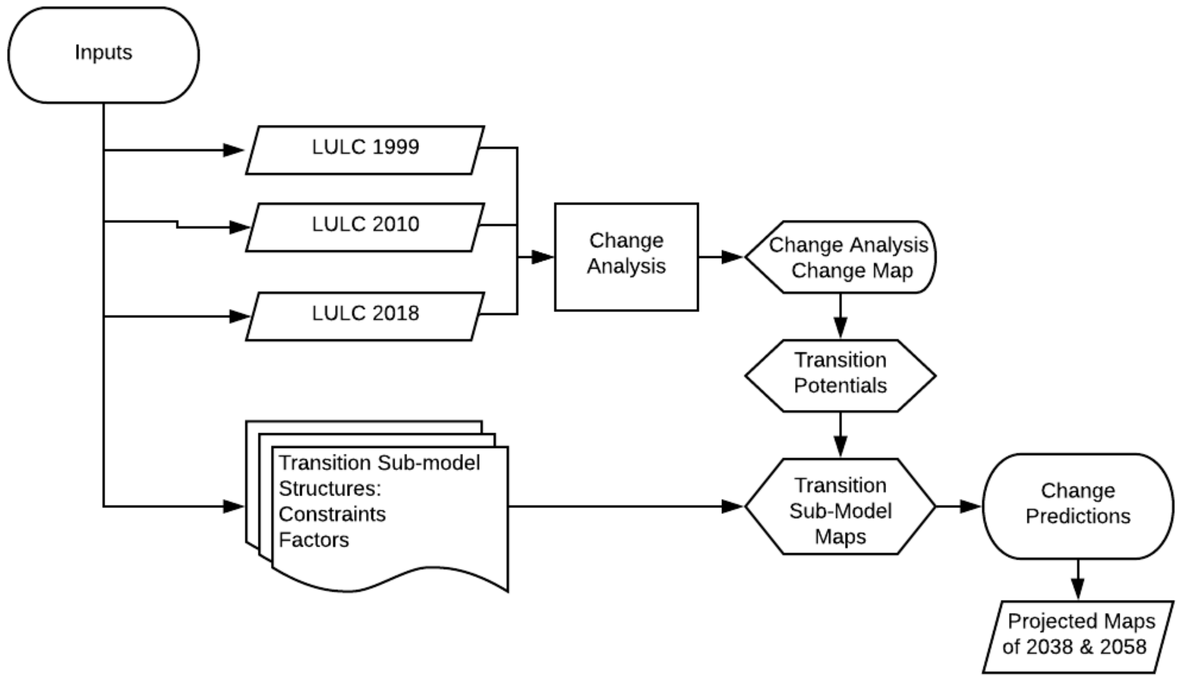


Figure 5.4. Methodology Flowchart for TerrSet Land Change Modeler.

LCM is organized into six major tasks, namely: 1) Change Analysis; 2) Transition Potentials; 3) Change Prediction; 4) Planning; 5) Reducing Emissions from Deforestation and Forest Degradation (REDD) Project; and 6) Harmonization. The first three tasks are structured in such a way that the set of operations follows one after another in this order (Eastman, 2016a). Each task must be performed before proceeding to the next. This study employed the first three and the sixth tasks, as it is only interested in assessing, modeling, and predicting the transitions.

In running the application, it was necessary to harmonize all land cover maps and raster driver datasets prior to change analysis and prediction. All inputs were formatted to satisfy the following conditions:

1. That the legends in both maps are the same.
2. That the categories in both maps are the same and sequential.
3. That the backgrounds in both maps are the same and have a value of zero.
4. That the spatial dimensions, including resolution and coordinates, are the same.

This study covers a period of 20 years, from 1999 to 2018, and is analyzed into three sets:

Earlier Images	Later Images
1999	2010
2010	2018
1999	2018

5.3.5 Analysis of Trends of Land Use Change

The modeling began with the first task, Change Analysis, where transitions from one class to another during the earlier and later years were assessed. In each period, gains and losses were quantified, exchanges between land cover categories were analyzed, and the contributors to net changes experienced by a single land cover were examined. Transitions of less than 100 hectares were excluded to model only those most prevalent transitions (> 100 ha). Each period represented a different scenario for the prediction of potential land use change in 2038 and 2058. Using the LULC spatial extent from the analysis' calculation, the annual rate of change was obtained through this equation:

$$Annual\ Expansion\ Rate\ (\%) = \frac{Area\ in\ Year_2 - Area\ in\ Year_1}{(Year_2 - Year_1)} \qquad (1)$$

5.3.6 Transition Potential Modeling using Multilayer Perceptron (MLP) Neural Network and Driving Forces Determination

The second task, Transition Potentials, was used to determine the location of the change. Land Cover categories were grouped into sub-models to simulate future land cover scenarios. Each sub-model comprises a group of transitions that have the same underlying variables.

Before the sub-modelling process, LCM allows for an optional quick testing of the potential explanatory powers of each variable using the explanatory tool, Cramer's V, to quantitatively measure their association with the LULC change (Eastman, 2016a). Cramer's V values range from 0.0, indicating no correlation, to 1.0, denoting perfect correlation (Gibson et al., 2018; Megahed et al., 2015). While a number of studies (Islam et al., 2018; Subiyanto & Suprayogi, 2019) consider 0.1 or higher as a good minimum threshold for suggesting a substantive relationship, Eastman (2016a) regards values of 0.15 or higher useful and 0.4 or higher to have strong predictive power. Therefore, values below these can be rejected for modeling. Although these cannot be regarded as definitive of the driver's strong performance, the values can help determine whether the driver is worth considering in the model (Eastman, 2016b; Gibson et al., 2018). However, in this study, all variables were kept and applied to the sub-models for the purpose of observing how the Multi-layer Perceptron Neural Network (MLP) will evaluate them.

The resulting sub-models were then used to generate a transition potential map for each transition. Transition is an expression of time-specific potential for change. Transitions can be modeled using different methods. There are several mathematical methods in forecasting land use change in the literature applied in various countries. One is the integrated Global Change Assessment Model and Future Land Use Simulation Model which was used to evaluate the potential land use projections of China from 2010 to 2100 (Dong et al., 2018) and an agent-based model that is used to determine the effects of oil land lease policy in land use (Li et al., 2017). Aside from those models, a number of authors claimed that MLP has been used as a benchmark model by many researchers because it is the most effective artificial network technique for modeling and prediction (Bui et al., 2018; Bui et al., 2017). For instance, one author emphasized that to be able to understand and solve modeling problems that have complex relationships between causal factors and responses, the Artificial Neural Network needs to be employed (Pham et al., 2019). Moreover, the MLP has been enormously utilized for both nonlinear and complex processes modeling of the real world because of its strength in universal approximation (Pham et al., 2017; Sadowski et al., 2018; Bui et al., 2016). Basically, MLP consists of an input layer, output layer, and hidden layer nodes (Amakdouf et al., 2018; Kavzoglu & Mather, 2003). In general, each node of a layer connects with all nodes of the other layer (Figure 5.5). Specifically, each node of the hidden layer must be connected with all nodes of the input layer. In the same way, each node of the output layers is connected to all hidden nodes (Pham et al., 2017).

The most used algorithm optimization method for training the weights of the MLP is the Back-Propagation, which is detailed in the following equations by Amakdouf et al. (2018).

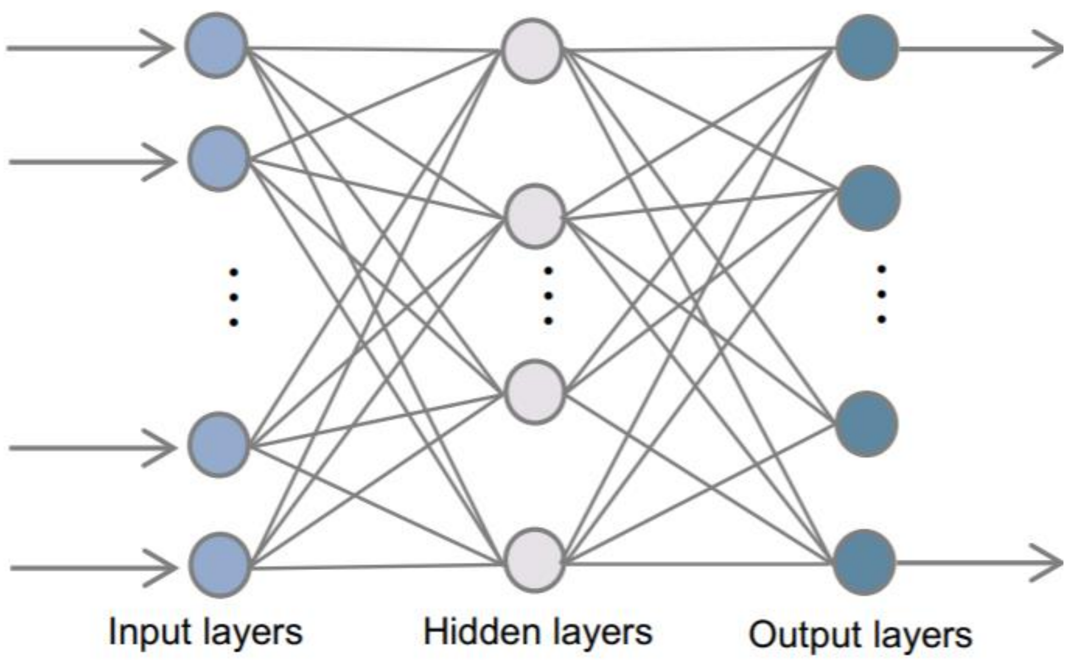


Figure 5.5. Structure of a common Multi-Layer Perceptron (Hudson et al., 2010).

Assumed that an input layer with n_0 neurons $V_{3D} = (x, x1, …., x_{n0})$ and a sigmoid activation function f(x) where:

$$f(x) = \frac{1}{1+e^{-x}} \quad (2)$$

Output of each unit in each layer is computed to obtain the network output. Consider a set of hidden layers ($h1, h2, …, h_N$) assuming that n_i are the neurons number in each hidden layer, $h_{i.}$,

$$h_1^i = f\left(\sum_{k=1}^{n_0} w_{kj}^0 x_k\right) \quad j = 1, \dots, n_1 \qquad (3)$$

A set of hidden layers is then considered (h_1 and h_2, h_N), and assumed that n_1 are the neurons number in each hidden layer, h_i. For the output, h^j_i, neurons in the hidden layers are calculated as follows:

$$h_1^j = f\left(\sum_{k=0}^{n_{i-1}} w_{kj}^{i-1} h_{i-1}^k\right) \quad i = 2, \dots, N \; and \; j = 1, \dots, n_i \qquad (4)$$

Where w_{kj}^i is the weight between the neuron k in the hidden layer i and the neuron j in the hidden layer i + 1, and n_i is the number of the neurons in the i^{th} hidden layer, the output of the i^{th} layers can be formulated by:

$$h_i = t\left(h_i^1, h_i^2, \dots \dots, h_i^{n_i}\right) \qquad (5)$$

The network outputs are computed by:

$$y_i = f\left(\sum_{k=1}^{n_N} w_{kj}^N h_n^k\right) \qquad (6)$$

$$Y = (y_1 \dots \dots, y_i \dots \dots, y_{N+1}) = F(W, X) \qquad (7)$$

Where w_{kj}^N is the weight between the neuron k of the N^{th} hidden layer and the neuron j of the output layer, N is the number of the neurons in the N^{th} hidden layer, y is the vector of output layer, F is the transfer function and W is the weights matrix, which is defined as follows:

$$W = \left[W^0, \dots \dots W^j, \dots \dots W^N\right] \qquad (8)$$

$$W = w_{j,k}^i{}_{0 \le i \le N \; 1 \le j \le n_{i+j} \; 1 \le k \le k_{n_i}} \text{ where } w_{j,k}^i \in \text{R} \qquad (9)$$

Where X is the input of neural network and f is the activation function and W^i is the matrix of weights between the i^{th} hidden layer and the $(i+1)^{th}$ for i=1,…,N-1, W^0

is the matrix of weights between the input layer and the first hidden layer, and W^N is the matrix of weights between the N^{th} hidden layer and the output layer.

Among the three modeling options, namely, SimWeight, Regression, and MLP that are built into TerrSet, only MLP can model multiple transitions as one sub-model, and there is a much stronger evaluation procedure that has been incorporated into the model development process (Eastman, 2016a).

In this study, the future trends of the land use change in Toowoomba Region were modeled using the MLP Neural Network. The network was trained with several influencing factors, namely: distance from roads, distance from man-made anthropogenic disturbances, elevation, slope, temperature, and rainfall. All drivers were given equal weights by default and were set to static, assuming that the rainfall and temperature values, as well as main road networks, will not change through the projected years. The Transition sub-models that exist between two land cover maps per period that have the same underlying driving determinants for prediction were set and specified for calculating the transition potentials.

5.3.7 Land Use Change Prediction Using Markov Chain Analysis

The MLP-modeled transition potential maps produced from the Transition Potentials Tab were processed to generate the transition area matrix and transition probability matrix in the Change Prediction Tab by means of the Markov Chain analysis, which is a default prediction model in LCM for determining the extent of change that will occur by the specified end prediction date (Eastman, 2016a).

Markov Chain is a random process in which the characteristics of the current state alone could determine the future evolution of the process. Simply put, the future state depends only on the present state along with a set of defined transitions and not on a set of previous states. As such, this unique feature renders this analysis "memoryless" (Singer et al., 2014; Soni, 2018).

Kumar et al. (2014) explains the methodology involved in the model. State transition refers to the conversion of one state of a system to another. If P is transition probability, namely the probability of converting a current state to another state in the next time, then the expression is as follows:

$$P = P_{ij} = | P_{11}\ P_{12}\ \cdots\ P_{21}\ P_{22}\ \cdots\ \cdots\ \cdots\ \cdots\quad P_{1n}\ P_{2n}\ \cdots\ P_{n1}\ P_{n2}\quad \cdots\ P_{nn}\ | \quad (10)$$

where P stands for the probability of the earlier state i to become later state j and P_n is the state probability of any time. Equation (10) must satisfy the next two conditions:

$$\sum_{j=1}^{n} P_{ij} = 1, \qquad (11)$$

$$0 \leq P_{ij} \leq 1. \qquad (12)$$

Hamad et al. (2018) adds that a probability near zero is an indication of low transition, while probabilities near one reflect high transitions.

Deriving the primary matrix and the matrix of transition probability (Pij) are the key steps of the model, from which the Markov forecast model proceeds as follows:

$$P_{(n)} = P_{(n-1)} \quad P_{ij} = P_{(0)} P_{ij}^{n}, \qquad (13)$$

where P_n stands for state probability of any time and $P_{(0)}$ stands for primary matrix (Kumar et al., 2014).

In land change analysis, Markov Chain has been extensively used to study the transition probability of land changes in large-scale simulation and analysis of different LULC types (Gibson et al., 2018; Gidey et al., 2017; Liping et al., 2018), especially of states that are difficult to describe (Kumar et al., 2014). Among the studies in which the analysis was applied to include the prediction of land use changes in Muzaffarpur City (Bihar), India (Varun et al., 2014), analysis of present and future growth of Vijayawada City of Andhra Pradesh, India (Sundara Kumar et al., 2015), land cover modeling of grassland-dominated catchments for the determination of its impact on catchment water and carbon fluxes (Gibson et al., 2018), monitoring and prediction of land use changes in the Meighan wetland in Iran (Ansari & Golabi, 2019), and the prediction and analysis of recent and future business-as-usual and two alternative scenarios of the Colombian Amazon and its intact forest (Armenteras et al., 2019).

The change modeling module of LCM is based on this inductive pattern approach (Mas et al., 2013; Gibson et al., 2018). Combined with the MLP, Markov Chain analysis enables LCM to analyze the land use transitions between two different land scenarios and use this to project the probability of future changes from the probability matrix generated by the cross-tabulation of two different images.

In this study, Markov Chain analysis was applied to all periods (1999-2010, 2010-2018, and 1999-2018) to simulate the future land use of Toowoomba Region for 2038 and 2058.

5.4 Results

5.4.1 Transition Potentials Modeling and Driving Force Determination

Results showed that, if based solely on the overall values, none of the variables can be considered useful given the minimum threshold value of 0.15 (Table 5.2). While the overall value tells how much a driver can influence land use change (W. Wang et al., 2016), it is the individual class values that are more important (Eastman, 2016b). For instance, the overall value of distance to road for 1999-2010 was 0.1145. However, the individual values of the same driver with areas for electricity generation, animal and livestock production, and residential were 0.2583, 0.1780, and 0.3867, respectively. This means that distance to road has a relatively stronger influence on the distribution of residential areas for that period. Cramer’s V value of distance to anthropogenic disturbances with the same land categories for the same period were 0.1870, 0.1464 and 0.3394, respectively. Thus, distance to roads appears to be a good predictor of settlement distribution as new settlements tend to occur in proximity to transport networks. These also indicate that distance to anthropogenic disturbances has a similar influence on residential areas as does distance to road. Rainfall showed a good association with irrigated farmland in all periods, with values of 0.2147, 0.2517, and 0.2518.

Table 5.2. Potential explanatory variables based on Cramer's V values for all three periods.

	Period	Distance to Roads	Dist. to Anthro Dist.	Ave. Mean Rainfall	Ave. Mean Temp.	Slope	Elevation
Overall	**1999-2010**	**0.1145**	**0.1019**	**0.1283**	**0.1171**	**0.0890**	**0.1162**
	2010-2018	**0.1149**	**0.1008**	**0.1406**	**0.1232**	**0.0946**	**0.1124**
	1999-2018	**0.1150**	**0.1009**	**0.1406**	**0.1232**	**0.0944**	**0.1125**
CPS	1999-2010	0.0000	0.0000	0.0567	0.0000	0.0000	0.0623
	2010-2018	0.0000	0.0000	0.0603	0.0000	0.0000	0.0878
	1999-2018	0.0000	0.0000	0.0603	0.0000	0.0000	0.0877
DAP	1999-2010	0.0679	0.0898	0.2971	0.0452	0.0149	0.1883
	2010-2018	0.0841	0.0886	0.2809	0.0669	0.0161	0.1733
	1999-2018	0.0842	0.0887	0.2808	0.0670	0.0160	0.1735
EG	1999-2010	0.2583	0.1870	0.0112	0.2719	0.2474	0.0136
	2010-2018	0.2660	0.2018	0.0067	0.3129	0.2498	0.0062
	1999-2018	0.2663	0.2021	0.0067	0.3130	0.2492	0.0062
Ind	1999-2010	0.0190	0.0092	0.0356	0.0321	0.0035	0.0374
	2010-2018	0.0122	0.0038	0.0388	0.0095	0.0016	0.0414
	1999-2018	0.0122	0.0038	0.0388	0.0095	0.0016	0.0413
Ins	1999-2010	0.0728	0.0513	0.0351	0.0449	0.0088	0.0250
	2010-2018	0.0642	0.0430	0.0584	0.0483	0.0099	0.0617
	1999-2018	0.0667	0.0430	0.0588	0.0483	0.0099	0.0611
IAP	1999-2010	0.0161	0.0187	0.2147	0.0264	0.0037	0.1899
	2010-2018	0.0200	0.0221	0.2517	0.0418	0.0074	0.2417
	1999-2018	0.0198	0.0221	0.2518	0.0419	0.0074	0.2416
L	1999-2010	0.1780	0.1464	0.0968	0.1687	0.1702	0.2333

	2010-2018	0.1807	0.1626	0.0258	0.1802	0.1792	0.0193
	1999-2018	0.1809	0.1627	0.0258	0.1802	0.1794	0.0192

Table 5.2. Potential explanatory variables based on Cramer's V values for all three periods *(continued)*.

	Period	**Distance to Roads**	**Dist. to Anthro Dist.**	**Ave. Mean Rainfall**	**Ave. Mean Temp.**	**Slope**	**Elevation**
M	1999-2010	0.0894	0.1217	0.0159	0.1583	0.0854	0.0159
	2010-2018	0.0266	0.0157	0.0396	0.0315	0.0123	0.0341
	1999-2018	0.0266	0.0158	0.0396	0.0315	0.0124	0.0341
NC	1999-2010	0.0141	0.0089	0.1500	0.0115	0.0133	0.1563
	2010-2018	0.0410	0.0213	0.1557	0.0613	0.0090	0.1524
	1999-2018	0.0411	0.0213	0.1557	0.0615	0.0092	0.1537
OMU	1999-2010	0.0658	0.0331	0.1770	0.1148	0.0954	0.0660
	2010-2018	0.0642	0.0334	0.2519	0.1122	0.0999	0.0792
	1999-2018	0.0643	0.0333	0.2518	0.1122	0.0996	0.0798
RNE	1999-2010	0.0700	0.0443	0.2823	0.0968	0.0734	0.1316
	2010-2018	0.0607	0.0296	0.3060	0.1430	0.1115	0.1753
	1999-2018	0.0609	0.0296	0.3061	0.1431	0.1110	0.1756
R	1999-2010	0.3867	0.3394	0.1258	0.3590	0.2283	0.1807
	2010-2018	0.3806	0.3256	0.1471	0.3705	0.2831	0.2042
	1999-2018	0.3811	0.3260	0.1470	0.3707	0.2827	0.2042
TC	1999-2010	0.1469	0.1681	0.0161	0.1156	0.0351	0.0149
	2010-2018	0.1605	0.1919	0.0178	0.3705	0.0506	0.0105
	1999-2018	0.1605	0.1919	0.0178	0.1382	0.0507	0.0105
WTD	1999-2010	0.0190	0.0261	0.0146	0.0250	0.0037	0.0113
	2010-2018	0.0732	0.0499	0.0179	0.0430	0.0096	0.0130

	1999-2018	0.0733	0.0498	0.0178	0.0431	0.0093	0.0129
WF	1999-2010	0.0207	0.0142	0.0503	0.0212	0.0028	0.0529
	2010-2018	0.0210	0.0159	0.0550	0.0206	0.0046	0.0598
	1999-2018	0.0207	0.0158	0.0549	0.0206	0.0045	0.0596

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

5.4.2 GIS Analysis of Historical LULC Maps

Spatial distribution (Figure 5.6) and assessment (Figure 5.7) of the 1999 LULC showed that the majority of the land area was covered by agriculture. Of these, natural environments composed the maximum, with 713,186 ha, followed by dryland (325,786 ha) and irrigated (99,362 ha) croplands. Additionally, there were areas designated for animal livestock and production (78,904 ha). Other minimally used areas covered 42,089 ha, while residential areas occupied only 13,636 ha. The rest of the key categories, namely spaces for commercial and public services, areas for electricity generation, industrial properties, institutional facilities, and mining areas, including other categories included in this study, each covered no more than 10,000 ha.

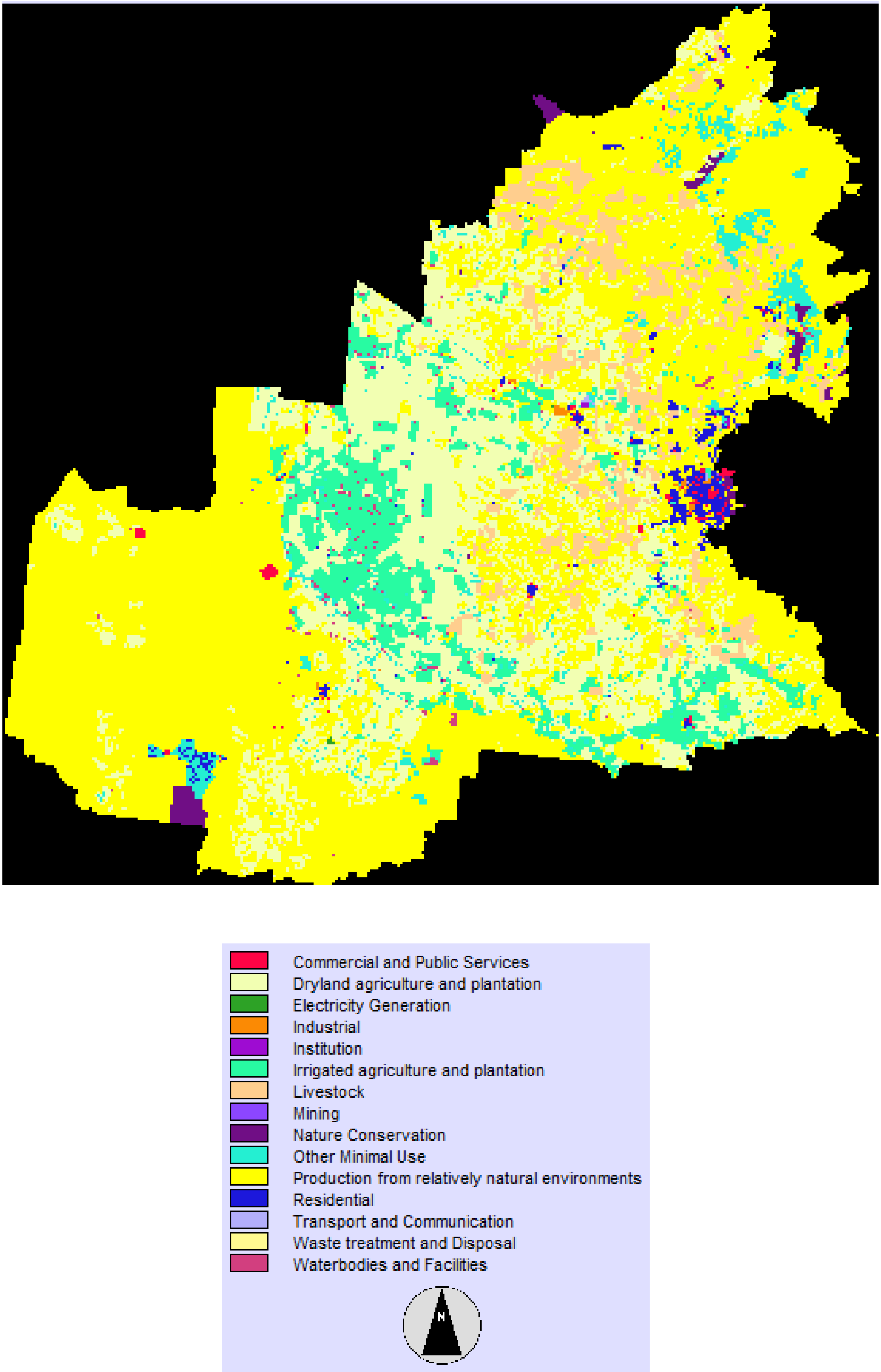


Figure 5.6. Toowoomba Region LULC Map of 1999.

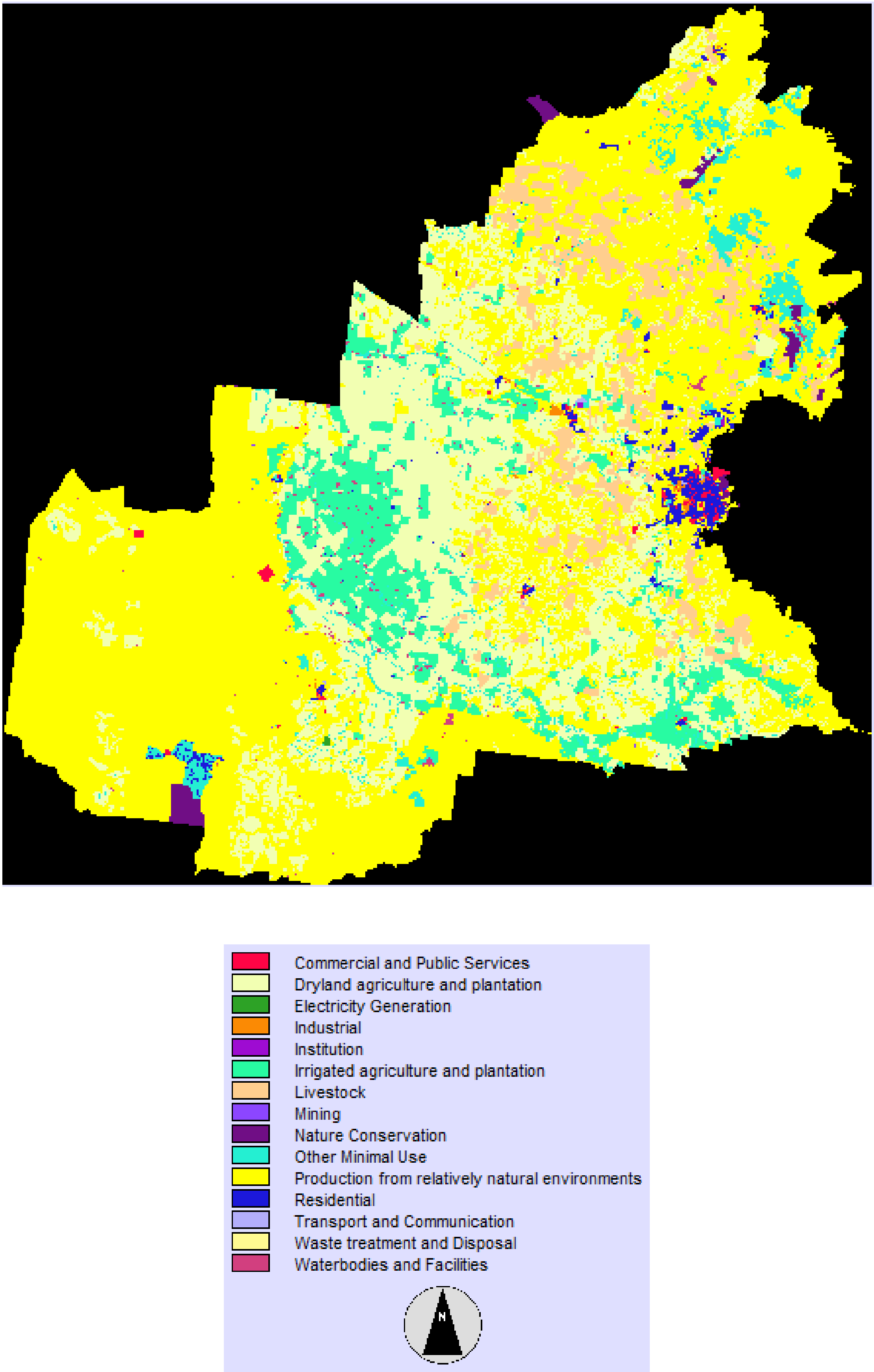


Figure 5.7. Toowoomba Region LULC Map of 2010.

Assessment of the 2010 LULC revealed that the region maintained its 1999 LULC distribution, with agriculture as the principal LULC category (Figures 5.8 and 5.9). There were no major expansions or reductions observed, and the distribution of the categories remained consistent with the previous study year.

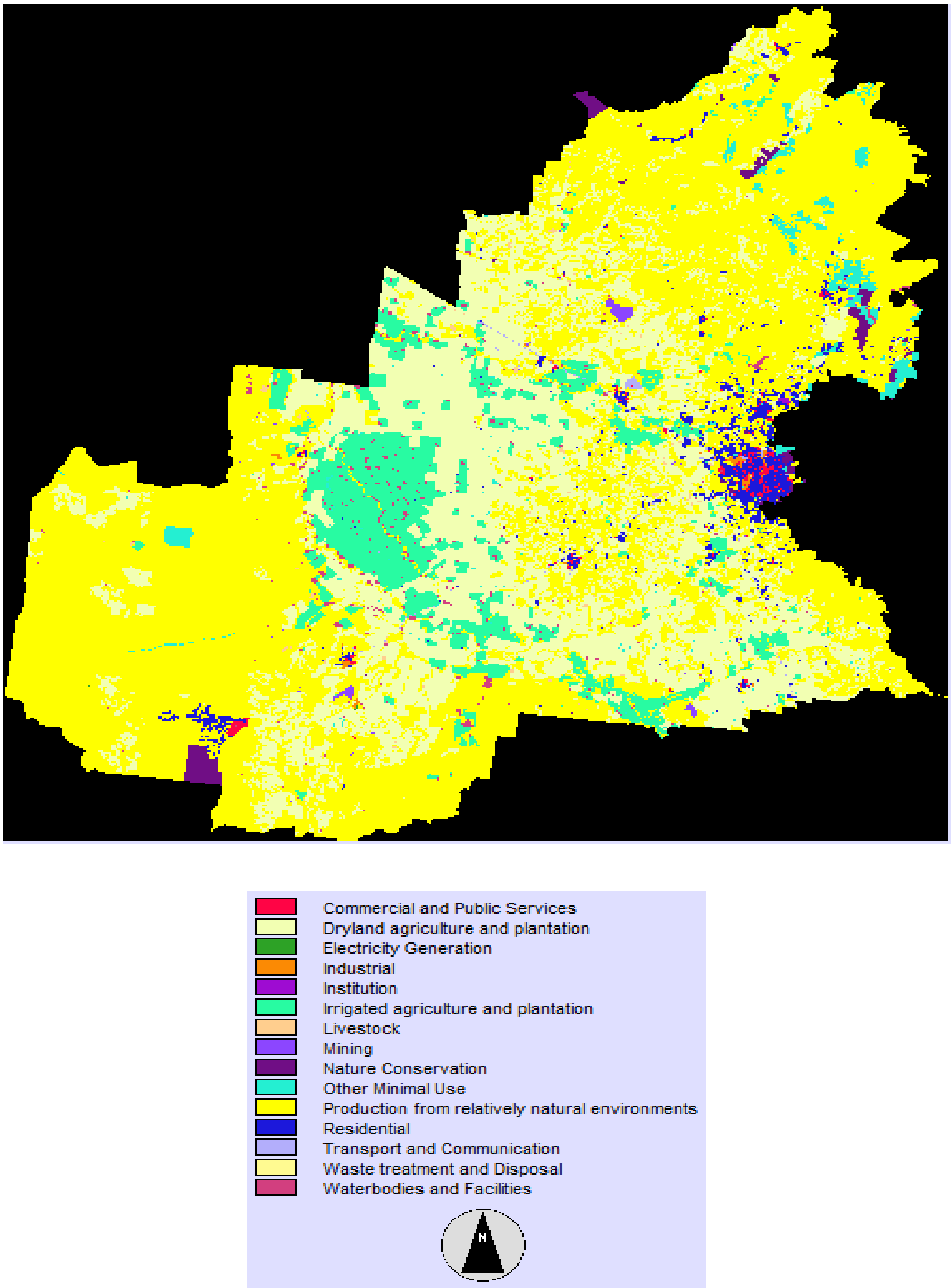


Figure 5.8. Toowoomba Region LULC Map of 2018.

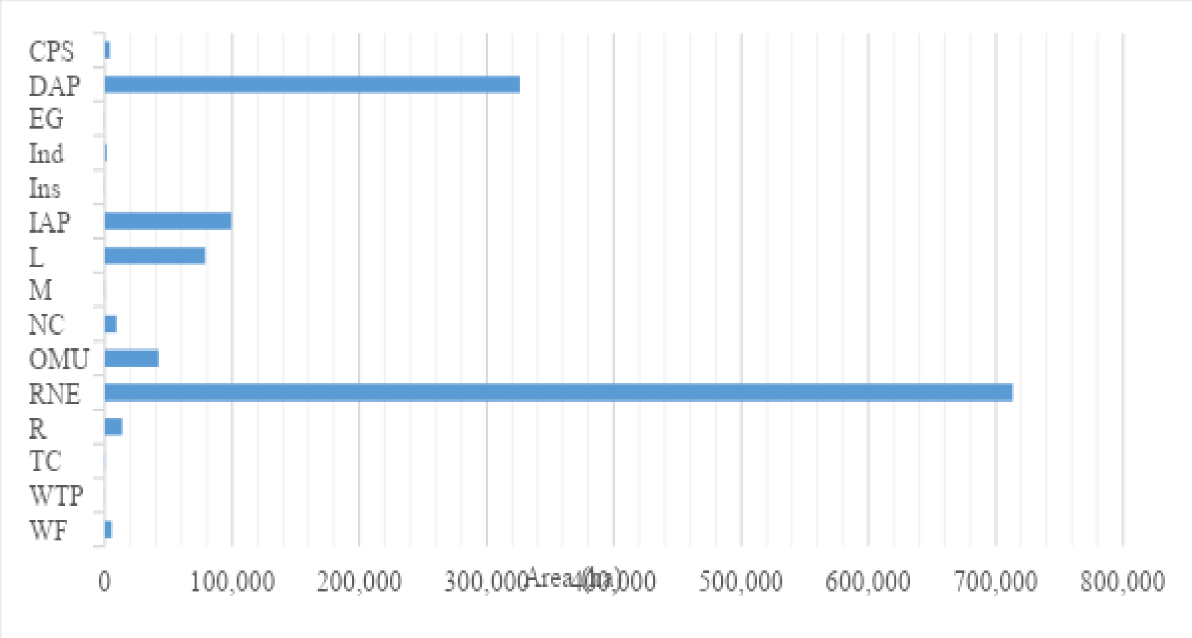


Figure 5.9. Area covered in percentage by each LULC category in 1999.

The analysis of the 2018 LULC showed that agriculture remained the dominant category in the region (Figures 5.10 and 5.11). Natural environments still occupied most of the agricultural landscape at 716,809 ha, followed by dryland agriculture (399,343 ha), irrigated cropland (105,979 ha). The area for livestock significantly reduced to 2,842 ha. By this time, other minimally used areas shrank to 16,100 ha, while the residential area slightly increased to 24,280 ha. Spaces for commercial and public services, areas for electricity generation, industrial properties, institutional facilities, and other LULC features each remained below 10,000 ha, with slight increases observed.

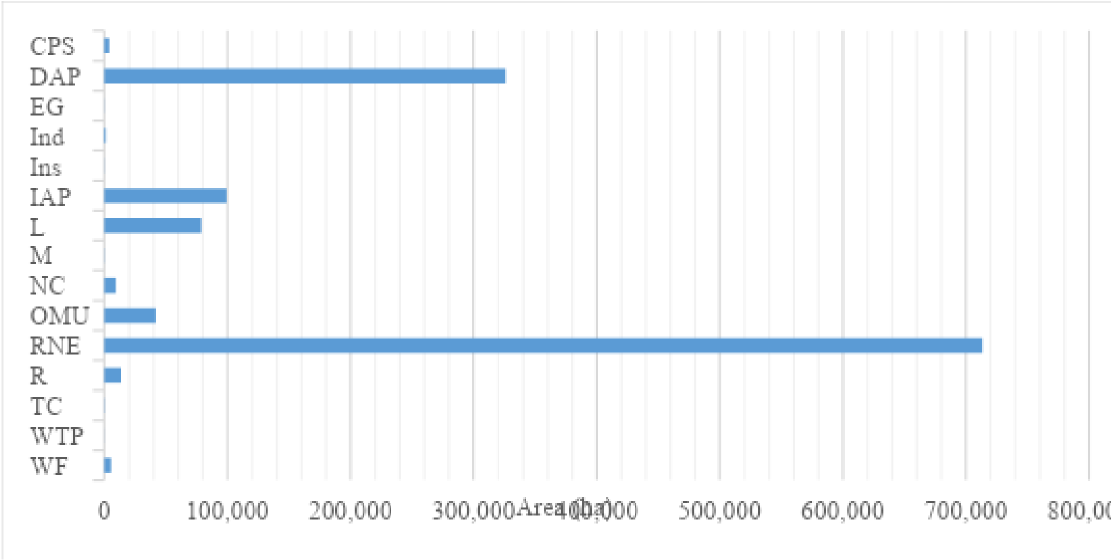


Figure 5.10. Area covered in percentage by each LULC category in 2010.

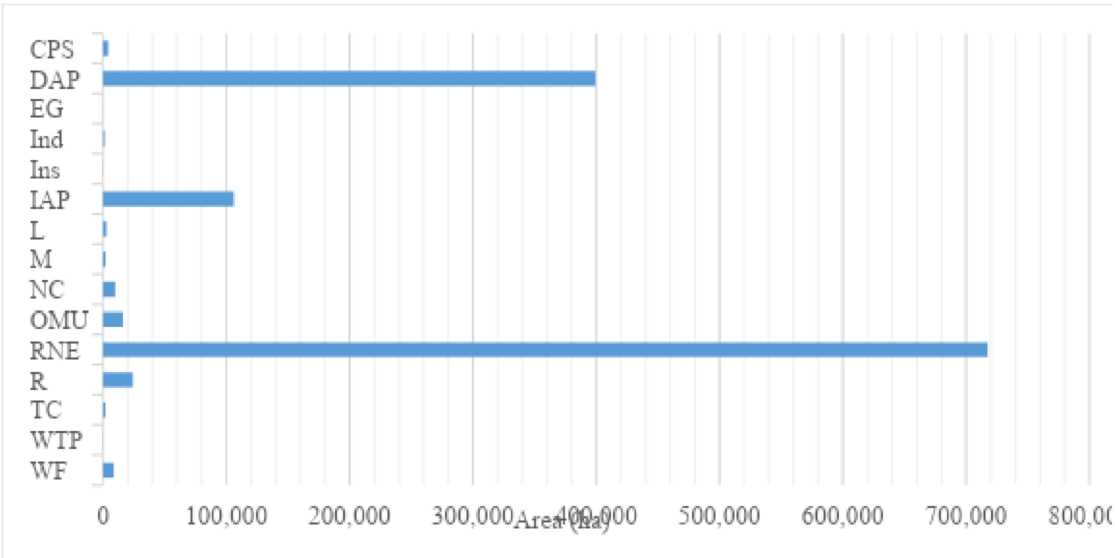


Figure 5.11. Area covered in percentage by each LULC category in 2018.

5.4.3 Trends of Land Use/Land Cover Change

Within the period of 20 years (1999-2018), major changes observed were the significant increase in the mining area and the sharp decline in the area for livestock. The mining area expanded by 88.80%, with an average annual growth rate of 100% (Figure 5.12). Most of the land was sourced from relatively natural environments, drylands, and irrigated croplands (Figure 5.13).

Although there were apparent overall expansions observed in the majority of the key classes during these years, the expansion pattern varied across individual periods, as outlined below. The land distribution of the categories in all periods is displayed in Table 5.3.

Table 5.3. Temporal distribution in hectares of land use categories by year.

LULC Types	*1999*		*2010*		*2018*	
	Area (ha)	**Percentage (%)**	**Area (ha)**	**Percentage (%)**	**Area (ha)**	**Percentage (%)**
CPS	3,957	0.31	3,924	0.30	4,229	0.33
DAP	325,786	25.18	326,077	25.21	399,343	30.87
EG	179	0.01	180	0.01	66	0.01
Ind	1,296	0.10	1,280	0.10	1,327	0.10
Ins	172	0.01	171	0.01	238	0.02
IAP	99,362	7.68	99,437	7.69	105,979	8.19
L	78,904	6.10	78,920	6.10	2,842	0.22
M	239	0.02	233	0.02	2,144	0.17
NC	9,181	0.71	9,149	0.71	9,660	0.75
OMU	42,089	3.25	41,673	3.22	16,100	1.24
RNE	713,186	55.12	713,260	55.13	716,809	55.41
R	13,636	1.05	13,632	1.05	24,280	1.88
TC	336	0.03	333	0.03	2,010	0.16
WTD	98	0.01	99	0.01	124	0.01
WF	5,410	0.42	5,322	0.41	8,539	0.66

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

5.4.3.1 Period One (1999-2010)

It was observed that the speed of the expansion of the key classes was slower before 2010. Expansion accelerated remarkably in the preceding periods (Figure 5.12). The increase in the area for electricity generation and the key agricultural categories, along with the decline in mining area and industrial space, were the major transformations observed. Irrigated cropland increased by 72 ha (0.07%) at a rate of 6.57% annually. This increase resulted from the use of large portions of other minimally used areas, a relatively natural environment, dryland agricultural area, and water bodies and facilities. The area for livestock production increased by 13 ha (0.02%) at an annual rate of 1.17%, mostly gained from dryland agricultural areas. Mining area and industrial space reduced by 2.51% and 1.21%, respectively, due to conversion mainly to a relatively natural environment. Space for commercial and public services reduced by 0.85%, having been lost to a relatively natural environment and residential area. Institutional facility and residential area, which decreased by 0.21% and 0.02%, respectively, experienced the least change (Figure 5.14).

5.4.3.2 Period Two (1999-2010)

Within a span of nine years, the region experienced significant expansions in the areas of mining, residential, and institutional facilities (Figure 5.12). The mining area expanded by 89.13%, gaining significantly from the relatively natural environment and dryland agricultural area. The expansion of residential areas by 43.86%, at a rate of 13 times annually, was attributed to the transition from other minimally used areas, dryland agriculture, and areas for animal and livestock production. The enlargement of institutional property (27.89%) resulted from gaining land from other minimally used areas. Irrigated cropland continued to increase by 6.17%, at the expense of the relatively natural environment, dryland agricultural area, areas for animal and livestock production, and other minimally used areas. Space for commercial and public services increased by 7.21%, mainly gained from residential areas, the relatively natural environment, and other minimally used areas. Lastly, industrial property increased by 3.56%, gaining portions from the relatively natural environment, areas for electricity generation, residential areas, and other minimally used areas. Meanwhile, the area for livestock production reduced sharply by almost 27 times, losing 98.91% in favor of the relatively natural environment, dryland and irrigated croplands. The area for electricity generation also decreased by 172.79%, mainly due to the transition to industrial property (Figure 5.15).

Figure 5.12. Trend of LULC change in Toowoomba Region from 1999 to 2018: (A) Production from relatively natural environments, and dryland agriculture and plantations; (B) Commercial and public services, industrial, nature conservation, and waterbodies and facilities; (C) Irrigated agriculture and plantations, livestock, other minimal use, and residential; (D) Mining, transport and communication, electricity generation, institutional, and waste treatment and disposal.

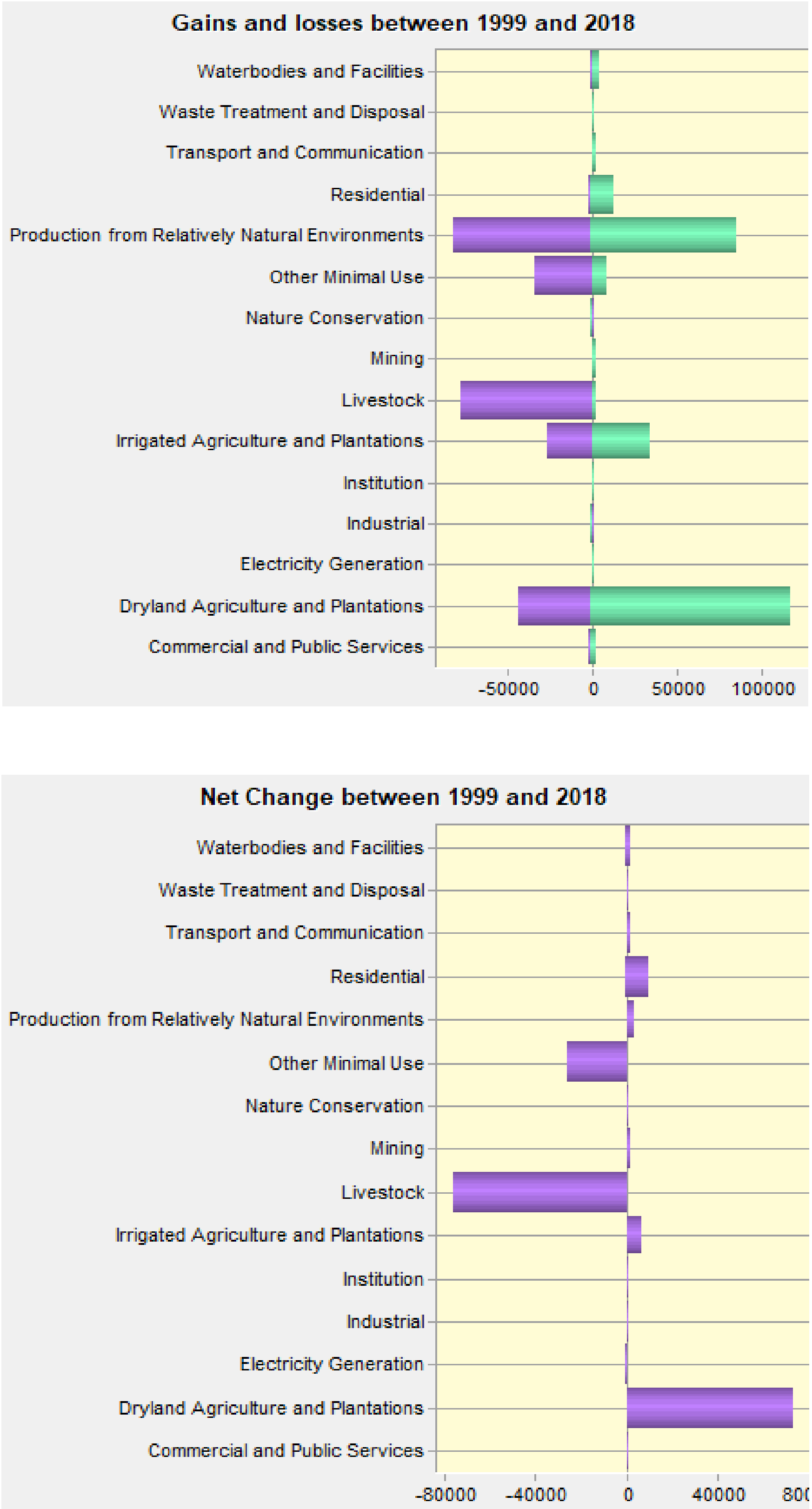
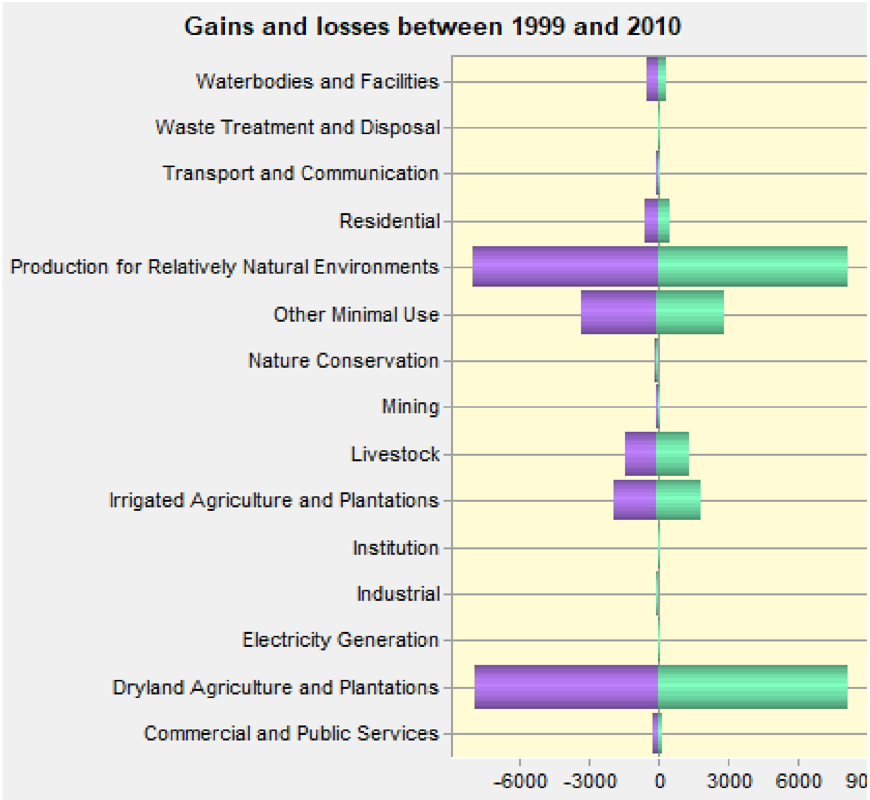


Figure 5.13. Change analysis for 1999-2018 LULC types.



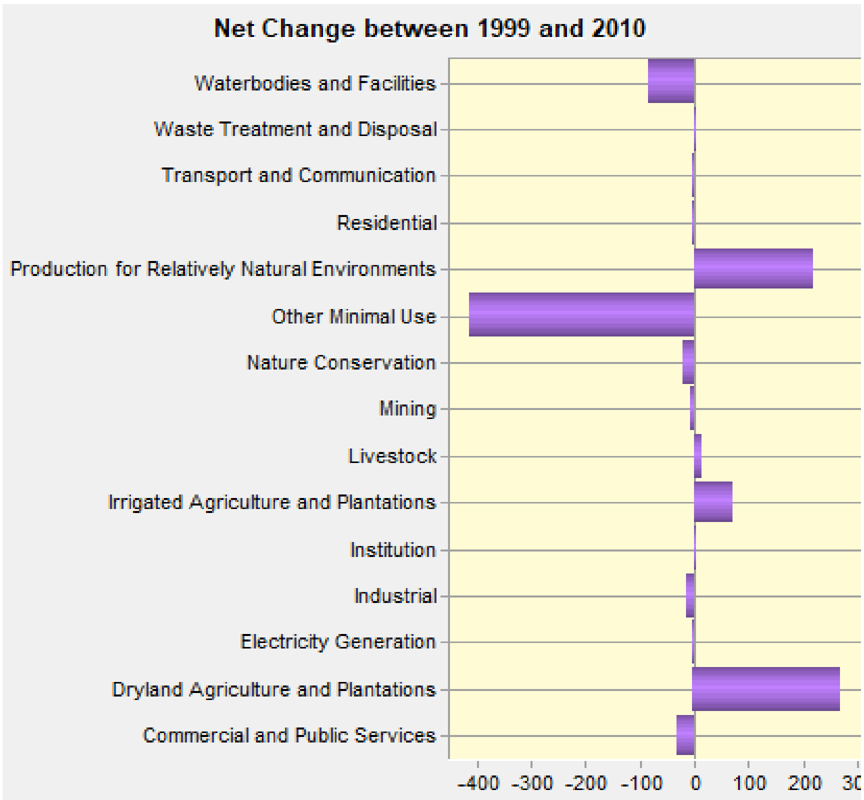
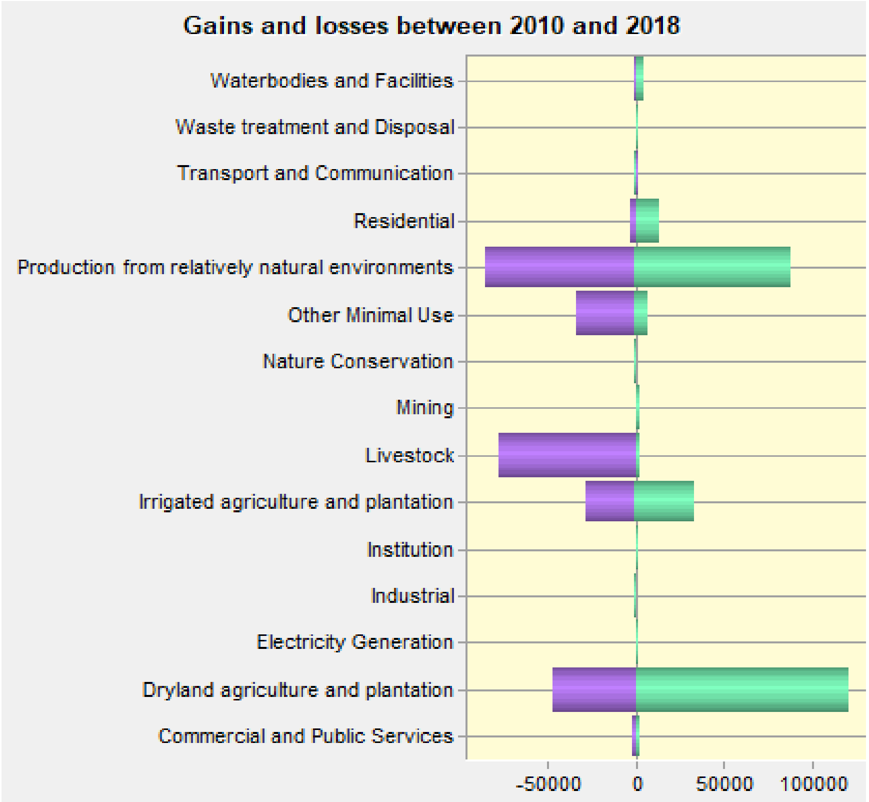


Figure 5.14. Change Analysis for 1999-2010 LULC types.



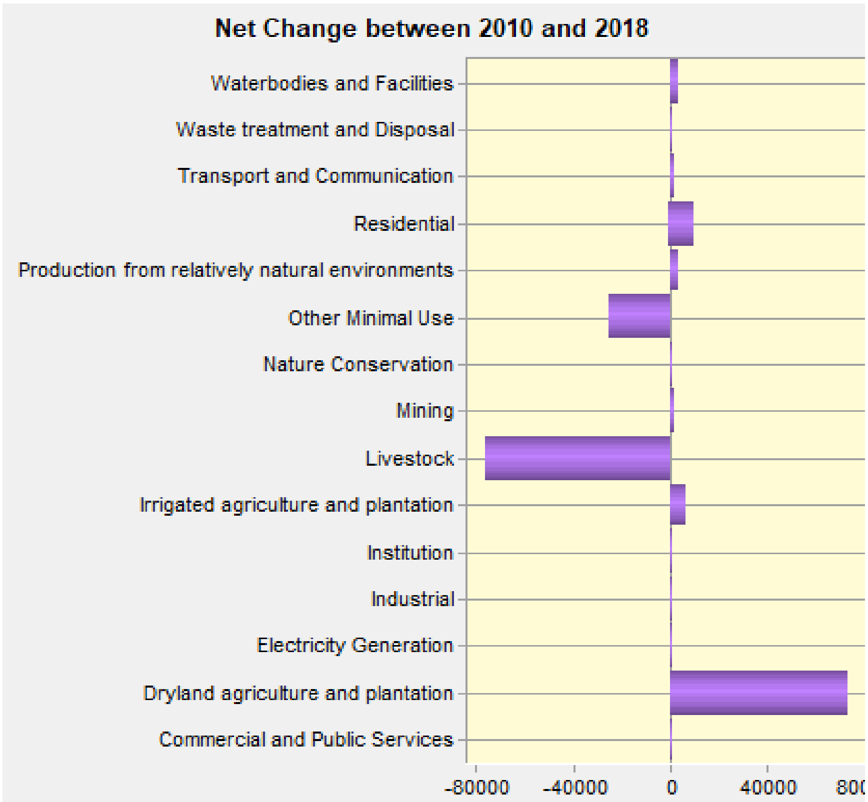


Figure 5.15. Change Analysis for 2010-2018 LULC types.

5.5 Discussion of Modeled Outcomes

Probable transition directions of the LULC categories in Toowoomba Region for 2038 and 2058 are shown in the transition probability matrix produced by the Markov Chain model for every period (Tables 5.4, 5.6, and 5.8). The transition probability matrices produced by the Markov Chain Analysis provide details on the probability of transition between categories during the periods. The rows indicate the earlier categories, while the columns denote the later categories (Hamad et al., 2018; Pontius et al., 2004; Varun et al., 2014). The diagonal values (in bold) indicate the amount of persistence or probability of a class to remain unchanged from the earlier state to the later state (Jazouli et al., 2019; Pontius et al., 2004).

5.5.1 Base Case Scenario (1999-2018)

Simulation of this period serves as the base case scenario. It reflects the actual trends and business-as-usual (BAU) status of the region. The possibility of each key category to persist from 1999 to 2018 was generally very low. The relatively natural environment was the class to which these areas are more likely to be converted (Table 5.4). After twenty years (2038), all key categories are projected to increase except for areas allocated for electricity generation, animal and livestock production, and residential properties, which are likely to decline to 28 ha, 1,114 ha, and 14,481 ha, respectively. After another twenty years (2058), areas allocated for electricity generation and residential properties are expected to regain, while areas for animal and livestock production would continue to decline to 1,110 ha. Institutional spaces would also decrease to 262 ha. Irrigated agricultural areas and plantations, spaces for commercial and public services, industrial spaces, and mining areas are expected to continue to expand until 2058 (Figure 5.16, Table 5.5).

These years were characterized by a series of droughts spanning practically the whole period. The Millennium Drought, more popularly known as the "Big Dry," commenced with low rainfall conditions around late 1996 through 1997 and gradually worsened through particularly dry years in 2001 and 2003. In particular, the year 1999 was dry for southeast Queensland, with temperatures recorded generally below normal (Commonwealth of Australia, 2000). The decade-long drought ended with destructive heavy rains in 2009 and 2010 (Heberger, 2012). As reported by BOM (2011), El Niño at the beginning of 2010 rapidly shifted into La Niña around autumn.

Table 5.4. Transition probability matrix (in %) based on land use maps of 1999 and 2018 for 2038 (top) and 2058 (bottom).

LULC	Proj. Year	**CPS**	DAP	**EG**	**Ind**	**Ins**	**IAP**	**L**	**M**	NC	OMU	RNE	**R**	TC	WTP	WF
CPS	2038	**36.29**	2.22	0	2.06	0.25	0	0.51	0.36	3.65	10.21	34.2	9.63	0.07	0.26	0.29
	2058	**16.67**	7.66	1	1.65	0.21	1.14	0.35	0.45	4.7	5.73	48.25	11.8	0.52	0.24	0.63
DAP	2038	0.01	**85.19**	0	0.02	0	8.52	0.08	0.3	0.01	0.1	5.24	0.29	0.06	0	0.19
	2058	0.05	**75.88**	0	0.05	0	12.82	0.09	0.45	0.02	0.17	9.33	0.58	0.13	0	0.42
EG	2038	2.4	8.46	**5.76**	57.7	0	1.93	1.64	0	0	0	20.23	0.46	1.05	0.1	0.26
	2058	5.6	16.44	**0.86**	28.6	0	7.24	1.28	0.05	0.04	1.01	29.05	4.61	3.07	0.29	1.84
Ind	2038	9.25	10.9	0.03	**36.65**	0	9.88	1.79	0	0	1.4	15.1	7.36	4.12	0.5	3.02
	2058	7.61	18.2	0.02	**16.37**	0.02	11.48	0.9	0.08	0.31	1.75	24.63	9.39	5.05	0.44	3.75
Ins	2038	4.37	0.2	0	0	**35.99**	0	0.02	0	0	0	0.45	0.89	58.08	0	0
	2058	7.76	1.06	0	0.48	**15.61**	0.03	0.14	0.01	0.11	0.43	3.5	1.65	69.21	0.01	0.01
IAP	2038	0.01	27.05	0	0.09	0	**69.62**	0.06	0	0	0.11	1.85	0.19	0.05	0	0.97
	2058	0.05	40.8	0	0.11	0	**52.11**	0.08	0.07	0.01	0.14	4.62	0.4	0.1	0	1.51
L	2038	0.04	43.2	0	0.01	0	2.65	**0.18**	0.06	0.08	0.58	52.41	0.56	0.1	0.01	0.13
	2058	0.17	42.05	0	0.04	0	5.74	**0.15**	0.24	0.13	0.66	48.9	1.35	0.19	0.01	0.37
M	2038	0	0.74	0	4.07	0	0	0.04	**69.16**	0	0.04	23.29	1.05	0	1.61	0
	2058	0.54	3.74	0	4.17	0	0.56	0.14	**48.96**	0.02	0.34	37.13	2.23	0.16	1.86	0.15
NC	2038	1	0.18	0	0	0	0.01	0.01	0	**94.12**	0.81	3.15	0.57	0.15	0	0.01
	2058	1.33	0.79	0	0.02	0	0.1	0.02	0.01	**88.64**	0.96	6.63	1.16	0.28	0	0.05
OMU	2038	0.23	16.05	0.01	0.09	0.33	4.22	0.23	0.16	0.46	**8.71**	62.8	4.27	1.08	0.01	1.36
	2058	0.58	21.25	0.01	0.14	0.17	5.23	0.18	0.26	0.54	**2.27**	61.77	4.75	1.31	0.01	1.51

RNE	2038	0.2	7.99	0	0.04	0	0.7	0.2	0.15	0.08	1.08	**87.72**	1.47	0.11	0.01	0.26
	2058	0.36	14.12	0	0.08	0.01	1.9	0.19	0.26	0.16	1.08	**78.61**	2.51	0	0.01	0.48
R	2038	6.26	2.14	0.03	1.07	0.01	0.67	0.11	0	0.26	0.94	7.84	**79.71**	0.81	0	0.16
	2058	7.15	4.92	0.03	1.33	0.02	1.4	0.16	0.04	0.69	147	16.14	**64.86**	1.41	0.02	0.36
TC	2038	8.53	1.01	0	0.8	0	0	0.2	0	0	0.1	1.57	0.21	**87.58**	0	0
	2058	10.35	2.35	0	1.13	0.02	1.4	0.16	0.04	0.69	1.47	16.14	64.86	**1.41**	0.02	0.36
WTP	2038	9.96	0	0	0.11	0	0	0.04	0	0	0.33	37.7	1.24	0.08	**50.54**	0
	2058	8.73	2.99	0	0.3	0.02	0.25	0.14	0.08	0.32	1.42	54.48	3.1	0.19	**27.87**	0
WF	2038	0.17	1.76	0.04	0	0	4.8	0.53	0.06	0	0.69	6.84	0	0.09	0.03	**85**
	2058	0.23	5.38	0.04	0.04	0	7.46	0.48	0.11	0.01	0.74	12.63	0.15	0.17	0.04	**72.54**

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

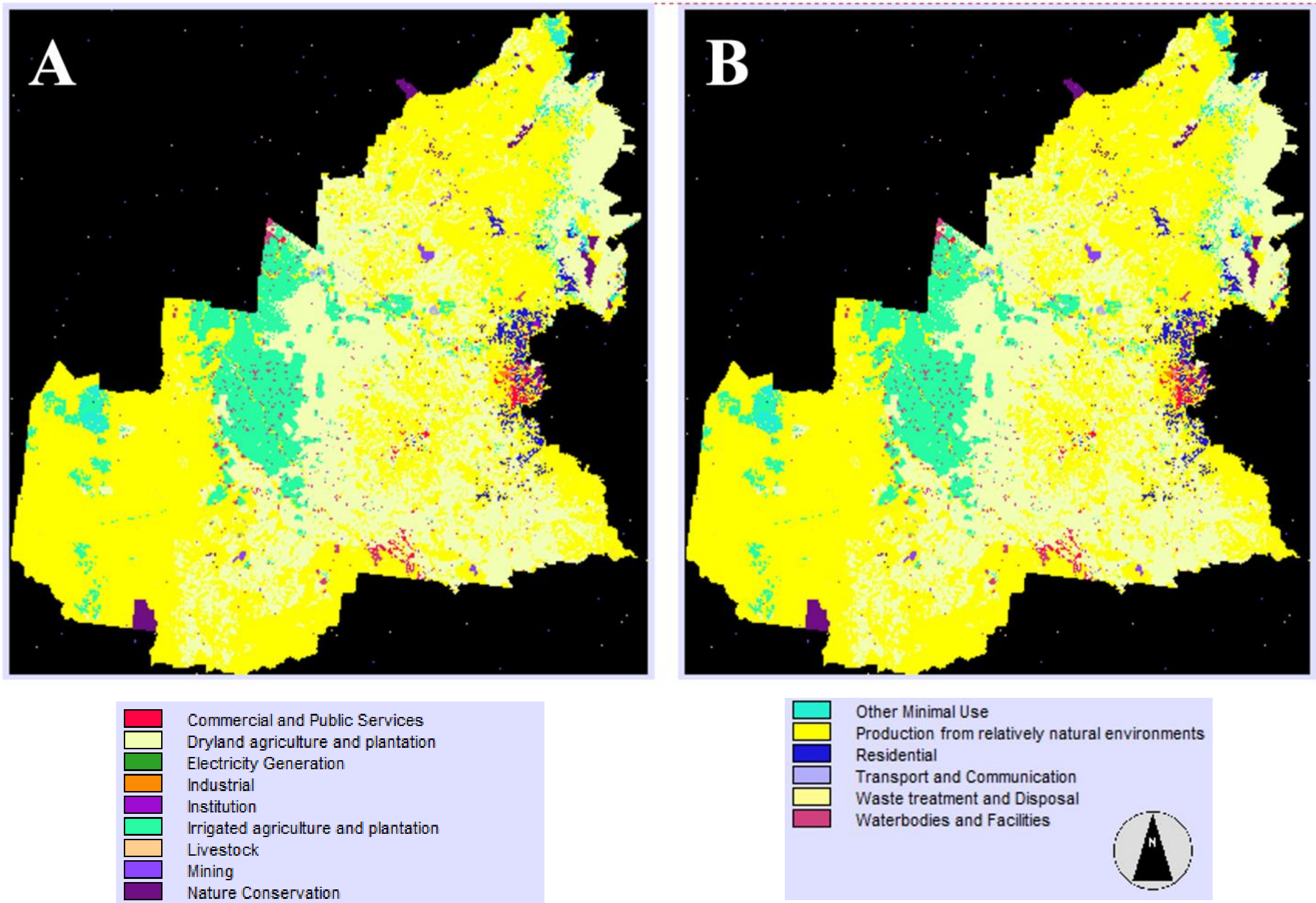


Figure 5.16. Land cover classes predicted for 2038 (A) and 2058 (B) using 1999 and 2018 datasets.

Table 5.5. Predicted distribution of LULC categories (in ha) based on 1999-2018 for 2038-2058.

LULC	1999	2018	2038		2058	
			Area	%Δ	Area	%Δ
CPS	3,956	4,229	5,734	26.25	6,503	11.83
DAP	325,783	399,403	452,129	11.66	490,449	7.81
EG	179	66	28	-137.10	47	40.84
Ind	1,296	1,327	1,435	7.51	1,521	5.64
Ins	172	238	290	18.17	262	-10.86
IAP	99,355	105,995	114,363	7.32	122,221	6.43
L	78,902	2,842	1,114	-155.10	1,110	-0.40
M	240	2,144	3,887	44.84	4,879	20.33
NC	9,187	9,658	9,992	3.34	10,233	2.36
OMU	42,096	16,090	9,625	-67.17	8,853	-8.72
RNE	713,577	717,281	666,597	-7.60	609,090	-9.44
R	13,638	24,279	14,481	-67.66	21,543	32.78
TC	336	2,013	3,170	36.50	4,132	23.38
WTP	98	124	124	-0.07	124	0
WF	5,410	8,538	11,259	24.17	13,266	15.13

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

During this year, Queensland experienced unusually heavy rainfalls, making it the wettest year on record for the state at that time. BOM further reported that the heavy rainfall significantly reversed the shortage across MDB from 26% in 2010 to 80% in early 2011. This was followed by rainfall deficiencies between April 2012 and January 2014, during which BOM recorded less than 70% of the long-term average rainfall for most of Queensland and the inland of the Great Dividing Range in New South Wales (Australian Institute for Disaster and Resilience (AIDR), 2016). Lastly, the 2017-2019 drought, during which most of MDB experienced dry conditions and significantly below-average rainfall (BOM, 2021b). The year 2018 marked the fifth-warmest year on record for Queensland, with drought affecting much of the state. Rainfall was reported at 15% below average across the south. Bushfires, heatwaves, extreme rainfall and flooding, and severe thunderstorms characterized this year (BOM, 2019).

5.5.1.1 Dryland and Irrigated Agriculture and Plantations, and Livestock

Assessment of the variables' predictive power using Cramer’s V revealed that rainfall had the strongest influence over the distribution of dryland and irrigated croplands during this period (Table 5.2). Despite the series of prolonged dry spells and below-average rainfalls between these years, the country experienced tropical cyclones and a general increase in the number of days of rainfall between 1900 and 2017 due to aberrant weather patterns (BOM, 2021). This is supported by records from observed weather stations, which showed that a higher proportion of total annual variability in the last decades came from heavy rains, despite the large range of natural variability in rainfall (BOM and CSIRO, 2018). Although cyclones could be damaging, especially to coastal areas, they are a major source of rainfall for the dryland inland areas (State of Queensland, 2018), such as the Toowoomba Region, which is prone to prolonged dry and warm conditions. Hence, this could have sustained the region’s croplands throughout the series of drought events between 1999 and 2018.

Results showed expansion in both dryland (11.66% and 7.81%) and irrigated (7.32% and 6.43%) croplands by 2038 and 2058, respectively (Table 5.5). Over the years, land area expansion has been the agriculture sector’s response to the pressure of the growing population and its changing dietary preferences. This is likely to continue in the future Toowoomba Region to keep pace with the populace within, around, and abroad. It is estimated that by 2031 and 2051, the regional population will reach about 210,484 (TRC, 2014) and 236,000 (TRC, 2019), respectively, while the global population is expected to grow to 8.5 billion by 2030, 9.7 billion by 2050, and 11.2 billion by 2100 (UN, 2015).

Several implications can arise from such expansions that could trigger a chain of more expansions. Liliane & Charles (2020) explained that as croplands expand, intensive management practices, including irrigation, application of large quantities of inorganic fertilizer, and synthetic chemicals, to name a few, become more intensive. Arora (2019) adds that long-term effects of such practices have shown to result in degradation, rendering the land infertile and non-arable. Consequently, this leads to the conversion of non-agricultural areas and disturbance of new ecosystems, while formerly productive croplands become abandoned. Another implication would be the increase in agricultural CO_2 and non-CO_2 emissions, as cropland expansion entails the use of fossil energy-consuming farm equipment as well as the use of manure for fertilizer. Campbell et al. (2017) also found that crop yield was reduced by anthropogenic GHGs from agriculture, particularly methane and nitrous oxide. Reduction in crop yield, according to Shindell (2016), will drive future expansion of agricultural lands.

Studies have shown that agricultural GHG emissions contribute to accelerated warming, thereby aggravating altered precipitation patterns. These studies have underscored the direct impact of intensified temperature on crop productivity reduction (Hatfield & Prueger, 2015; Liliane & Charles, 2020; C. Zhao et al., 2017). Kumaraswamy & Shetty (2016) reported that drought or moisture stress accounts for 30-70% loss of crop yield. The immediate response of certain plants to drought stress is the activation and accumulation of abscisic acid (ABA), which triggers stomatal closure (W. Li & Cui, 2014), as a means to save water at the expense of CO_2 uptake, which is important in photosynthesis and plant growth as well as the formation of carbohydrates. Drought also results in abnormal metabolism that impairs plant growth, therefore, limiting crop productivity (Hussain et al., 2019) and/or causing plant mortality (Liliane & Charles, 2020). As a result, crop producers need to expand their cropping area to compensate for low production. Therefore, these could also possibly explain the future expansion of both dryland and irrigated croplands.

The predicted expansions of both dryland and irrigated croplands in this study align with several agricultural land use simulations, which have highlighted population as a major factor in the expansion. According to the Organization for Economic Co-operation and Development (OECD) Environmental Outlook to 2050 (2012), there will be a global expansion of agricultural land, albeit at a decreasing rate, in the next decade to correspond to the increasing demand for food and changing dietary preferences of the growing population, unless new mitigation policies will be established before 2050. The report further suggested that increasing competition for scarce land is expected in the coming decades as a consequence of inaction.

The increase in dryland agricultural area in this study appears logical in the context of climate change. The study by Yao et al. (2020) projected that drylands will substantially expand at an accelerated rate from extended warming and drying conditions. It further stated that the conversion of humid ecosystems into dryland ecosystems and the eventual degradation of fragile dryland subtypes will become widespread as prolonged extreme heat prevails in the next century. Reporting a similar outcome, Huang et al. (2016) added that dryland area may possibly cover half of the global land surface by the end of the century at a rate of 11% under the Representative Concentration Pathway (RCP) 5.4 and 23% under RCP8.5 scenarios. The observed strong association of rainfall with dryland expansion in this study is consistent with the findings of Yao et al. (2020) and other previous studies that highlighted precipitation as the most important driver of dryland vegetation dynamics. On the aspect of productivity, Yao et al. (2020) found that the productivity of drylands will experience an overall increase by 12% by 2100. However, as more drylands replace productive ecosystems in response to irregular patterns in precipitation and temperature, productivity is expected to eventually decline.

The expansion of irrigated cropland in this study is similar to the existing projection trends of other simulations. Alexandratos & Bruinsma (2012) and Fischer et al. (2007) reported a global increase in irrigated cropland of around 240-450 million hectares by 2050. However, a recent study by Puy et al. (2020) contested these figures, arguing that the extent of irrigated cropland by 2050 could reach as high as 1.8 billion hectares. Pointing to the likelihood of underestimating population growth, the latter study emphasized that previous projections assumed that the extent of land and water will be available for agriculture without having to find new sources.

In contrast to croplands, the model predicted a reduction in animal and livestock production area by 2038 and 2058. Proximity to roads and temperature were found to have strong influences over its decline. Due to the intense hot and dry weather conditions of the most recent drought during this period, much of eastern Australia experienced poor pasture growth, high grain prices, and low water shortages. Therefore, this could explain the reduction of pastureland and grazing area for livestock. Farrell (2018) reported that cattle producers either reduced stocking rates or destocked properties as pasturelands were significantly affected by lower rainfall. Thornton

(2010) and Rojas-Downing et al. (2017) both stated that production will be limited by climate variability, carbon constraints, and competition over land and water as agricultural products will increase by 70% by 2050 (FAO, 2009). CSIRO forecasted that by 2030, water availability in MDB will drop to 35-50% (Heberger, 2012). In connection to the projected expansion of croplands in this study, competition or shift in land use in favor of cropland due to increasing population and its effect on water availability could possibly explain the decline of the area for livestock production.

Relatively natural environments, primarily composed of grazing native vegetation, were also seen to decrease by 2038 and 2058, suggesting that this category could also be converted to agricultural use. This observed decline is similar to the result of the scenario model by Mu et al. (2017), which showed the inverse relationship of marginal and pasturelands with the increase of cropland by the end of the 21st century.

5.5.1.2 Mining

The remarkable increase in mining area during this period is likely due to the revival of the mining boom in 2011-2012 (Koukoulas, 2015; T. D. Pham et al., 2013), which saw the international surge in demand for liquified natural gas, coal, and iron ore (Phillips, 2016).

Projections in this study revealed that mining area will increase by 2038 and 2058. The results align with what analysts say, that fossil fuels will still account for 80% of the world's primary energy mix (State of Queensland, 2010) and will still dominate throughout 2050 (Nyquist, 2016). These expansions reflect the region's "bold ambition" by 2038. Global trends have shown that population growth, industrialization, and urbanization result in an increase in demand for commodities from the mining and metal industries (State of Queensland, 2010; World Economic Forum, 2010), although the fuel mix demand will be dictated by the pattern of development (State of Queensland, 2010). In addition, the increase in mining area could also be a reflection of Queensland's efforts to maintain its position as a reliable source of fuel for Asia and the Pacific region (State of Queensland, 2010).

Considering the international pressure to reduce carbon emissions, the transition away from fossil fuels could prove to be a challenge because mining is Queensland's largest economic contributor, and coal is its biggest export and its primary energy source for electricity. Despite this, both the Australian and Queensland governments have committed to meet the three climate targets under the Paris Agreement. The first target is to curb carbon emissions to at least 30% less than that of its 2005 levels. The second is to power half of Queensland with renewable energy by 2030. The third is to achieve zero net emissions by 2050. Queensland is lagging behind in expanding its renewables sector and is more unwilling to let go of fossil fuel compared to its neighboring states. Despite this, there is optimism in Queensland's potential to become a renewable energy superpower given its location. The Australian Conservation Foundation reported that renewable energy projects could provide more than a third of Queensland's electricity by 2025, which puts the state on track for its second commitment (Clark, 2020). Darling Downs already has renewable projects since 2017, which includes some 1,000 megawatts of projects around Darling Downs, Toowoomba, and Surat Basin regions (Russel, 2017).

5.5.1.3 Commercial and Public Services, Electricity Generation, Industrial, Institutional, Residential, and Transportation and Communication

In 2012-2018, the region saw a 4.2% growth in registered businesses (Southward, 2019). The prosperity enjoyed by the region today can be traced back to the development of the coal seam gas industry, which widely opened the doors for international companies to invest in the region. Three key projects are also considered to have played a major role in the further increase in infrastructure development: the Toowoomba Wellcamp Airport, which opened in 2014, Toowoomba Second Range crossing, and the proposed inland railway that would link Melbourne and Brisbane (Southward, 2019).

By 2038 and 2058, the region is projected to witness a further increase in infrastructures in the commercial and public services, institutional, residential, and transportation and communication sectors as a result of the influx of economic developments and projects. These expansions align with the envisioned economic growth and development in the region by 2038 and beyond.

The expansion of electricity generation, residential area, and transportation and communication sectors is likely due to accessibility made possible by the construction of road networks that will link Toowoomba to neighboring regions and states. The increase of the area for electricity generation by 2058 most likely indicates the expansion of the renewable energy sector. As of 2019, the region has about 14 renewable and sustainable projects in its jurisdiction, which are mostly solar and wind power plants (Sutrin, 2019). Recently, there has been an overwhelming amount of interest in the development of renewable energy zones (REZ) in Darling Downs, one of the three proposed REZs in Queensland (Scully, 2020).

The region's manufacturing industry has always been strongly linked to its agricultural foundation. Hence, with the expansion and increased demand for products of the agricultural sector, the industrial area is also expected to expand. This signifies the goal of the region to grow its key industries in agriculture and food product manufacturing, transport and logistics, and mining services, and promote opportunities to continue to grow the region's knowledge-based business services (TRC, 2018).

5.5.2 Alternative Scenario One (1999-2010)

All classes showed high persistence during this period, as seen in the probabilities which ranged from 83% to above 90%, indicating low and minimal LULC changes. By 2038 and 2058, all classes would likely remain part of the status quo, although at a slightly lower likelihood for the latter year (Figure 5.17, Table 5.6).

Table 5.6. Transition probability matrix (in %) derived from LULC maps during 1999-2010 for 2038 (top) and 2058 (bottom).

LULC	Proj. Year	**CPS**	DAP	**EG**	**Ind**	**Ins**	**IAP**	**L**	**M**	NC	OMU	RNE	**R**	TC	WTP	WF
CPS	2038	**36.29**	2.22	0	2.06	0.25	0	0.51	0.36	3.65	10.21	34.2	9.63	0.07	0.26	0.29
	2058	**16.67**	7.66	1	1.65	0.21	1.14	0.35	0.45	4.7	5.73	48.25	11.8	0.52	0.24	0.63
DAP	2038	0.01	**85.19**	0	0.02	0	8.52	0.08	0.3	0.01	0.1	5.24	0.29	0.06	0	0.19
	2058	0.05	**75.88**	0	0.05	0	12.82	0.09	0.45	0.02	0.17	9.33	0.58	0.13	0	0.42
EG	2038	2.4	8.46	**5.76**	57.7	0	1.93	1.64	0	0	0	20.23	0.46	1.05	0.1	0.26
	2058	5.6	16.44	**0.86**	28.6	0	7.24	1.28	0.05	0.04	1.01	29.05	4.61	3.07	0.29	1.84
Ind	2038	9.25	10.9	0.03	**36.65**	0	9.88	1.79	0	0	1.4	15.1	7.36	4.12	0.5	3.02
	2058	7.61	18.2	0.02	**16.37**	0.02	11.48	0.9	0.08	0.31	1.75	24.63	9.39	5.05	0.44	3.75
Ins	2038	4.37	0.2	0	0	**35.99**	0	0.02	0	0	0	0.45	0.89	58.08	0	0
	2058	7.76	1.06	0	0.48	**15.61**	0.03	0.14	0.01	0.11	0.43	3.5	1.65	69.21	0.01	0.01
IAP	2038	0.01	27.05	0	0.09	0	**69.62**	0.06	0	0	0.11	1.85	0.19	0.05	0	0.97
	2058	0.05	40.8	0	0.11	0	**52.11**	0.08	0.07	0.01	0.14	4.62	0.4	0.1	0	1.51
L	2038	0.04	43.2	0	0.01	0	2.65	**0.18**	0.06	0.08	0.58	52.41	0.56	0.1	0.01	0.13
	2058	0.17	42.05	0	0.04	0	5.74	**0.15**	0.24	0.13	0.66	48.9	1.35	0.19	0.01	0.37
M	2038	0	0.74	0	4.07	0	0	0.04	**69.16**	0	0.04	23.29	1.05	0	1.61	0
	2058	0.54	3.74	0	4.17	0	0.56	0.14	**48.96**	0.02	0.34	37.13	2.23	0.16	1.86	0.15
NC	2038	1	0.18	0	0	0	0.01	0.01	0	**94.12**	0.81	3.15	0.57	0.15	0	0.01
	2058	1.33	0.79	0	0.02	0	0.1	0.02	0.01	**88.64**	0.96	6.63	1.16	0.28	0	0.05
OMU	2038	0.23	16.05	0.01	0.09	0.33	4.22	0.23	0.16	0.46	**8.71**	62.8	4.27	1.08	0.01	1.36

	2058	0.58	21.25	0.01	0.14	0.17	5.23	0.18	0.26	0.54	**2.27**	61.77	4.75	1.31	0.01	1.51
RNE	2038	0.2	7.99	0	0.04	0	0.7	0.2	0.15	0.08	1.08	**87.72**	1.47	0.11	0.01	0.26
	2058	0.36	14.12	0	0.08	0.01	1.9	0.19	0.26	0.16	1.08	**78.61**	2.51	0	0.01	0.48
R	2038	6.26	2.14	0.03	1.07	0.01	0.67	0.11	0	0.26	0.94	7.84	**79.71**	0.81	0	0.16
	2058	7.15	4.92	0.03	1.33	0.02	1.4	0.16	0.04	0.69	147	16.14	**64.86**	1.41	0.02	0.36
TC	2038	8.53	1.01	0	0.8	0	0	0.2	0	0	0.1	1.57	0.21	**87.58**	0	0
	2058	10.35	2.35	0	1.13	0.02	1.4	0.16	0.04	0.69	1.47	16.14	64.86	**1.41**	0.02	0.36
WTP	2038	9.96	0	0	0.11	0	0	0.04	0	0	0.33	37.7	1.24	0.08	**50.54**	0
	2058	8.73	2.99	0	0.3	0.02	0.25	0.14	0.08	0.32	1.42	54.48	3.1	0.19	**27.87**	0
WF	2038	0.17	1.76	0.04	0	0	4.8	0.53	0.06	0	0.69	6.84	0	0.09	0.03	**85**
	2058	0.23	5.38	0.04	0.04	0	7.46	0.48	0.11	0.01	0.74	12.63	0.15	0.17	0.04	**72.54**

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

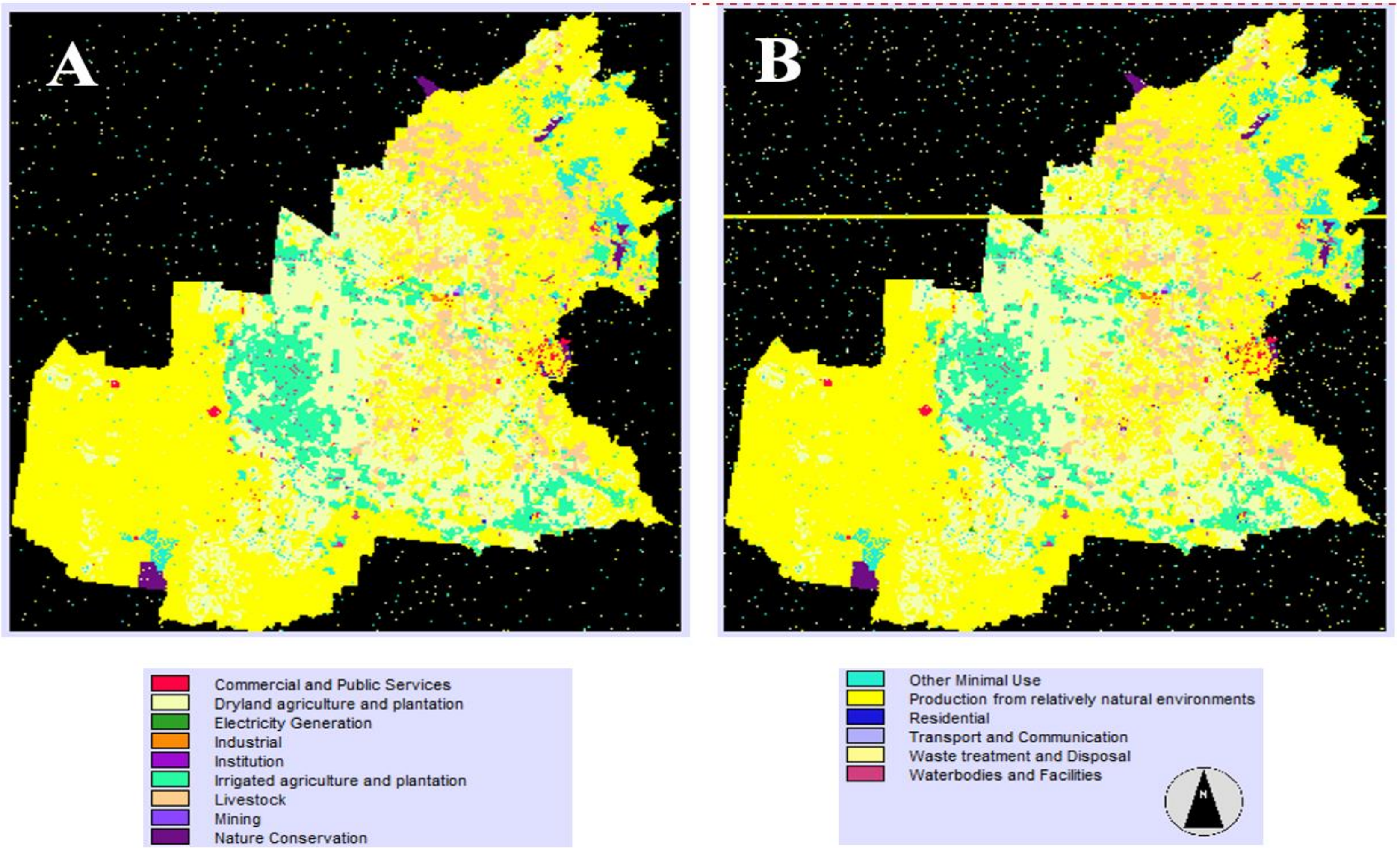


Figure 5.17. Land cover classes predicted for 2038 (A) and 2058 (B) using 1999 and 2010 datasets.

From 2010, irrigated cropland and the area for animal and livestock production are projected to expand until 2038 then decline by 2058. On the other hand, the mining area was predicted to decrease by 2038 and 2058 to 231 and 229 ha, respectively. The space for commercial and public services and industrial property is projected to slightly decrease from 3,879 ha and 1,264 ha, respectively, by 2038 to 3,847 ha and 1,255 ha, respectively, by 2058. Residential areas will likely experience the most drastic decline, from 13,633 ha in 2010 to 897 ha in 2038. This is expected to regain to 994 ha by 2058 (Table 5.7).

This period is best described as the years within the occurrence of the Millennium Drought as well as when the region underwent minimal developments. The prediction was performed for 2038 and 2058 based on BAU assumptions, in which the above conditions would have continued.

5.5.2.1 Dryland and Irrigated Agriculture and Plantations, and Livestock

The predicted spatial patterns showed an increasing trend for cropland from 2010 to 2038 and 2058, with rainfall having the strongest association in the expansion of both cropland categories. The area for animal and livestock production also increased up to 2058 and is associated with all variables except for rainfall. Comparing this with the base case, it can be surmised that the Big Dry was much more tolerable and not as dry as the recent 2017-2019 drought for the pasturelands. In contrast, relatively natural environments expanded under the influence of rainfall.

5.5.2.2 Mining

Historical data of CSG production in Surat Basin showed that operations only started around 2004-2005. Production peaked around 2009-2010 and has gained steam since then (Towler et al., 2016), hence the small mining area size.

Table 5.7. Predicted distribution of LULC categories (in ha) based on 1999-2010 for 2038-2058.

LULC	1999	2010	2038		2058	
			Area	**%Δ**	**Area**	**%Δ**
CPS	3,957	3,923	3,879	-1.13	3,847	-0.84
DAP	325,786	326,058	339,593	1.90	347,252	0.82
EG	179	181	179	-1.21	178	-0.66
Ind	1,296	1,280	1,264	-1.31	1,255	-0.70
Ins	172	171	169	-1.49	169	0.16
IAP	99,362	99,434	191,113	0.97	102,057	0.53
L	78,904	78,917	81,222	2.84	82,435	1.47
M	239	233	231	-.1.13	229	-0.79
NC	9,181	9,161	8,807	-4.02	8,568	-2.78
OMU	42,089	41,675	43,295	-3.39	43,953	-2.73
RNE	713,186	713,403	720,056	0.66	722.207	-0.46
R	13,636	13,633	897	-1,419	994	9.74
TC	336	333	330	-1.01	329	-0.36
WTP	98	99	98	-1.29	97	-1.30
WF	5,411	5,327	5,492	3.0	5,571	1.41

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

5.5.3 Alternative Scenario Two (2010-2018)

Markov Chain Analysis of 2010 and 2018 LULCs revealed generally low persistence probabilities among the key categories. The residential area showed the highest likelihood of remaining unchanged, while areas for animal and livestock production and electricity generation showed the highest likelihood of being converted to other types. This trend is seen to continue to 2038 and 2058, although at lower probabilities for the latter predicted year (Table 5.8).

Twenty years after 2018, only industrial space is predicted to increase among the eight key categories. Irrigated cropland, areas allocated for electricity generation, animal and livestock production, mining, and residential property are projected to decrease, while space for commercial and public services, and industrial property are predicted to remain the same. There is no increase expected by 2058 (Figure 5.18). Irrigated cropland will remain the largest class type. However, it is predicted to continually decrease from 105,979 ha in 2018 to 105,971 ha by 2038 and 105,908 ha by 2058. Since its decline in 2018, the area for animal and livestock production is expected to remain with a small portion of 2,841 ha by 2038 and 2,840 ha by 2058. Space for commercial and public services is projected to be relatively stable by 2038 (4,228 ha) then decrease by 2058 (2,402 ha). The area for electricity generation is seen to decrease from 66 to 68 ha by 2038 then remain the same by 2058. Industrial property will likely maintain its area of 1,327 ha until 2038 then decrease to 1,292 ha in 2058. Institutional facility is seen to maintain its area until 2058. Mining area will likely decrease in 2038 and will retain the same area after 20 years. The residential area is expected to further decrease in 2038 and 2058 from 24,280 ha in 2018 to 24,264 ha and 22,840 ha, respectively (Table 5.9).

Lastly, this period examines the period within the 2017-2019 drought, wherein researchers have found, using satellite data from the Gravity Recovery and Climate Experiment (GRACE) mission, that this drought was drier than the Big Dry in 2009 (Australia’s Science Channel, 2019; Foley, 2019). This period also saw the surge of constructions and build-up of infrastructures as well as the boom of the mining industry. In 2011, Surat Basin surpassed Bowen Basin as the primary supplier of CSG. Simulation of all categories for 2038 and 2058 exhibited either a reduced or unchanged area.

Table 5.8. Transition probability matrix (in %) based on land use maps of 2010 and 2018 for 2038 (top) and 2058 (bottom).

LULC	Proj. Year	**CPS**	DAP	**EG**	**Ind**	**Ins**	**IAP**	**L**	**M**	NC	OMU	RNE	**R**	TC	WTP	WF
CPS	2038	**84.82**	0.71	0	0.6	0	0.25	0.2	0.01	0.21	0.31	5.99	6.75	0.12	0	0.04
	2058	75.49	1.27	0	0.93	0	0.44	0.34	0.01	0.34	0.57	9.85	10.52	0.18	0	0.06
DAP	2038	0	**93.99**	0	0.52	0.26	0	0.01	1.05	4.08	0.04	0	0	0.04	0	0.01
	2058	0.01	**90.04**	0	0.01	0	0.88	0.44	0	0.02	1.65	6.81	0.08	0	0	0.07
EG	2038	0	0.04	**92.75**	0	0	0.01	0.01	0	0	0.12	68.2	0.24	0	0	0
	2058	0.01	0.16	**87.89**	0	0	0.02	0.03	0	0	0.21	11.28	0.4	0	0	0
Ind	2038	1.84	1.15	0.23	**83.08**	0	0.34	0.11	0.08	0.02	1.09	7.31	4.11	0.23	0	0
	2058	2.83	2.64	0.36	**72.8**	0	0.58	0.21	0.11	0.04	1.7	11.92	6.44	0.35	0	0.01
Ins	2038	0.01	1.89	0	0	**90.54**	0.07	0.01	0	0	6.46	0.12	0.26	0.62	0	0.01
	2058	0.02	3.49	0	0.01	**84.34**	0.23	0.04	0	0.02	9.95	0.43	0.45	0.98	0	0.03
IAP	2038	0.01	1.65	0	0	0	**95.34**	0.09	0	0	1.01	1.53	0.07	0	0	0.3
	2058	0.02	2.8	0	0.01	0	**92.18**	0.16	0	0.01	1.61	2.63	0.11	0	0	0.47
L	2038	0.01	0.93	0	0	0	0.09	**95.52**	0	0.01	0.41	2.97	0.04	0	0	0.02
	2058	0.01	1.6	0	0.01	0	0.17	**92.45**	0	0.01	0.65	5	0.08	0	0	0.03
M	2038	0.67	2.23	0	0.41	0	0.06	0.03	**70.92**	0.01	3.85	21.1	0.71	0	0	0.01
	2058	0.98	3.85	0	0.59	0	0.19	0.11	**55.49**	0.02	5.49	31.25	1.1	0	0	0.03
NC	2038	0.13	0.38	0	0	0	0.03	0.17	0	**95.66**	0.7	2.76	0.17	0	0	0
	2058	0.21	0.7	0	0.01	0	0.07	0.3	0	**92.67**	1.1	4.65	0.29	0	0	0

OMU	2038	0.04	10.29	0.01	0.03	0.01	2.8	0.43	0.03	0.21	**81.15**	4.1	0.49	0.02	0.01	0.38
	2058	0.07	16.13	0.01	0.05	0.02	4.45	0.7	0.04	0.33	**70.02**	6.81	0.76	0.03	0.01	0.57
RNE	2038	0.03	1.84	0	0.01	0	0.2	0.33	0.01	0.03	0.23	**97.2**	0.08	0	0	0.04
	2058	0.04	3.07	0	0.01	0	0.35	0.56	0.01	0.05	0.38	**95.31**	0.14	0	0	0.07
R	2038	1.69	1.14	0	0.37	0	0.47	0.27	0.01	0.12	1.69	4.42	**89.75**	0.04	0.01	0.01
	2058	2.64	2.03	0	0.58	0	0.81	0.46	0.02	0.2	2.62	7.39	**83.16**	0.06	0.01	0.03
TC	2038	2.13	3.03	0	1.18	0.06	0.15	0.66	0	0	1.32	3.33	1.4	**86.73**	0	0
	2058	0.64	0.56	0	1.81	0.1	0.29	1.07	0	0.01	2.05	5.67	2.32	**78.35**	0	0.01
WTP	2038	0.42	0.16	0	0	0	0.03	0.02	0	0	2.08	14.67	0.02	0	**82.59**	0
	2058	0.64	0.56	0	0.01	0	0.1	0.07	0	0.01	3.11	23.37	0.06	0	**72.05**	0.02
WF	2038	0.02	3.37	0	0	0	6.41	0.31	0	0	3.43	6.75	0.03	0	0	**79.67**
	2058	0.04	5.6	0	0	0	10.07	0.52	0	0.01	5.1	10.84	0.06	0	0	**67.76**

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

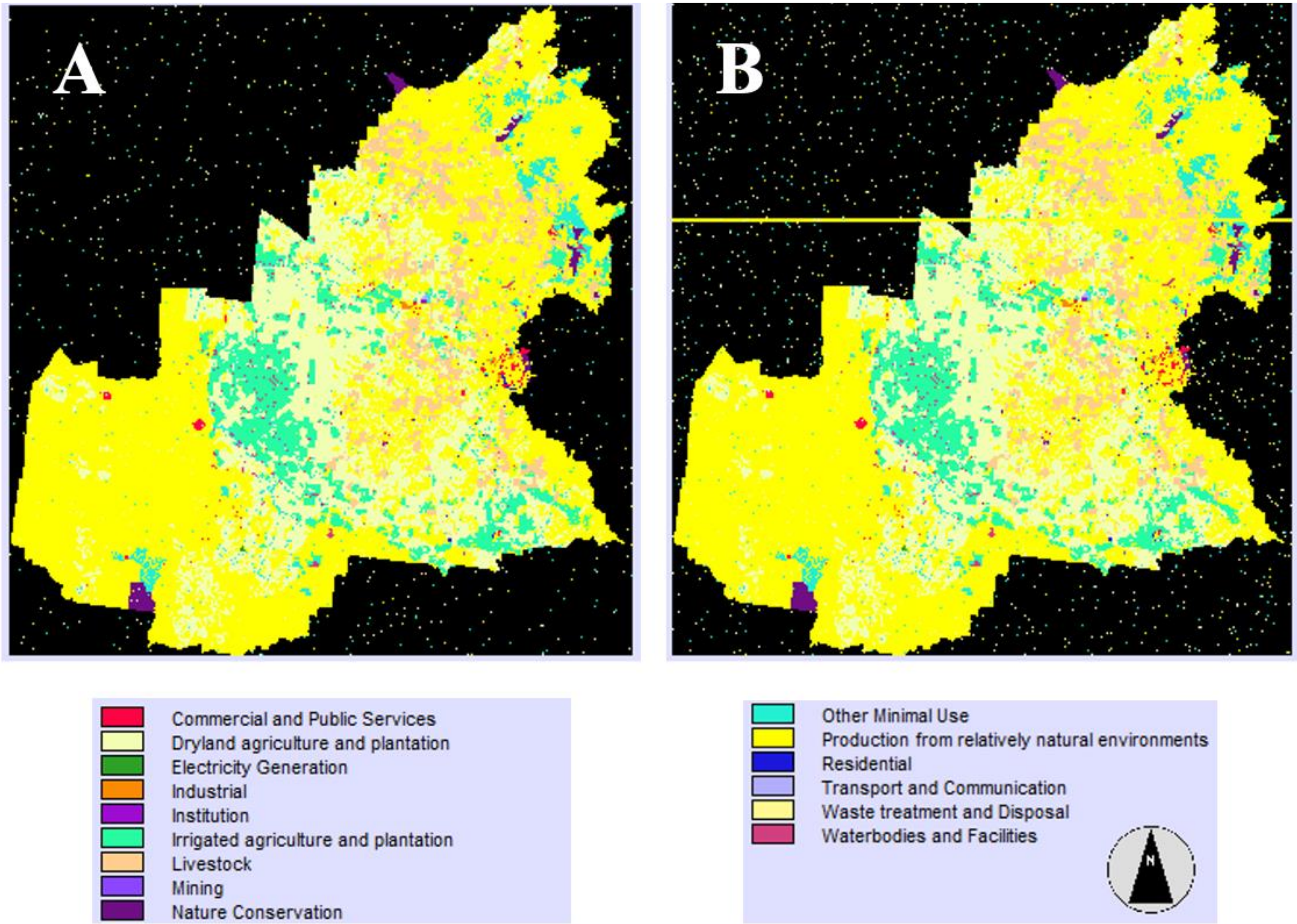


Figure 5.18. Land cover classes predicted for 2038 (A) and 2058 (B) using 2010 and 2018 datasets.

Table 5.9. Predicted distribution of LULC categories (in ha) based on 2010-2018 for 2038-2058.

LULC	2010	2018	2038		2058	
			Area	%Δ	Area	%Δ
CPS	3,924	4,229	4,228	-0.01	2,402	-76.02
DAP	326,077	399,343	399,273	-0.02	399,246	-0.01
EG	180	66	66	-0.55	66	-0.41
Ind	1,280	1,327	1,327	0.0	1,292	-2.72
Ins	171	238	238	0.0	237	-0.04
IAP	99,437	105,979	105,971	-0.01	105,971	0.00
L	78,920	2,842	2,841	-0.02	2,840	-0.04
M	233	2,144	2,143	-0.05	2,143	-0.01
NC	9,149	9,660	9,616	-0.46	9,599	-0.17
OMU	41,673	16,100	16,037	-0.40	11,357	-41.21
RNE	713,260	716,809	716,105	-0.10	715,911	-0.03
R	13,632	24,280	24,264	-0.07	22,840	-6.23
TC	333	2,010	2,006	-0.22	1,988	-0.90
WTP	99	124	124	0.0	124	0.00
WF	5,322	8,539	8,528	-0.13	8,525	-0.03

CPS (Commercial and Public Services), DAP (Dryland Agriculture and Plantations), EG (Electricity Generation), Ind (Industrial), Ins (Institutional), IAP (Irrigated Agriculture and Plantations), L (Livestock), M (Mining), NC (Nature Conservation), OMU (Other minimal use), RNE (Production from Relatively Natural Environments), R (Residential), TC (Transport and Communication), WTD (Waste Treatment and Disposal), WF (Water Bodies and Facilities).

5.6 Conclusion

Geographic Information System and modeling techniques were employed in this chapter to study the LULC dynamics in Toowoomba Region. LULC map images were used to study the characteristics of LULC change, model the transitional potential, and project the future LULC pattern under three different scenarios.

Using the combination of Multi-Layer Perceptron and Markov Chain Analysis, future land use scenarios of Toowoomba Region, using historical land use data between 1999 and 2018, were predicted for 2038 and 2058 under three different scenarios. Transitions in land categories were quantified using the LCM application of TerrSet. Factors such as accessibility, natural environment, and potential productivity were considered to understand the land use dynamics of the eight key water user sectors highlighted in this study.

Agriculture dominated the region's landscape throughout the study period. Several factors were observed to be strongly associated with the transitions, and the impact of drought was evident in them. Overall expansions were noted between 1999 and 2018, yet variations were seen across individual periods.

Prediction of the base scenario (using 1999-2018) revealed expansions of the croplands and mining area, while the area for animal and livestock production exhibited decline by 2038 and 2058. The decrease was likely a result of competition over land and water resources with croplands. The first alternative scenario (using 1999-2010) showed that all categories are highly likely to persist by 2038 and 2058. Agriculture is expected to expand while infrastructures are seen to reduce in area by 2038 and 2058. On the other hand, all categories are still likely to be part of the status quo by 2038 and 2058 in the second alternative scenario (using 2010-2018) yet at a lower degree. Key classes were predicted to either decrease or maintain the 2018 area by 2038 and 2058.

It is suggested that the prediction map outputs and other important information generated from this study be used by stakeholders and policymakers of the Toowoomba Regional Council for better planning and management of land use in relation to water resource management and utilization.

5.7 Recommendations

Instead of using existing land cover datasets, it is recommended to independently produce land cover maps for the analysis of LULC change by performing actual image processing and supervised image classification using cloud-free high-resolution satellite imageries for a more uniform land area of the area of interest.

Due to time constraints and a lack of data, fair market price was not tested for its explanatory power. Hence, it is recommended to explore this factor in future land use studies in addition to the commonly used socio-economic factors (accessibility, spatial configuration, political restrictions, etc.) and natural environmental factors (topography, potential productivity, etc.). Likewise, it is recommended to include population to test its influence on changes related to agriculture and infrastructure.

In order to identify the main drivers of land use change, it is recommended to consider employing the Binary Logistic Regression Model (BLRM) in addition to Cramer's V. The BLRM was found to be useful in modeling land use changes where the dependent variable may be a binary or categorical variable (Islam et al., 2018; X. Zhao et al., 2018), such as the market price.

While Markov Chain estimates the quantity of change (Hamad et al., 2018), it does not provide a spatial distribution of landscape change (Gidey et al., 2017; Liping et al., 2018). Therefore, it is recommended that the combination of Cellular Automata and Markov Chain Model (CA_Markov) be explored in predicting and simulating the future land use of the region to generate a more accurate future likelihood spatiotemporal pattern of its land use changes.

CHAPTER 6

WATER USE PROJECTION UNDER CHANGING LAND USE AND CLIMATE IN TOOWOOMBA REGION

6.1 Introduction

Changes in land use have long been globally recognized to have serious and significant impacts on water resources (Kaushal et al., 2017; Jianwei Liu et al., 2017; Stonestrom et al., 2009; Touch et al., 2020). Impacts from such changes are simultaneously compounded by changes in climate driven by natural processes (Gebremeskel & Kebede, 2018) and human-induced activities (Zhang et al., 2019). For instance, Gebremeskel & Kebede (2018) reported that climate change resulted in a decrease in surface runoff. This finding is supported by Zhang et al. (2019), which showed that human activities and climate change are two factors influencing the variation of the total amount of available surface and groundwater.

In its report State of the Climate 2018, BOM and CSIRO reported a rise in Australia's average temperature by over 1.0 °C since 1910. This has led to the increasingly frequent incidence of extreme heat. Southeast Australia has been experiencing an 11% decline in April to October rainfall since the late 1990s. For the Toowoomba Region, rainfall decile ranges from very much below average to the lowest on record for the last 20 years. This is parallel to the research of Radcliffe & Page (2020), which mentioned that most of Australia has exceptionally low rainfall, and the water limitation is aggravated by climate change. The same authors also reported that from 1961-1990, the average rainfall of Australia was 465.2 mm; but plunged by 40% in 2019, resulting in only an average of 277.6 mm.

According to the report of the University of Southern Queensland's Australian Centre for Sustainable Catchments, which modeled the potential impact of climate change on rainfall patterns and temperature for the region, as cited in the Toowoomba Sustainable Agriculture and Rural Activity Study (TRC, 2013), three of the five models showed an increase in summer rainfall with a major decrease in autumn, winter, and spring rainfall. No change to a 16% decrease in rainfall is projected from 2010 to 2039, while a reduction of 10% to 20% by 2040 to 2069 and 9% to 33% by 2070 to 2099 are predicted. Mean temperature changes are projected to increase significantly, with the highest increase in late winter. An increasing trend in temperature from 1.0 to 1.5 °C, 2.1 to 2.4 °C, and 3.7 to 4.0 °C is anticipated by 2010 to 2039, 2040 to 2069, and 2070 to 2099, respectively.

CSIRO (2008b), as cited by Stonestrom et al. (2009), reported that the incidence of declining water levels in the critical aquifer systems of MDB is due to over-extraction of groundwater resources. Although water restrictions are in place, the provision and conservation of water remain a major issue for the future of the region. It is also reported that the surge of extreme heat, decline of rainfall, the inappropriate development controls on existing uses of water, and the anticipated demands due to economic and population growth in the region are putting even more pressure on its dwindling water supply.

With these challenges, there is a need to quantify the balance between water supply and demand through model simulations to identify whether the demand of each water user sector of the Region has been met. The objective of this study is to project the future water demand and water supply in Toowoomba Region for each climate scenario and land use, as well as to recommend possible strategies to minimize water stress within the region.

6.2 Methodology

Water Evaluation and Planning (WEAP) was used to evaluate future water demand and supply in the Toowoomba Region for the nine major water user sectors. WEAP is a modeling and simulation tool developed by the Stockholm Environment Institute (SEI) for water systems studies (Fard & Sarjoughian, 2021). WEAP works threefold: (1) a database providing a system for maintaining water demand and supply information; (2) a forecasting tool to simulate water demand, supply, flows, and storage and pollution generation, treatment, and discharge; and (3) a policy analysis tool to evaluate a full range of water development and management options while taking into account multiple and competing uses of water systems (SEI, 2016). It addresses a wide range of issues, including sectoral demand analyses, and it offers integration of agricultural, industrial, and municipal water demands (P. Schneider et al., 2019).

WEAP has been widely used by researchers around the world for various purposes in the last decade. For instance, WEAP was used to examine complex water systems and to analyze interactions of water supply and demand in the Middle Draa Valley in Morocco (Johannsen et al., 2016). In a more recent study, Touch et al. (2020) used WEAP to evaluate the impacts of climate change on the hydrological regime by predicting the change in both monthly and seasonal streamflow. The paper further identified water supply and demand relations under supply management options and environmental flow maintenance.

In this study, WEAP was applied to simulate the future water demand of agriculture, livestock, population, residential, mining, commercial, institutional, industrial, environmental flow, and parks and gardens; and the supply from rivers and creeks, groundwater bores, and from three reservoirs (i.e., Perseverance, Cressbrook, and Cooby dams). Supply and demand were simulated for 2038 and 2058 normal water year, very dry water year, and very wet water year.

Water demands for the residential, agriculture, livestock, mining, commercial, industrial, energy generation, and parks and garden sectors were computed for the next 20 years (2018 to 2038) and 40 years (2018 to 2058) using future climate regimes. The water demands were calculated by considering the annual water use rate of each sector. For agriculture water use rate, the average annual water use coefficient of cotton (6.7 ML/ha), fruits (6 ML/ha), vines (3.8 ML/ha), vegetables (4 ML/ha), and pasture (3 ML/ha) were used. For livestock, the water use coefficient of piggery (14.09 ML/ha/yr), poultry (0.04 ML/ha/yr), and cattle feedlots (0.13 ML/ha/yr.) were utilized. For other sectors like residential, mining, commercial, industrial, institutional, and parks and gardens, the water demands were computed using the following water use coefficients: 0.46 ML/ha/yr.; 0.004 ML/ha/yr.; 0.48 ML/ha/; 0.53 ML/ha; 0.16 ML/ha/yr, respectively. The quantification of water demands was also based on the number of hectares of each sector as indicated in the 2018 Toowoomba Region land use map.

The details of the water use coefficient and water demand are given in Table 6.1.

6.2.1 Study Area

Toowoomba Region is traversed by the Condamine River and its tributaries. It is hydrologically divided into four major catchments, namely, Balonne-Condamine, Border Rivers, Brisbane, and Moonie. Except for the Brisbane catchment, these form part of the MDB. Balonne-Condamine covers 62.9% of the total regional area and is the biggest among the four. It occupies the flat lands in the central part of the region from Bowenville to Oakey and southwest to Brookstead, Millmerran, and Cecil Plains. Border Rivers (20.5%) covers the undulating lands to the south and west of Millmerran. Brisbane (16.5%) spans the hilly to steep terrains to the north of Toowoomba to Maclagan and along the escarpment on the eastern edge of the region to the south of Toowoomba (TRC, 2013). The extent of these catchments is shown in Figure 6.1.

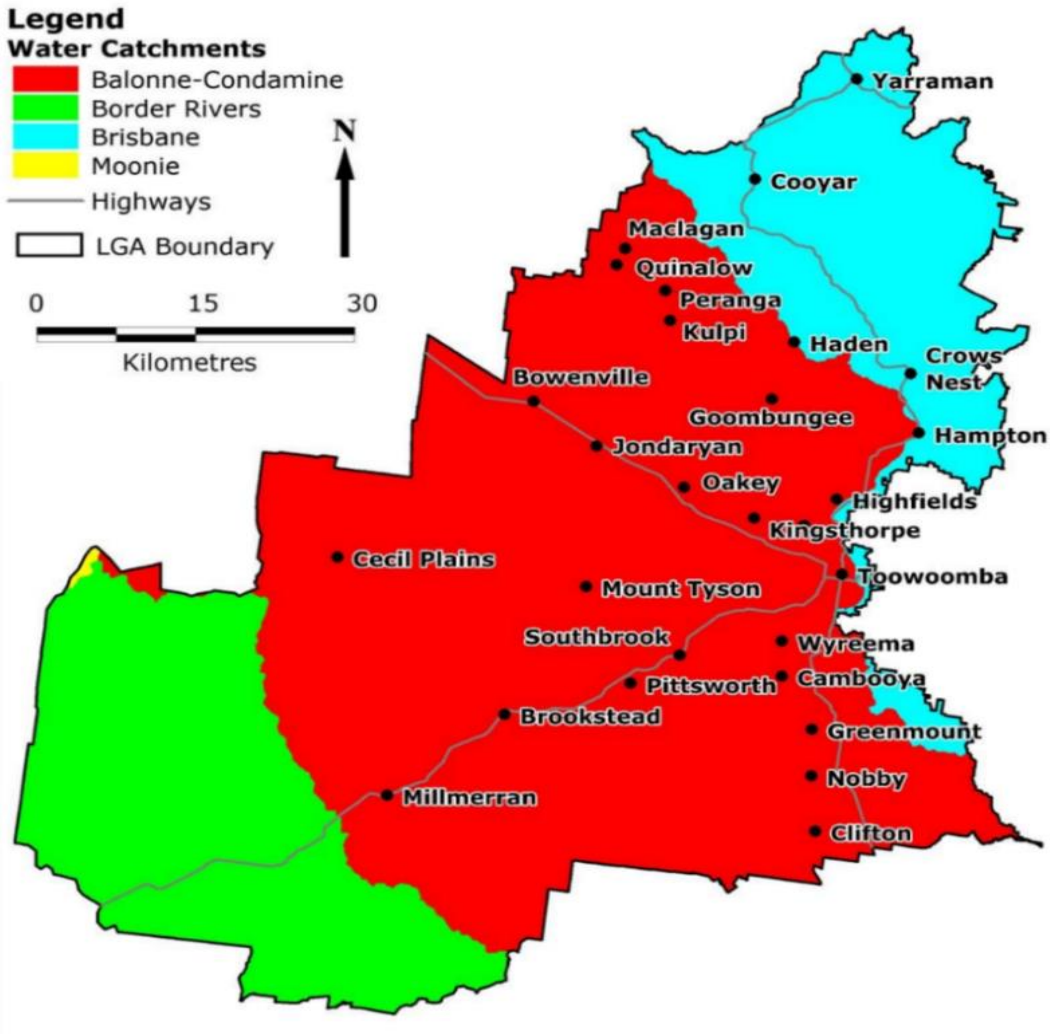


Figure 6.1. Map of the major water catchments in Toowoomba Region.

Currently, the region is supplied by three main water sources. These are the three local dams (Cooby, Cressbrook, and Perseverance), 47 bores that access groundwater, and the Wivenhoe Dam pipeline which provides emergency supply once Cressbrook dam falls below 40% capacity (Toowoomba Region, 2020).

While groundwater is generally used for stock and domestic purposes to supply the rural and some town properties, it is largely consumed for irrigated agricultural lands that are clustered in the central part of the region as well as small horticulture users to the north of Toowoomba. The National Land and Water Resources Audit categorizes the groundwater in the Condamine-Balonne catchment as high priority, signifying its importance for agriculture, for both crops and animal production.

6.2.2 Data

The data utilized in this chapter are the water requirements of each key water user sector, namely: agriculture, livestock, population, residential, mining, commercial, institutional, industrial, environmental flow, and parks and gardens. These constitute the demand side. For the supply side, the following data were used: the average monthly inflows of the Condamine Rivers and streams, inflow of local reservoirs such as Cooby Dam, Cressbrook Dam, Perseverance Dam, and the Cecil Plains Weir.

6.2.2.1 Supply Side Data

The supply details (monthly average of head flow and inflow) of the rivers and the local reservoirs based on the Year 2018 available data are shown in Figures 6.2 and 6.3 below.

Headflow (monthly) (CMS)												
	Jan 2018	Feb 2018	Mar 2018	Apr 2018	May 2018	Jun 2018	Jul 2018	Aug 2018	Sep 2018	Oct 2018	Nov 2018	Dec 2018
Condamine_River_Cecile_Weir	20.4	20.9	12.9	11.7	13.7	9.6	6.6	4.2	2.3	5.4	7.2	14.6
Condamine_River_Warwick	6.6	5.3	3.9	3.3	3.3	2.0	2.5	1.2	1.0	1.1	1.5	3.7
Condamine_River_Tummaville	14.6	12.8	8.8	8.4	9.2	5.1	4.4	2.5	2.5	3.0	5.2	49.2
Oakey_Creek_Fairview	2.7	2.4	1.1	2.1	2.6	1.1	1.1	0.4	0.3	0.2	1.7	1.9
Oakey_Creek_Upper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oakey_Creek_Dalmeny	0.5	0.0	0.0	0.0	0.2	0.6	0.5	0.5	0.8	0.5	0.3	0.2
Oakey_CReek_Lower2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oakey_Creek_Middle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oakey_Creek_Lowest_Left	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oakey_Creek_Bowenville_Reserve	0.3	0.0	0.0	0.1	0.1	0.3	0.3	0.2	0.6	0.3	0.1	0.1
Sum	45.0	41.5	26.7	25.5	29.0	18.8	15.3	9.0	7.5	10.6	15.9	69.7

Figure 6.2. The average monthly inflows (in cms) at heads of Condamine Rivers and streams.

Inflow (monthly) (CMS)												
	Jan 2018	Feb 2018	Mar 2018	Apr 2018	May 2018	Jun 2018	Jul 2018	Aug 2018	Sep 2018	Oct 2018	Nov 2018	Dec 2018
Cooby Dam	2.8	2.8	2.8	2.7	3.3	3.3	3.0	3.0	2.9	2.9	2.9	2.9
Cressbrook Dam	10.6	10.7	11.4	10.3	10.1	12.5	14.1	11.4	11.1	10.8	10.7	10.6
Perseverance Lake_Dam	3.5	3.6	13.5	3.6	4.4	4.8	4.8	3.9	3.9	3.8	3.7	3.7
Cecil Plains Weir	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	16.9	17.1	27.6	16.7	17.8	20.5	21.9	18.4	17.9	17.5	17.3	17.1

Figure 6.3. The monthly inflows (in cms) of local reservoirs.

6.2.2.2 Demand Side

The major water sectors identified in the previous chapters are reflected in Table 6.1 below. The area (in hectares) occupied by each sector, based on the 2018 TRC land use map, was analyzed and calculated, while the water use coefficient per hectare was extracted from existing literature.

6.2.3 ArcGIS Data Cleaning and Processing

Using ArcGIS, the datasets were organized in preparation for the WEAP analysis to include the following:

- Toowoomba Regional Council Administrative Boundary
- Condamine River and Streams
- Land Use
- Locations of water treatment plants, groundwater bores, Cooby Dam, Cressbrook Dam, and Perseverance Dam.

Table 6.1. Water demand sectors within the Toowoomba Region based on the 2018 land use map.

Demand Side	Water Coefficient (ML)	Area (ha)	Water Consumption (ML)
Agriculture			
Cotton	6.7/ha/yr.	24,089	158,987.4
Fruits	6.0/ha/yr.	1,814	10,884.0
Vines	3.8/ha/yr.	128	486.4
Vegetables	4.0/ha/yr.	314,776	1,259,104.0
Pasture	3.0/ha/yr.	426,344	1,279,032.0
Livestock			
Piggery	14.09/ha/yr.	810	11,412.9
Poultry	0.0387/ha/yr.	299	11.6
Cattle Feedlots	0.13/ha/yr.	707	91.9
Residential	0.4555/ha/yr.	9,928	4,522.2
Mining	0.0004/ha/yr.	551	0.2
Commercial	0.4779/ha/yr.	1,623	775.6
Industrial	0.5284/ha/yr.	685	361.9
Institutional	0.1597ha/yr.	2,400	383.3
Parks and Gardens	0.0736/ha/yr.	390	28.7
Population	0.073/p/yr.	167,657 persons	12,238.9
Environmental Flow	51 GL/month		

These datasets set up the spatial, system components, and configuration of the problem in WEAP. The rivers and streams, groundwater bores, and reservoirs/dams represent the various water supply sources, while land use represents the water demand component. The following section fully discusses the operation of WEAP to analyze the water supply and demand in the study area.

6.2.4 Defining the Geographic Area for WEAP

To define the extent of the study area, the Toowoomba Regional Council administrative boundary was overlaid on a map that is readily available in WEAP, as shown in Figure 6.4.

6.2.5 Setting the General Parameters

For the WEAP model of the Toowoomba Region, the water system was characterized by water demand sites, river head flows, local reservoirs, and groundwater bores. The study area, as reflected in Figure 6.4, was used to define the spatial location of the water system. The "Year and Time Step" menu on the WEAP model was utilized to organize the data as follows:

First Run. The Current Accounts Year was set to 2018, and the Last Year of Scenarios was set to 2038. The year 2018 served as the recent baseline year, for which the water availability and demands can be confidently determined. On the other hand, the Last Year scenario was set to 2038, considering that Toowoomba Region set their Bold Ambitions or the Blueprint for Regional Prosperity in the same year.

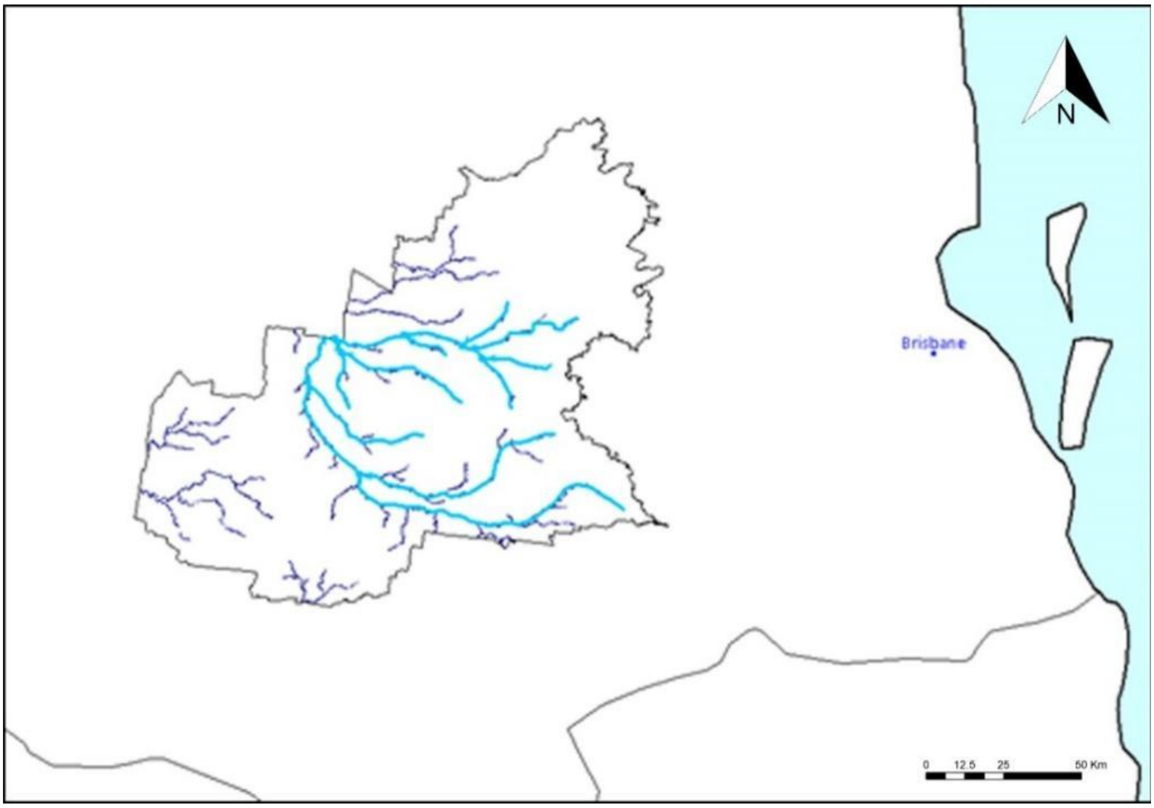


Figure 6.4. The extent of project area defined in WEAP.

Second Run. The Current Accounts Year was set to 2018, and the Last Year of Scenarios was set to 2058.

The year 2018 served as the reference year, considering that this was the latest available land use map of the Toowoomba Region. The number of hectares of each identified water user sector was analyzed and calculated from this map. The water use coefficients of each sector per hectare were searched from available literature. These data served as the demand side.

On the other hand, water supply from rivers, reservoirs, and groundwater bores was organized and quantified on a monthly basis during the Current Accounts Year, as presented in Figures 6.5, 6.6, and 6.7.

Figure 6.5 displays the monthly inflow to local supply generated from groundwater bores for the year 2018. Figures 6.6 and 6.7 provide visual representations of water inflow data for the Condamine Rivers and local reservoirs, respectively, for the same year. Figure 6.6 illustrates the average monthly inflows at the heads of the Condamine Rivers and Streams, offering insights into seasonal variations and flow patterns across multiple locations within the river system. Figure 6.7 focuses on the monthly inflows into local reservoirs, highlighting the fluctuation of water resources available for storage and subsequent use

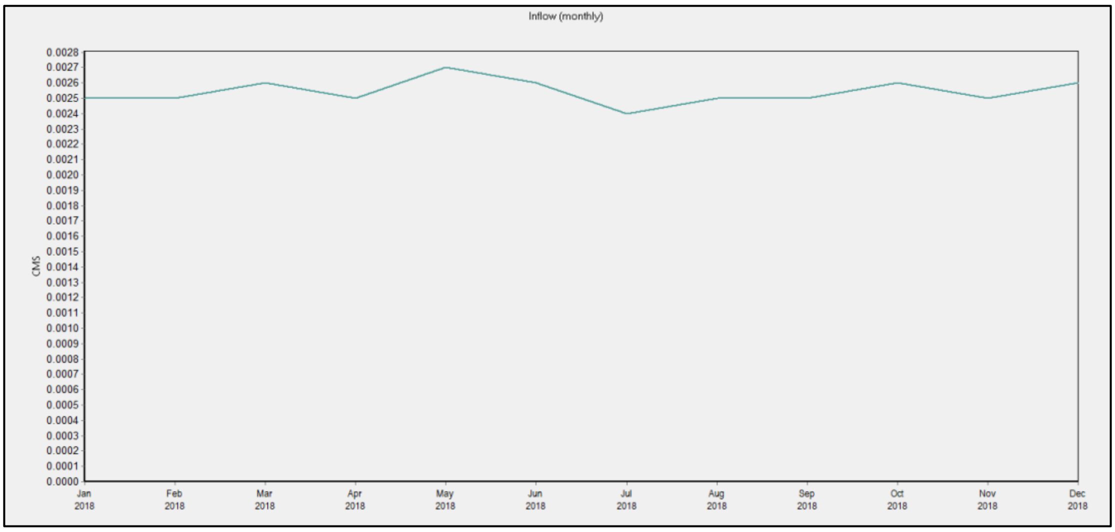


Figure 6.5. The monthly inflow to local supply generated from groundwater bores.

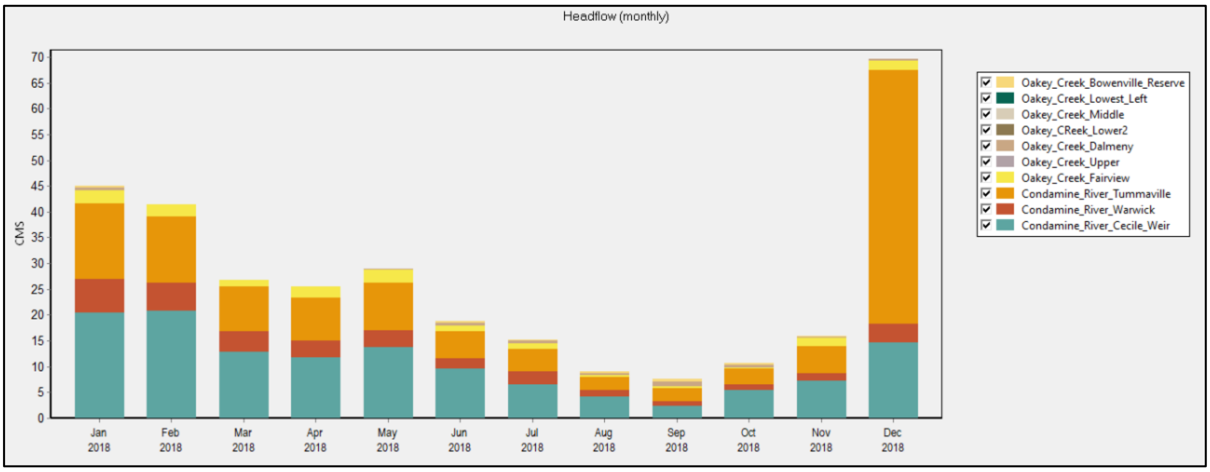


Figure 6.6. The average monthly inflows (in cms) at heads of Condamine Rivers and Streams.

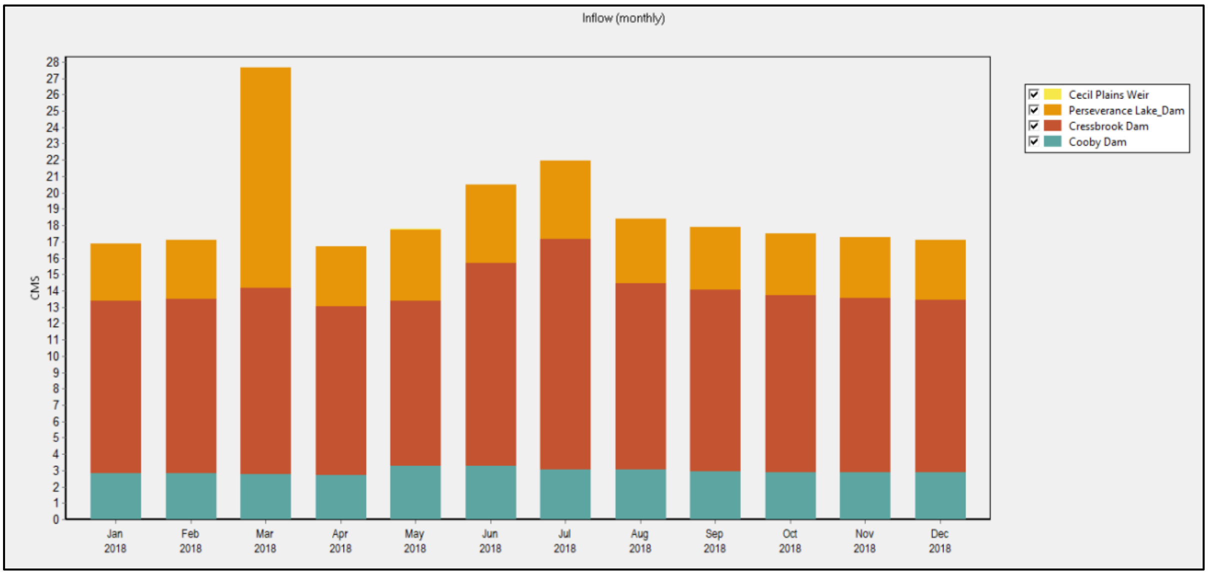


Figure 6.7. The monthly inflows (in cms) of local reservoirs.

6.2.6 Creating the Demand Component and Related Data

The demand nodes were generated using the land use categories as discussed in Chapter 4. The annual water use rate is presented in Table 6.1. This table shows the demand sectors within the Toowoomba Region based on the 2018 land use map with their water coefficients. The demand side is composed of Agriculture, further classified into cotton, fruits, vines, vegetables, and pasture. The Livestock sector is also included in the demand side, composed of piggery, poultry, and cattle feedlots. Other sectors included in the demand side were Residential, Mining, Commercial, Industrial, Institutional, and Parks and Gardens. The water demand of each sector was quantified by multiplying their water coefficient per hectare per year into the number of hectares these sectors covered based on the 2018 Toowoomba Region Land Use Map. In addition to the annual water use rate, a key assumption on the population growth rate of 1.76% per annum was integrated. Moreover, Environmental Flow was included in the demand side with a demand requirement of 51 GL/month.

6.2.7 Connecting the Demand with Supply

To analyze how water demand is satisfied, the supply resources were connected to the demand sites by creating transmission links (Figure 6.8). This figure shows the water model in the WEAP system, which is the graph of node and link entities. The predefined node and link entities were used to construct the nodes and links assigned to a geospatial map. The entity types are the supply sources, which are the river, reservoirs, groundwater, and water treatment plant. Some entities are presented as nodes representing the demand side. The WEAP Model optimizes water allocation based on priorities. This process allows providing all the land use categories (water user sectors) with water supply considering the set preference level.

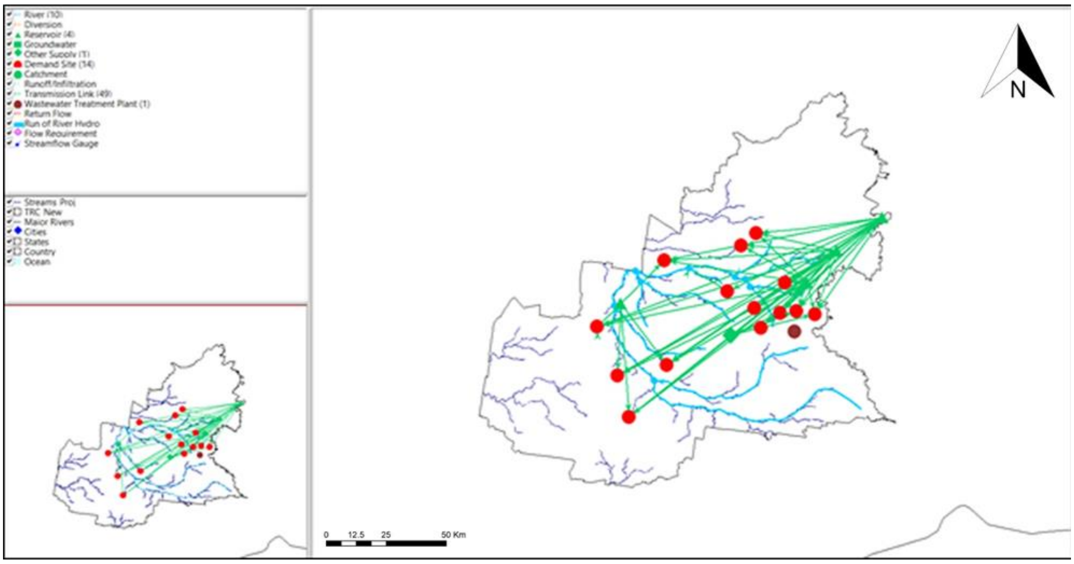


Figure 6.8. Connecting the various elements of water demand with supply in the WEAP environment.

6.2.7.1 Demand Priorities and Supply Preferences

One of the objectives of allocating water is to maximize satisfaction of demand from different sources through preferences and mass balance constraints (Fard & Sarjoughian, 2021). In doing so, a standard linear programming presented below was used to solve the allocation problem (Yates et al., 2005). As explained by Yates et al. (2005), "the constraint set is iteratively defined at each time step to sequentially consider the ranking of the demand priorities and supply preferences." He further discussed that individual demand sites, reservoirs, and in-stream flow requirements are assigned a unique priority number, which ranges from 1 (highest priority) to 99 (lowest priority). The details of the linear algorithm discussion can be found in Yates et al. (2005).

For each $p = 1$ to P — for each demand priority

For each $f = 1$ to $F \in (D_k^{p,t-n})$ — for each supply preference to demand, k

maximize (Coverage to all demand sites$k \in N$ with priority p

$$Z = C_p$$

subject to

$\sum_{j=1}^{n} \quad x_{j,i}^{p} - \sum_{r=1}^{m} \quad x_{i,r}^{p} + S_i^{t-1} = S_i^t$ — mass balance constraint with storage for node i to r

$\sum_{j=1}^{F} \quad x_{j,k}^{p} = D_k^{p,t-n}$ — demand node constraint or demand k from j sources

$\sum_{j=1}^{m} \quad x_{j,k}^{p} = D_k^{p,t-n} * C_k^p$ — coverage constraint for demand k from j sources

$\sum_{j=1}^{m} \quad x_{j,k}^{p} \geq D_k^{p,t-n} * C_k^p$ — coverage constraint for ifr and reservoirs k from j sources

$c_k^p = C$ equity constraint for demand site k with priority p

$c_k^p \geq C$ equity constraint for ifr and reservoirs with priority p

$0 \leq c_k^p \leq 1$ bound for demand site coverage variables (not ifr or reservoirs)

$x_{i,l}^{>p} = 0$ for demand site l with priority $> p$

$x_{i,k}^{p}$ for demand sites k with priority $= p$

$x_{i,k}^{f} \geq 0$ for demand sites k with priority $= f$

$x_{i,k}^{>f} = 0$ for demand sites k with priority $> f$

Solve LP, then

1. Evaluate shadow prices (h_k^p) of each equity constraint, is $h_k^p > 0$?
2. If so, set $X_{j,k}^p$ and c_k to optimal values from the solution.
3. Remove equity constraints with $h_k^p > 0$.

Next iteration for current, p Next f Next p.

6.2.8 Creating and Running 2038 and 2058 Scenarios

The Water Year Method was used to represent the variation in streamflow, rainfall, and groundwater recharge. As summarized in Table 6.2, this method defines how different climate regimes (e.g., very dry, very wet) compare in relation to a Normal Year (Mounir et al., 2011). Each water year type is assigned a coefficient in the Water Year Method that represents the relative amount of water available compared to a normal year. In Table 6.2, these coefficients range from 0.2 for very dry years to 0.8

for very wet years. A coefficient of 1.0 represents a Normal Year. Water Evaluation and Planning System (WEAP) uses these coefficients to calculate water availability and demand throughout the simulation period related to the 2038 and 2058 scenarios. For instance, in a dry year with a coefficient of 0.4, WEAP would assume that only 40% of the normal amount of water is available. These assigned coefficients impact how WEAP calculates water supply, water demand, and other variables in the model.

Table 6.2. Classification of the water year type with corresponding water year coefficient relative to normal.

Water Year Type	Relative to Normal Water Year
Dry	0.2
Very Dry	0.4
Normal	1.0
Wet	0.6
Very Wet	0.8

Figures 6.9 and 6.10 from a WEAP analysis depict the categorization of climate conditions from 2018 to 2038 into "Very Dry," "Dry," "Normal," "Wet," and "Very Wet" to evaluate water availability. Figure 6.9 outlines the monthly definitions of these climate regimes, while Figure 6.10 combines a table and a trend graph, showing a predominance of "Very Dry" years throughout the period with brief intervals of "Normal" conditions. This data is critical for understanding the temporal distribution of water year types and aiding in the management of water resources under varying climatic conditions.

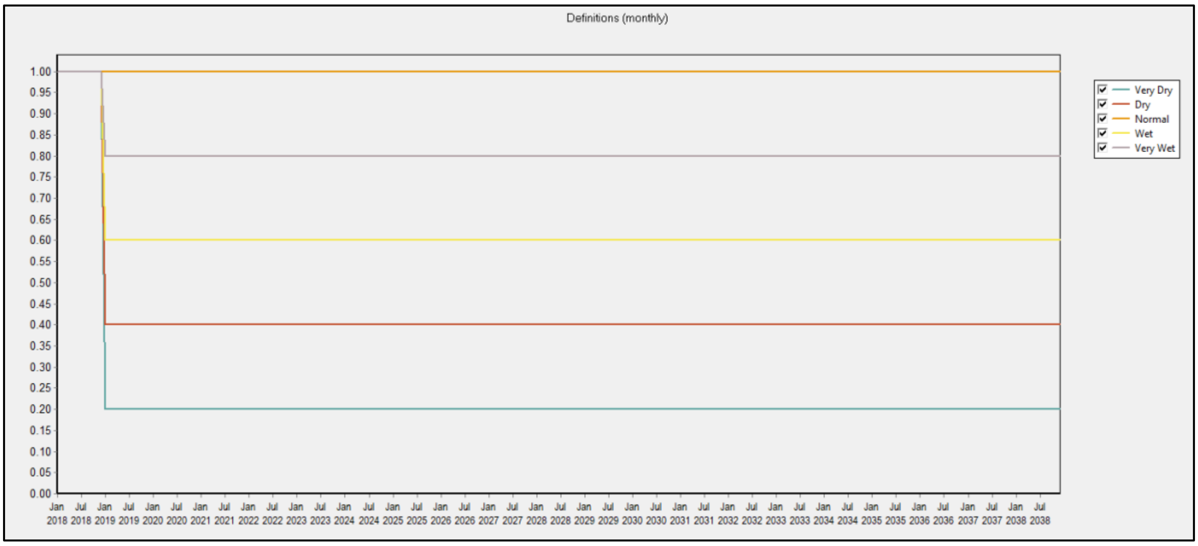


Figure 6.9. Defining the different climate regimes in WEAP according to water year type.

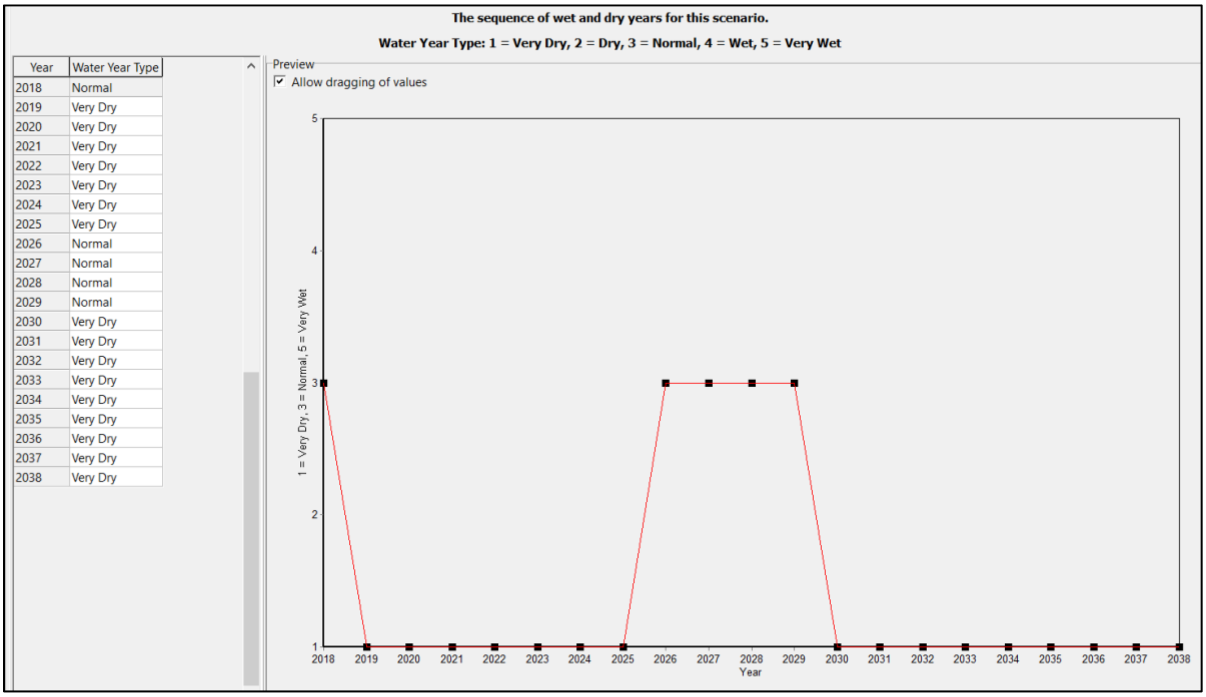


Figure 6.10. The sequence of dry and wet years.

6.2.9 Setting up the Model to Use the Water Year Method

The monthly headflows from the main rivers and the inflows from the reservoirs were set in the WEAP model to account for their variability over time. Utilizing the values from these figures, the Water Year Method was selected to determine the sequence of dry and wet years and to assess the impacts of natural variation on water resources management (Mounir et al., 2011) for the 2038 and 2058 scenarios. This assessment was conducted for both the monthly inflows from the reservoirs and the monthly headflows from the main rivers.

Figures 6.11 and 6.12 present the baseline monthly water data used in the Water Evaluation and Planning (WEAP) model, with Figure 6.11 illustrating the headflows from main rivers and Figure 6.12 showing the inflows from reservoirs for the reference year 2018. These figures are crucial for establishing a benchmark against which future scenarios, such as those for 2038 and 2058, can be compared. The bar charts in both figures break down the data by month and by specific rivers or reservoirs, allowing for a detailed understanding of seasonal variations and water distribution that informs water resource management and policy decisions. This baseline data provides the context for evaluating changes in water availability and the impact of management strategies over time.

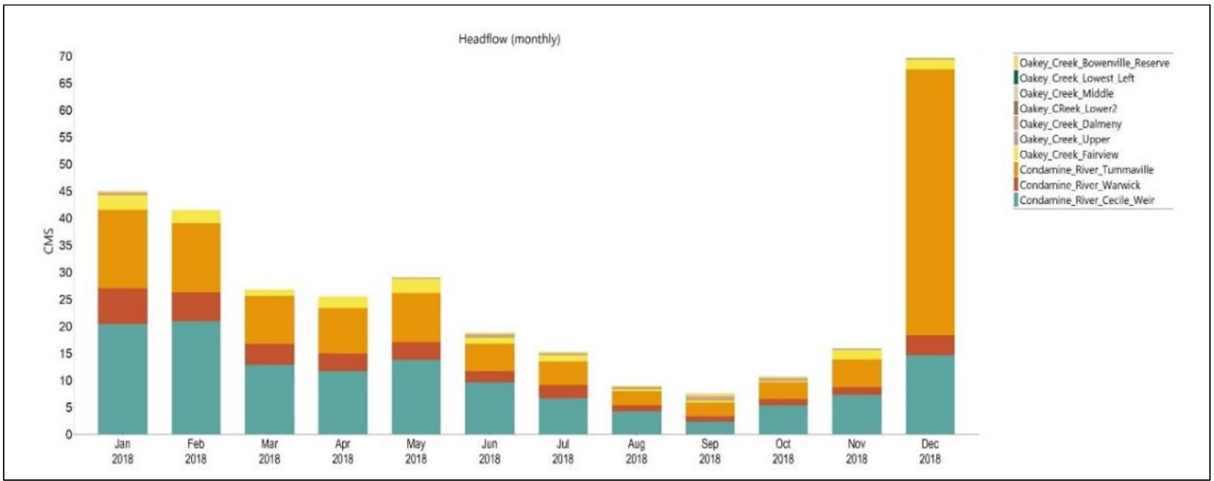


Figure 6.11. The monthly headflows from the main rivers used as reference in the WEAP model.

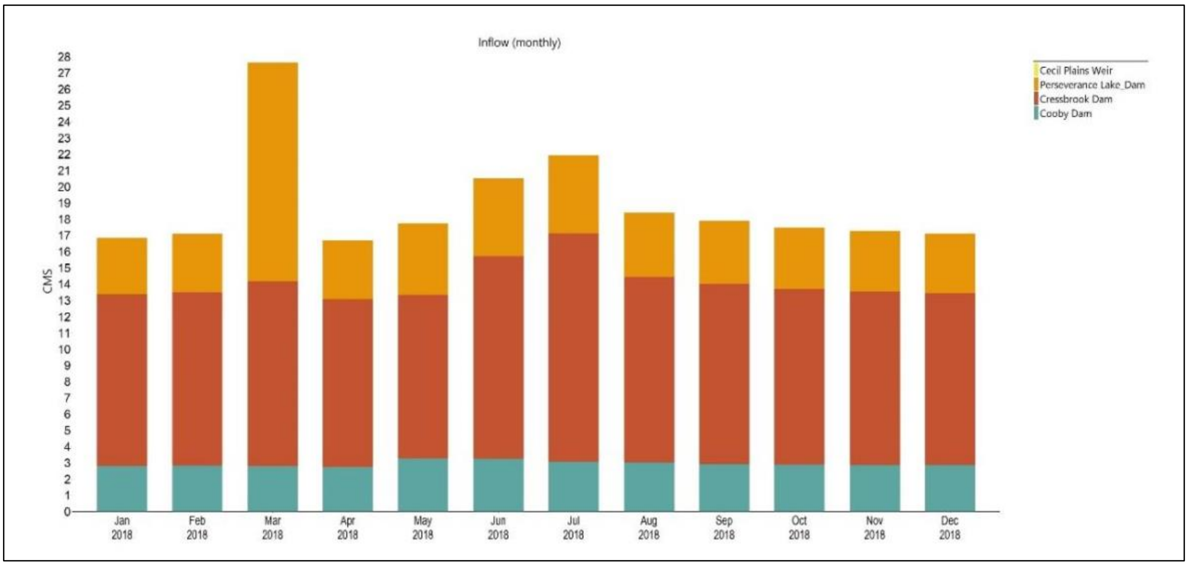


Figure 6.12. The monthly inflows from the reservoirs used as reference in the WEAP model.

Figures 6.13 and 6.14 depict the Water Year Model projections of monthly inflows into reservoirs for two different time scenarios, 2038 and 2058 respectively. These figures provide a visual representation of water inflow patterns and help to illustrate the seasonal and annual variability expected in the future. Such models are crucial for water resource management, allowing for the anticipation of periods of high and low water availability. The projections are broken down by individual reservoirs, which is essential for planning at both the local and regional levels in the context of water supply, flood control, and ecological conservation. Each bar in the graphs likely represents monthly inflow data, with colors indicating different reservoirs, thereby facilitating a comparative analysis of inflow dynamics across multiple locations.

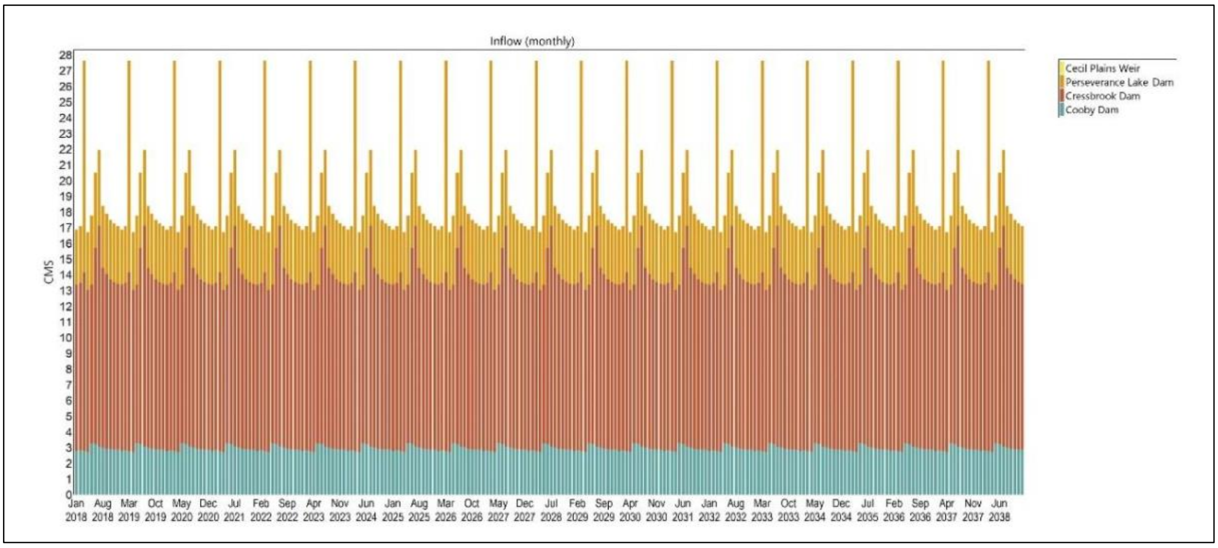


Figure 6.13. The Water Year Model of monthly inflows from the reservoirs for the 2038 scenario.

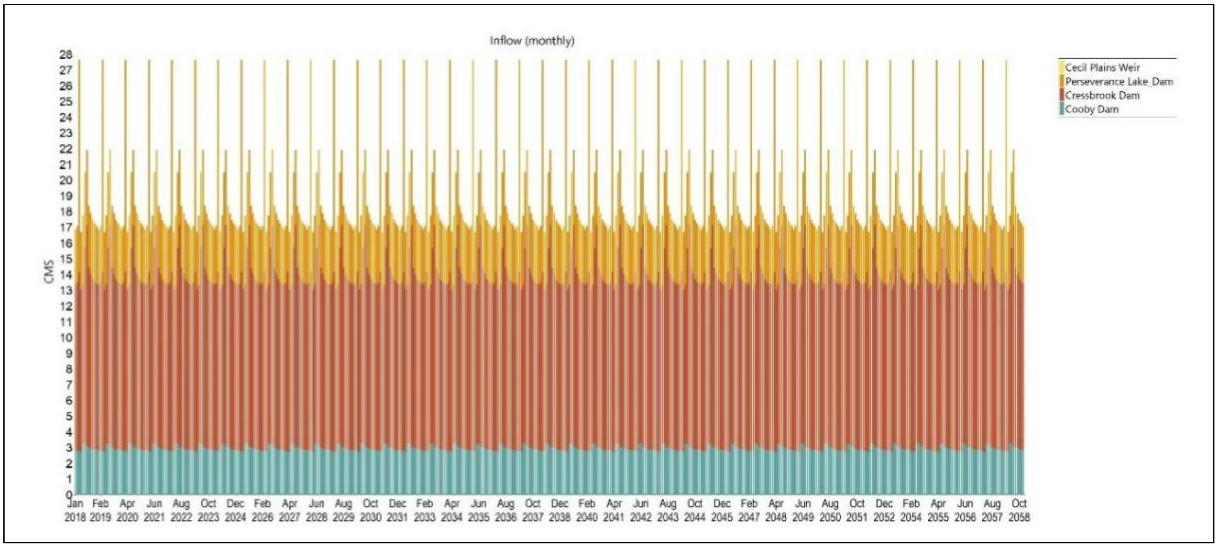


Figure 6.14. The Water Year Model of monthly inflows from the reservoirs for the 2058 scenario.

Figures 6.15 and 6.16 are graphical representations of the Water Year Model for monthly headflows from major rivers under two different future scenarios, one for the year 2038 and the other for 2058. These figures visualize changes in river head flows over time, providing a monthly breakdown across a span of years. The data illustrated in these graphs is crucial for hydrological forecasting, water resource planning, and understanding the impacts of climate change on water availability. Each line in the graphs represents a different river or a specific location within a river basin, allowing for a detailed analysis of temporal variations in water flow across the regions considered in the scenarios.

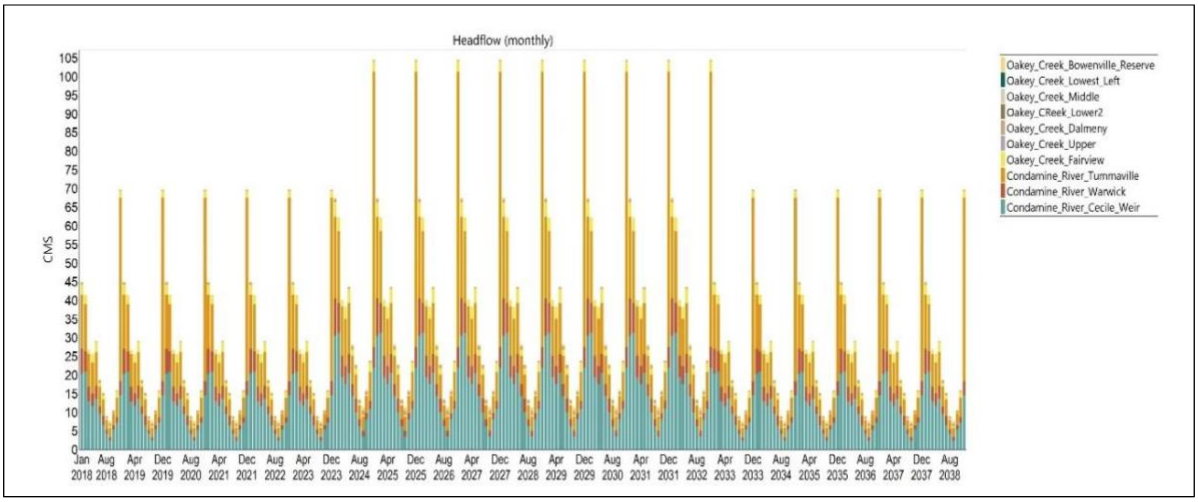


Figure 6.15. The Water Year Model of monthly headflows from the main rivers for the 2038 scenario.

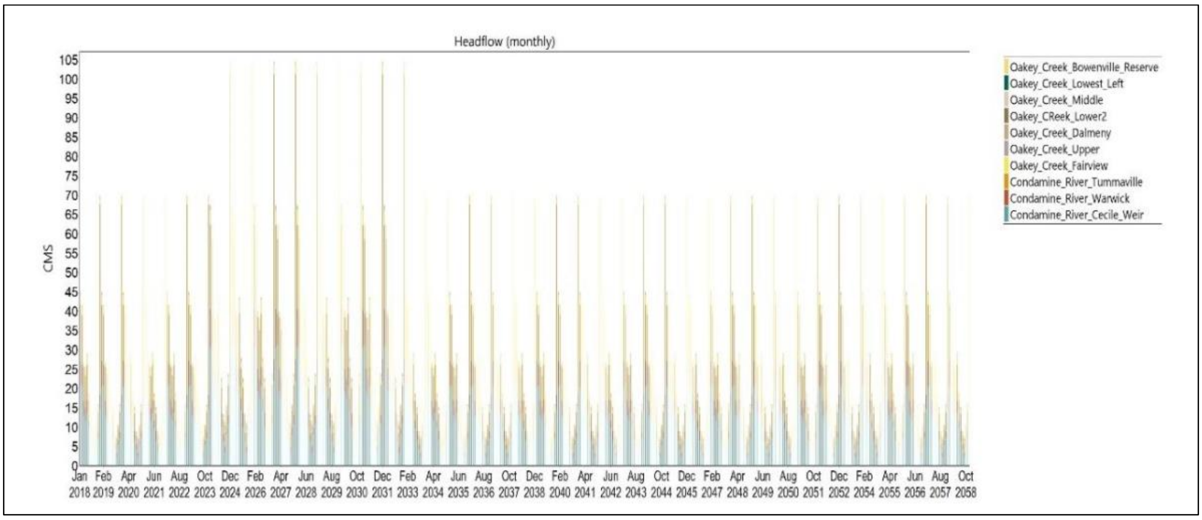


Figure 6.16. The Water Year Model of monthly headflows from the main rivers for the 2058 scenario.

6.3 Results

The results of this study are presented in three parts and illustrated in Figures 6.17–6.22. The first part addresses the unmet water demands under the Reference Scenario/Normal Water Year for 2038 and 2058. The second part focuses on the unmet water demands under the Very Dry Water Year for 2038, and the third part examines the unmet water demands under the Very Wet Water Year for 2038 and 2058.

6.3.1 Unmet Water Demand in Reference Scenario: Normal Water Year

The bar charts in Figures 6.17 and 6.18 display the results of the analysis on the monthly average unmet water demands of each sector for the years 2038 and 2058 under a scenario termed the Normal Water Year. A thorough examination of these charts discloses significant insights into the dynamics of water demand and the pressure on water resources within different sectors. Given that the results of unmet water demand under Normal Water Year and Very Dry Water Year are similar, a detailed discussion is provided in the Very Dry Water Year Section.

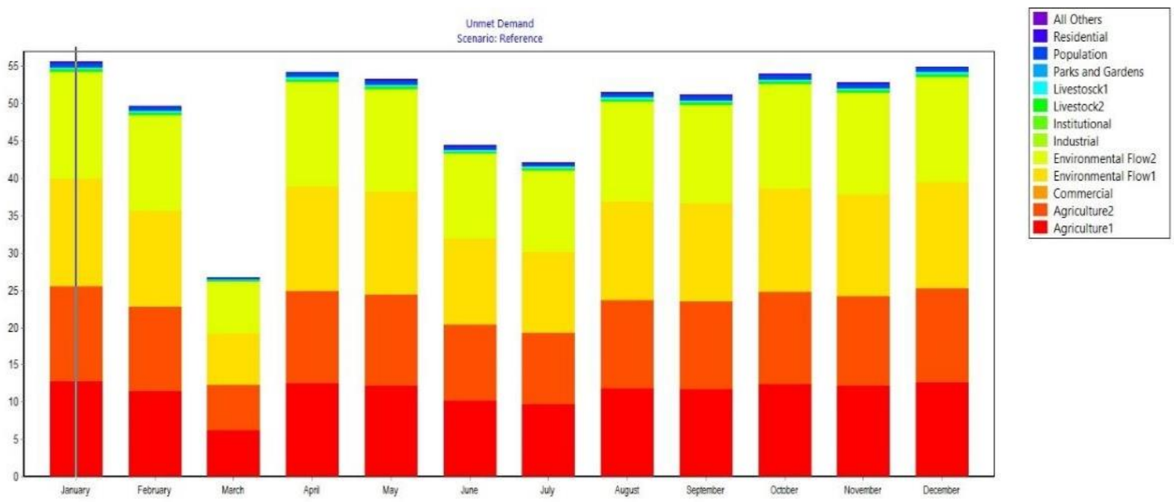


Figure 6.17. Average monthly unmet water demand for different water user sectors in 2038 under Normal Water Year.

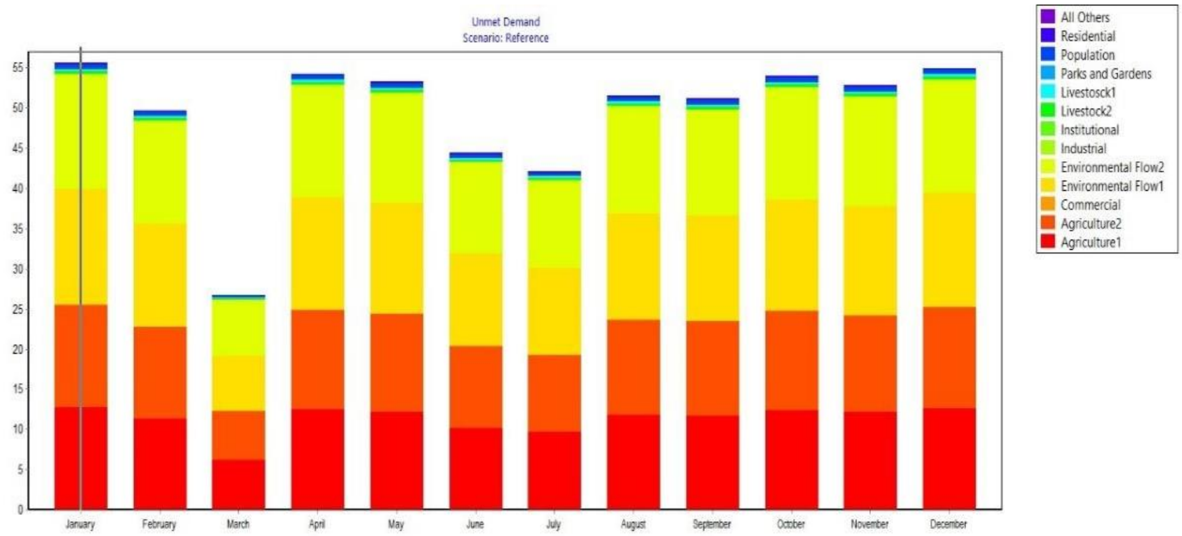


Figure 6.18. Average monthly unmet water demand for different water user sectors in 2058 under Normal Water Year.

6.3.2 Unmet Water Demands in 2038 and 2058 under Very Dry Water Year

The monthly average unmet water demands of each sector in the year 2038 under the Very Dry Water Year are presented in Figure 6.19, while the unmet demand for the year 2058 is depicted in Figure 6.20. The bar charts provided in Figures 6.19 and 6.20 are the result of the analysis of monthly average unmet water demands of each sector for the years 2038 and 2058 under a scenario termed the Very Dry Water Year. A thorough examination of these charts discloses significant insights into the dynamics of water demand and the pressure on water resources within different sectors. Across both datasets, a pronounced seasonality is evident, with the highest levels of unmet water demand concentrated in the summer months (December to February), peaking notably in January, which is 55.64 million cubic meters.

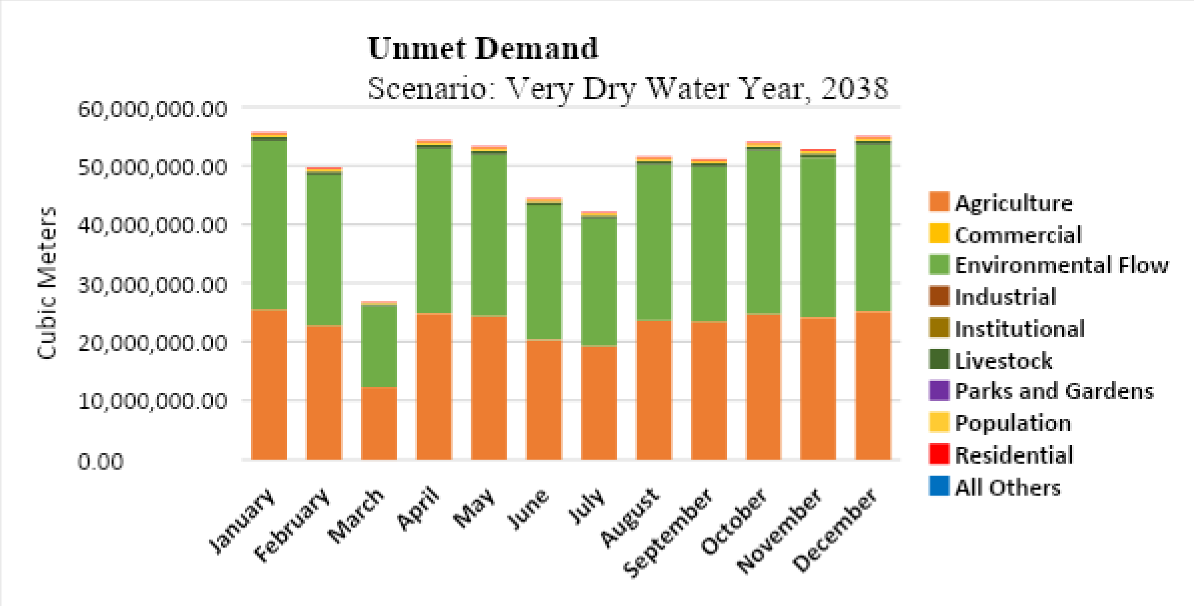


Figure 6.19. Monthly average unmet water demands for different water user sectors in 2038 under Very Dry Water Year.

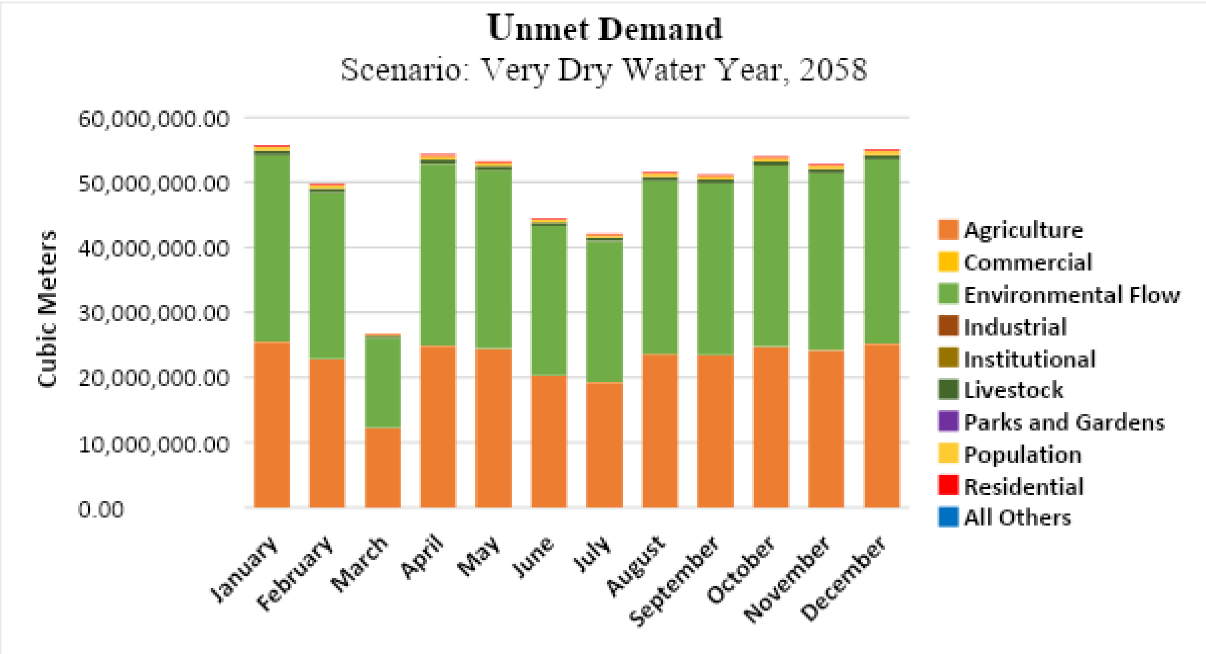


Figure 6.20. Average monthly unmet water demand for different water user sectors in 2058 under Very Dry Water Year.

The observed surge in unmet water demand during the warm months likely aligns with heightened agricultural activity. This result also unveils that the agricultural sector exhibits the most substantial unmet demand across all months. This is parallel to global observations that an increase in water unmet demand is attributed to the rise in agricultural activity (Rostam, 2019). Based on Rostam's analysis, a business-as-usual trajectory suggests a potential increase of 30-40% in India's agricultural water demand by 2050. Similarly, in the study by Mekonnen (2020), he predicts a 14-20% increase in agricultural water demand by 2050 compared to the 2017 levels. Furthermore, it aligns with the report of Australia's National Land and Water Resources Audit that agriculture accounts for around 64% of the total water consumption in the Murray-Darling Basin, the largest river in Australia and a significant river system in Queensland that supports a diverse range of ecosystems and habitats. In line with this, the research findings of Grafton (2019) suggest a 20-30% increase in water demand by 2030 for Southeast Queensland alone.

A notable feature of the unmet water demand data for both 2038 and 2058 projections is the abrupt decline observed in March, which typically marks the beginning of autumn in the Southern Hemisphere. Unmet water demand dropped by 49.1%, equivalent to 22.9 million cubic meters. One of the major reasons is attributed to seasonal rainfall. The study by Prosser et al. (2020) and Grafton R. P. (2021) emphasizes that during autumn months, irrigation water use decreases when rainfall is higher. This finding also aligns with the study of Rahman (2019), where the author found that demand for water in the residential sector during autumn decreases due to reduced outdoor water use for gardening and lawn maintenance because of sufficient rainfall.

For other sectors like livestock, commercial, industrial, institutional, parks and gardens, and others, they contribute less to the overall unmet demand, indicating either lower requirements or perhaps a better balance between supply and demand in these areas. On the other hand, some studies paint a concerning picture of the impending water crisis facing commercial and industrial sectors. For instance, it was reported that even with aggressive water conservation efforts, they might not be enough to meet industrial water demand by 2030 (Zhang, 2020). Similarly, another study conducted by the International Institute for Applied Systems Analysis in 2021 reveals that the global industrial water demand might double by 2050 in a business-as-usual scenario. Furthermore, the Organization for Economic Co-operation and Development (OECD) projects a 50% increase in global industrial water withdrawals by 2060 (OECD, 2019).

While originally only 8 sectors are covered by this study, the author decided to include Environmental Flow in the analysis, considering that neglecting this sector can lead to inaccurate and misleading water demand projections. The study by Jaramillo (2021) demonstrates how prioritizing other sectors without considering environmental flow can result in unreliable water supplies to all sectors in the long run. Further corroborating the importance of environmental flow integration, Zhang (2022) highlights the significant reshaping of global water scarcity assessments when ecological water needs are factored in. His research underscores how accounting for environmental flow adjustments yields a more accurate picture of water availability and scarcity, thereby fostering informed decision-making that benefits both human communities and ecosystems. This alignment reinforces the critical role of environmental flow inclusion in achieving sustainable water management. Cognizant of the aforementioned predicaments, the present study incorporates environmental flow considerations within its projections. Consequently, the results reveal a substantial unmet demand within this sector during Normal Water Years, persisting both in 2038 and 2058. This finding underscores the critical importance of prioritizing environmental flow needs in water resource management to ensure long-term sustainability and ecological well-being.

6.3.3 Unmet Water Demand for Scenario 3: The Very Wet Water Year

Figures 6.21 and 6.22 present bar charts illustrating the monthly unmet water demands for a variety of user sectors in 2038 and 2058 under the Very Wet Water Year scenario. The data indicate that, even during periods characterized by higher overall water availability, certain sectors still experience significant unmet water demand. Agriculture, in particular, exhibits the highest unmet demand throughout the year in the 2038 chart, even during a wetter year. However, unlike drier years with their pronounced seasonal fluctuations, the unmet demand in a Very Wet Water Year is more evenly distributed across months, averaging 8.825 million cubic meters. This aligns with recent research highlighting the role of climate in shaping agricultural water demand. For example, Addis (2023) notes that even with increased rainfall, the timing of precipitation can change. Cooler temperatures in Very Wet Water Years further contribute to lower unmet demand compared to Very Dry Water Years. As Duzkale (2019) explains, reduced evapotranspiration due to cooler temperatures lowers irrigation requirements, minimizing freshwater use.

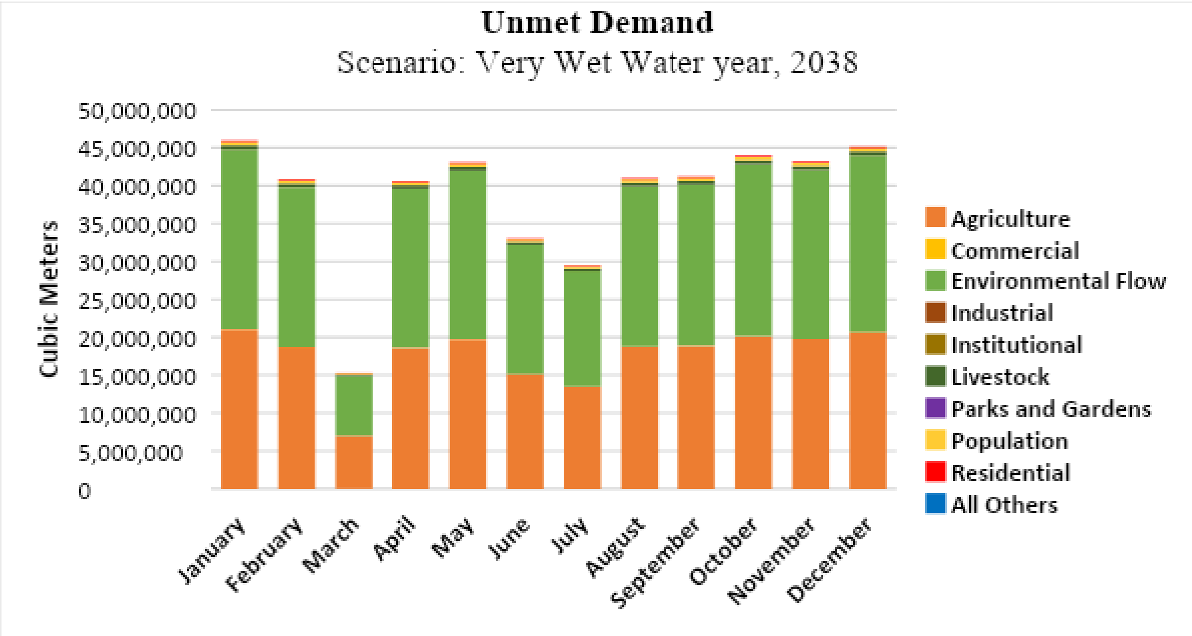


Figure 6.21. Monthly average unmet water demands for different water user sectors in 2038 under Very Wet Water Year.

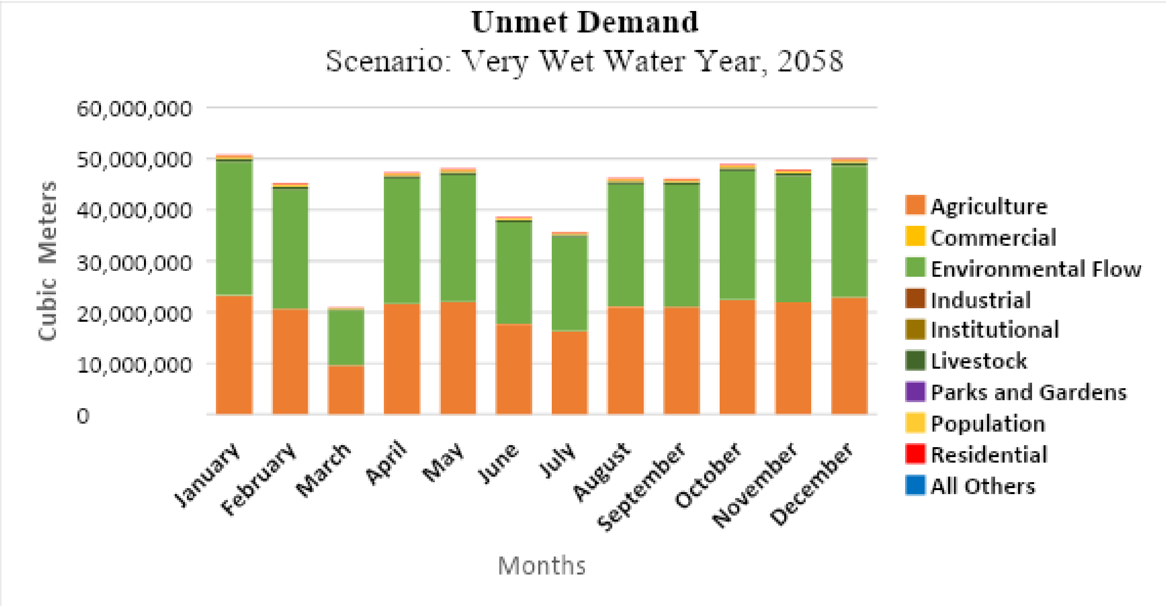


Figure 6.22. Monthly average unmet water demand for different water user sectors in 2058 under Very Wet Water Year.

On the other hand, it is important to note that even Environmental Flow, though not originally belonging to the identified water users, is included in the projection of water demand. In this study, environmental flow also exhibits considerable unmet demands, underscoring the challenge of balancing human water consumption with the needs of natural ecosystems. Unmet demand of this additional sector is higher than agriculture, hitting 9.944 million cubic meters on a monthly average. The implications of this are significant, as insufficient environmental flows can lead to degraded water quality, loss of habitat, and reduced biodiversity.

Fast forward to 2058, the chart reflects a similar distribution of unmet demand across sectors, with a slight overall increase in the unmet demand for some months. This uptick could be indicative of increasing pressures on water resources, even in wet years, which may also be attributed to factors like temperature increase. It can be noted that the analysis of the agriculture water consumption model (Chapter 4) reveals that, holding other factors constant, a one-unit increase in temperature leads to a 557-unit increase in water consumption of the agriculture sector. Furthermore, the model's exceptionally high coefficient of determination (R^2) of 0.967 implies that nearly 97%

of the variability in agricultural water consumption can be explained by the variations in December temperature and water charges.

The slight increase in unmet demand from 2038 to 2058, despite the abundance of water in very wet years, implies that there might be other possible factors that trigger significant unmet demand. Many authors suggest different issues such as inefficiencies in water use (Stuchte, 2019), aging infrastructure (Walshaw, 2021), or perhaps a decline in the reliability of surface water despite a relatively stable precipitation level. With this, it is deemed necessary to adopt forward-looking water management strategies that include more efficient water use practices, investments in infrastructure for water storage and distribution, and policies that support sustainable water use across all sectors.

6.3.4 Total Water Unmet Demand in Toowoomba Region

The projected unmet water demands in the Toowoomba Region for 2038 and 2058 are presented in Table 6.3. This table contains the major water user sectors of the region and their unmet demands for the next two and four decades, respectively. The results show possible unmet water demands in all water years across various water user sectors. Unmet demand is evident for all sectors. For instance, among major water user sectors under normal and very dry water years, agriculture will have the most projected unmet demands, amounting to 270 million cubic meters, followed by the livestock sector, amounting to 6.6 million cubic meters. The least projected unmet demand will be in the parks and garden sector, which will be 14 thousand cubic meters. It can be observed that the difference in unmet water demand for all sectors in both 2038 and 2058 under normal and very dry water years is insignificant.

On the other hand, the projected unmet demand of the agriculture sector under a very wet water year will be reduced by 21% and 11% in 2038 and 2058, respectively. Similarly, the projected unmet demand of the livestock, population, and other sectors will also be lessened by an average of 11-21%.

Table 6.3. Summary of projected unmet water demands in 2038 and 2058 for all scenarios.

Water User Sectors	Unmet Demand (million cubic meters)					
	Normal Water Year		Very Dry Water Year		Very Wet Water Year	
	2038	2058	2038	2058	2038	2058
Environmental Flow	304,538,794	304,538,726	304,538,794	304,538,726	238,656,876	270,794,328
Agriculture	270,273,820	270,273,712	270,273,820	270,273,712	211,804,024	240,325,768
Livestock	6,684, 600	6,684,600	6,684, 600	6,684,600	5,228,372	5,938,739
Population	6,057,581	6,057,582	6,057,581	6,057,582	4,737,937	5,381,667
Residential	2,238,250	2,238,250	2,238,250	2,238,250	1,750,657	1,988,507
Institutional	189,223	189,222	189,223	189,222	147,854	168,034
Industrial	178,694	178,694	178,694	178,694	139,628	158,685
Commercial	382,917	382,917	382,917	382,917	299,202	340,038
Parks and Gardens	14,079	14,079	14,079	14,079	10,972	12,488
All others	1,079	1,079	1,079	1,079	840	956
TOTAL	590,559,035	590,558,860	590,559,035	590,558,860	462,776,363	525,109,198

6.4 Discussions

One of the world's pressing issues is the imbalance between water supply and water demand that causes water scarcity (Sun et al., 2018). In most parts of the year, water scarcity is experienced in many watersheds. The agriculture and domestic sectors are always affected by water shortages (Agarwal et al., 2019). Rainfall seasonality, the wet and dry seasons, affects water availability (Maliehe & Mulungu, 2017). It was reported that global water demand is increasing at around 1% per year and projected to increase at a similar rate until 2050 (UNESCO World Water Assessment Programme, 2019). It was also reported that by 2075, water scarcity would be experienced by around 9 billion people around the world, including Australia (Zubaidi et al., 2020). For instance, during dry periods, competing water users in several catchments of Australia experience medium to high water stress (Nair & Timms, 2020). In fact, responding to climate change is one of the issues the Australian Government is facing, more specifically within the MDB (Commonwealth of Australia, 2019). Hence, the government requested the Bureau of Meteorology to produce an annual climate statement on the future impacts on water resource availability.

Toowoomba, situated in the northeastern portion of the Basin, where the Condamine River drains, experiences variable seasonal rainfall patterns with longer dry periods, i.e., less frequent but more intense rainfall. Groundwater contribution to streamflow ranges from 20-70% in northern tributaries of the Condamine River while 8-50% in the upstream of the main river channel (Martinez et al., 2015).

Among the competing users for water resources in the Region are residential, agriculture, livestock, mining, commercial, industrial, institutional, parks and garden, electricity generation, mining, and environmental flow. Martinez et al. (2015) reported that changes in land use put pressures on the water resources of Condamine Catchment, considering that 90% of groundwater extracted from it is being utilized for agriculture. The population of the Region is expected to increase by 27% for the next 15 years, reaching 210,000 in 2038 (TRC, 2018). The population is one of the major water user sectors. The Toowoomba Region is facing a challenging situation with water scarcity, competing water users, and changes in land use and its possible effects on future climatic conditions on water. With all these challenges, there is a need to project future water supply and demand because Australia needs to ensure that there is a sustainable water supply in the face of a drying climate and water demand (DAWR, 2018).

This study was conducted to determine the future water demands of the major water user sectors to be used as inputs in the planning and decision-making of water allocation in the region.

6.4.1 Monthly Average Unmet Water Demands

Overall, the comparison between long-term monthly average unmet water demands for 2038 and 2058 normal years and very dry water years showed no seasonal bias; hence, there was no difference in their values (Table 6.3). Simulations of unmet water demands under climate trends for 2038 and 2058 for very dry water years revealed that there would be a total water deficit of approximately 590 million cubic meters. Under very wet water years, on the other hand, there would be a total deficit of 462 million cubic meters and 525 million cubic meters by 2038 and 2058, respectively. This outcome is congruent with the report that, due to water variability, people living in water-scarce regions will increase in 2050 (Liu et al., 2020). Further, the result of this research is concomitant with the study conducted by Williams et al. (2018). Based on the report, there will be a reduction in water availability by the years 2030 and 2050 in Southern Queensland compared to 1960-2010 due to climate change and water policy decisions. Moreover, the results obtained were consistent with the study of Grouillet et al. (2015). In this research, simulations of water demand under anthropogenic and climate trends found that by 2050, there would be a significant increase in total water demand. Finally, the result is also similar to the research recently conducted in Pakistan and in Morocco. In Pakistan, the results reveal water shortfall in all future scenarios in the two catchments being studied (Mehboob & Kim, 2021), while under the influence of climate change, future unmet water demand is expected to reach 64 million cubic meters (MCM) by 2100 in Morocco (Ayt Ougougal, 2020).

Generally, unmet water demand for the community means a shortage of indispensable commodities affecting everyone. Each individual showed different perceptions of water use, which were affected by gender, age, education, resource and environmental attitude, water-saving behaviors, water price, and residential water source (Hui Liu, 2022). Aside from other key stakeholders, unmet water demand harms energy, specifically hydropower and thermal power; industry; health and sanitation, which may lead to disease outbreaks and water-borne diseases. Based on the 6th IPCC Report, inequities in access to safe water amplified during the COVID-19 pandemic. Moreover, freshwater ecosystems, which are vital in sustaining livelihood, are also affected. Not meeting the needs of various water users due to the climate change effect will be a real challenge for decision-makers with regards to water management and water allocation (Mena, 2021).

6.4.2 Environmental Flow Demands

Environmental flow must be maintained to sustain life in freshwater and estuarine ecosystems (Hua & Cui, 2018). The importance of environmental flow to a healthy freshwater ecosystem was recognized around the 1990s, and several attentions were given from then on. For very dry water years and very wet water years of all time frames, Environmental Flows ranked as the highest average monthly unmet water demands. Environmental unmet demands reached 300 million cubic meters in 2038 of very dry water years, while 238 million cubic meters and 270 million cubic meters for

2038 and 2058, respectively, under very wet water years. Figures 6.18 to 6.21 give a clear picture of the average monthly water demands of environmental flows in the Toowoomba Region. The average monthly unmet water demands have been projected based on the environmental flow requirement of 51 GL/month. The unexpected top-ranking unmet demands in environmental flow, despite being given the highest preference in the model, can be attributed to the declines in groundwater levels due to increasing water abstraction (Joseph et al., 2021). The result also shows that significant percentage changes in monthly average unmet demands would occur in the onset of Autumn (March), and the significant reductions are summarized as follows: 2058 very dry water year - 40% reduction, 2038 very wet water year - 60% reduction, and 2058 very wet water year - 59% reduction. An abrupt surge in unmet demands was observed in the months of April and May and suddenly plunged in June and July. Given this situation, this will have negative effects on the downstream ecosystem, considering that the purpose of environmental flows is to maintain or improve the health of the river, to maintain ecosystem functions, and support biodiversity.

6.4.3 Agriculture Water Demands

The agriculture sector ranked second with unmet water demands in all time-frames and all climate regimes. For very dry water years, its unmet demand reached 270 million cubic meters in 2038 and 2058, and it decreased to 240 million cubic meters and 211 million cubic meters by 2058 and 2038, respectively, for very wet water years. This outcome is related to the study conducted in southern Queensland where an irrigated cotton farm was investigated to determine the importance of water management options in adapting to climate change. Results of this study showed that the available water would decrease in the 2030s and 2050s due to climate change and water policy decisions (Williams et al., 2018). Moreover, Xiang et al. (2017) reported that water demand in agriculture will continue to increase. Furthermore, some authors mentioned that an increase in global agricultural demand, especially in an irrigated region, is expected. Hence, competition between agriculture and the environment is a growing problem (Dehghanipour et al., 2020). Additionally, it has been reported that in the 21st century, increasing trends for the annual irrigation water demands are expected (Gorguner & Kavvas, 2020). Moreover, in one recent study, it has been reported that water deficiencies will be encountered in catchments with agricultural land development (Mehboob & Kim, 2021).

Toowoomba's agriculture is the second-largest generator of export values, and it directly supports the largest food product manufacturing. It also accounts for more than 8% of Queensland production. In fact, this region considered agribusiness as the top priority industry in 2038 (TRC, 2018). It has been reported that agriculture is a water-intensive industry (Li et al., 2021), and considering the projected huge amount of unmet water demand, it will pose great problems in the future. Given this projection, the plan of the Toowoomba Region, as declared in their "2038 Bold Ambitions" (TRC, 2018), will be affected by climate variability and drought conditions. This will mean the reduction of water availability for many Australian farming businesses even though the unmet demand for the agriculture sector would recover by 60 and 30 million cubic meters, respectively, under very wet water years.

Looking at Figures 6.18 to 6.21, it reflects that summer months would have the highest average annual water unmet demand for agriculture with greater intensity in January. This accounts for 25M m3 in very dry water years for 2038 and 2058. On the other hand, the unmet demands for 2038 and 2058 very wet water years for this sector were estimated to be 21M m3 and 23M m3, respectively. Similar results were found by other studies in various places worldwide, although they used different crops. For instance, Gorguner & Kavvas (2020) cited this result of Wada et al. (2013), that there will be a significant increase in future irrigation water demands by more than 20% by 2100 during summer in the Northern Hemisphere. In addition, Fader et al. (2016) reported that there would be a 4 to 8% increase in irrigation water requirement in the Mediterranean region for the years between 2080 and 2090.

Under future conditions, Figures 6.18 to 6.21 show that unmet demand will not follow any significant trend on an annual scale. Overall, the substantial decrease (by 46%) in the average unmet demands is generally observed in the month of March during the very dry water year. On the other hand, for very wet water years, a considerable reduction of 62% and 53% is observed during a similar month for both time frames. Dramatic plunges in unmet demand for agriculture sectors in March can be associated with the volume of headflows available during that month

6.4.4 Livestock Water Demands

Livestock water demand in this study is estimated based on livestock production and water consumptive use per unit of livestock, including piggery, poultry, and cattle feedlots. Consumptive use coefficients for water for livestock are estimated from lactating up to weaning in the case of piggery.

The livestock sector ranked third with unmet water demand in the Toowoomba Region in all time frames and in all climate regimes, as shown in Table 6.3. For normal and very dry water years, unmet water demand reached 6.7 million cubic meters, and it decreases by 21% in 2038 of very wet water years. On the other hand, livestock unmet water demand rises again by 13% in 2058 of the same climate regimes.

There were several studies on livestock consumption. For instance, one author highlighted that 99% of the water footprint in animal production comes from feed that animals consume rather than from the water that they drink; hence, water productivity in livestock farming depends on the selection of diets and fodder production (Maria Siwek, 2021). On the other hand, a study carried out in the Mara River Basin of Kenya in 2018 reported that the current available water for livestock cannot meet the competing sectoral demands. Meanwhile, similar to the result of this study, it is also projected that unmet water demands in the livestock sector will increase by 50% in 2050 in the Indus River Basin (Asghar, et al., 2019).

Agriculture and food product manufacturing in which livestock is a part of are one of the current and emerging drivers of the Toowoomba Region's Economy (TRC, 2018). Based on Toowoomba Bold Ambitions 2038 Report, the fourth largest industry by value, in 2015/2016 Agriculture was worth $640 million or 8% of the region's industry, and the key agricultural outputs among grain and cotton are poultry, beef, pork, and dairy products. Considering the projected unmet water demand for the livestock sector in the Toowoomba Region in 2038 and 2058, it is no doubt that this industry will be greatly affected; hence, better water management policies are needed to ensure the sustainability of water resources in the long term.

6.4.5 Population Water Demands

Within the population sector, projections for unmet water demands have been delineated for the years 2038 and 2058 under three distinct hydrological scenarios: Normal Water Year, Very Dry Water Year, and Very Wet Water Year.

During Normal Water Years, the anticipated unmet water demand within the population sector is projected at 6,057,581 million cubic meters for both 2038 and 2058, with no variations expected between these two time points.

In the context of Very Dry Water Years, the unmet water demand for the population sector is projected to remain consistent with that of Normal Water Years for both 2038 and 2058, maintaining at 6,057,581 million cubic meters.

Conversely, Very Wet Water Years are associated with a significant reduction in unmet water demand within the population sector. For the year 2038, this demand is forecasted to reduce to 4,737,937 million cubic meters, markedly less than the projections for the other two scenarios. This decreasing trend in unmet water demand is expected to continue into 2058, with a further reduction to 5,381,667 million cubic meters.

This dataset suggests that climatic conditions exert a significant influence on the unmet water demand within the population sector. Dry conditions appear to have no impact on the level of unmet demand, whereas wetter conditions are associated with a considerable alleviation of unmet water demand. This indicates that increased precipitation, and consequently enhanced water availability, can potentially narrow the gap between water demand and supply for the population. It is also notable that, despite variations in unmet demand across different scenarios in other sectors, the unmet demand within the population sector remains constant in both normal and dry conditions, underscoring a persistent yet unfulfilled demand irrespective of these climatic variations.

6.4.6 Residential Water Demands

The residential sector consistently ranks fourth in terms of unmet water demands across various timeframes and climate regimes, highlighting a critical challenge for future water management. Under very wet water year scenarios, unmet demand for the residential sector is projected to reach 1.8 million cubic meters by 2038, further escalating to nearly 2 million cubic meters by 2058 – a worrying 14% increase. Even under extreme dry conditions, the residential sector's demand remains significant, reaching around 2.24 million cubic meters in both 2038 and 2058.

This concerning trend aligns with findings from various studies around the globe. A study conducted in Addis Ababa, Ethiopia, similarly predicts water shortages in 2037 under both low and high population growth scenarios, with the highest unmet demand anticipated under high population growth and dry climate conditions (Arsiso et al., 2017). This aligns with observations in the Ourika Watershed in Morocco, where unmet water demand for domestic use is projected to rise by 2100 (Ayt Ougougal, 2020). Furthermore, a study in the Ur River Watershed, Madhya Pradesh, India, anticipates significant unmet water demands for domestic purposes in 2030, particularly during dry years (Agarwal, 2018).

These concerns are particularly relevant for Toowoomba, Queensland, Australia. As the regional health hub of the Darling Downs and home to the West Moreton Primary Health Network, Toowoomba boasts a thriving aged care sector and diverse industries. This confluence of factors is expected to drive continued population growth and, consequently, increasing water demands within the residential sector.

Findings in this study align with several studies documenting a positive correlation between surface water availability and residential water consumption. For instance, Wang et al. (2020) reported that their study conducted in China within the Yellow River Basin reveals that a 10% increase in surface water availability led to a 4.2% increase in residential water use. Further, Meyer et al. (2021) also found a positive correlation between reservoir levels and residential water consumption in cities without water restrictions.

By effectively connecting these findings, we can paint a clearer picture of the looming challenge posed by unmet water demand in the residential sector. Understanding the scope and drivers of this challenge is crucial for informing proactive water management strategies and ensuring sustainable water supplies for future generations.

6.4.7 Commercial Water Demands

This research investigated the commercial sector's water use and future unmet demand in Toowoomba, Queensland, Australia. Among eight sectors analyzed, the commercial sector, encompassing hotels, shopping centers, restaurants, and more (Appendix A.2), ranked fifth in terms of unmet water demand with 383K cubic meters in normal and very dry water years in both timeframes 2038 and 2058. Notably, this ranking remained consistent across multiple scenarios even under very wet water years in both 2038 and 2058 where unmet demand reached 299K and 340K cubic meters. Further analysis, presented in Chapter 4, revealed a positive correlation between surface water supply and commercial water demand. This suggests that a one-unit increase in surface water availability leads to a 0.763-unit increase in commercial water use.

While seemingly counterintuitive, this finding diverges from other existing research that observed an inverse relationship between surface water availability and commercial water demand. For instance, Wang et al. (2020) reported that a 10% decrease in surface water availability led to a 4.8% increase in unmet commercial water demand in the Yellow River Basin, China. However, the projected increase in unmet commercial water demand in Toowoomba aligns with other studies examining future water scarcity challenges. Otieno et al. (2020) projected that the commercial sector's unmet water demand in the Tana River Basin, Kenya, could reach 3.4 million cubic meters by 2050, citing population growth and economic expansion as key drivers. Similarly, Ahmad et al. (2021) predicted that unmet water demand for commercial activities in the Indus River Basin of Pakistan could reach 25% by 2030.

These comparisons underscore the importance of considering diverse research findings and contextual factors when evaluating water demand trends. While surface water availability may act as a driver of commercial water use in some settings, other studies highlight the influence of population growth, economic activity, and water pricing structures. To effectively address future water scarcity challenges, comprehensive analyses considering other socio-economic factors are necessary.

6.4.8 Institutional Water Demands

The burgeoning institutional sector, encompassing diverse entities like tourist attractions, aged care facilities, hospitals, and educational institutions, faces significant water security concerns under future climate scenarios. This sector ranks sixth in terms of unmet water demand across all timeframes and climate regimes simulated in this study. During normal and very dry years, this unmet demand reaches a concerning 0.18 million cubic meters, highlighting the potential for water shortages impacting vital services. Interestingly, this trend exhibits some fluctuation – decreasing by 22% in 2038 during a very wet year but then rebounding by 14% in 2058.

These findings resonate with existing research exploring public water service demands. Li et al. (2020) project an overall increase in water consumption for public services in China by 2030, with institutions likely contributing significantly. Similarly, Chen (2021) in the United States identifies educational institutions as facing escalating water needs due to population growth and infrastructure expansion.

Temperature emerges as a key driver of institutional water demand in this study's water consumption model. For every one-degree Celsius increase, institutional consumption rises by 55.5 units, assuming other factors remain constant. This direct influence of temperature aligns with observations by Wang (2020) and Liu (2021) in university buildings. They report heightened water consumption as temperatures rise, fueled by increased reliance on cooling systems and expanded landscape irrigation needs.

6.4.9 Industrial Water Demands

The industrial sector presents a unique water utilization pattern in this study. Despite ranking seventh in unmet water demand across all climate regimes and timeframes (2038 and 2058), it exhibits significant fluctuations.

This is most evident in the contrasting scenarios of dry and wet years. During dry years, industrial unmet demand surges to 17.8 million cubic meters, revealing the sector's vulnerability to water scarcity. However, in the wet year of 2038, a surprising decrease brings demand down to 13.9 million cubic meters, demonstrating its adaptability to abundant water. This trend continues until 2058, albeit with a 14% rise in demand despite the wet conditions.

Unlike other sectors, industrial water demand is influenced by a diverse set of drivers. Its direct relationship with surface water supply is undeniable, with each additional unit of surface water resulting in a 6-unit increase in industrial consumption. Similarly, average rainfall exerts a strong influence, driving a significant 111-unit rise in industrial demand for every 1-unit increase in rainfall. This confirms the intuitive notion that industries thrive on readily available water resources.

However, water restrictions offer a surprising twist. This study reveals that a 1-unit increase in water restrictions leads to a substantial reduction of 3,264 units in industrial water demand.

These findings align with concerns raised by Zhou (2020), who projected significant water demand increases in manufacturing sectors due to population growth and economic development. Similarly, Ahmad et al. (2022) highlighted the anticipated rise in industrial water needs during dry periods.

6.4.10 Parks and Gardens Water Demands

In examining the projected unmet water demands for parks and gardens as presented in Table 6.3, the data indicates a consistent pattern for the years 2038 and 2058 under normal and very dry water year scenarios. The unmet demand for Parks and Gardens is projected to be unchanged at 14,079 million cubic meters across these scenarios and years. However, a different trend emerges during very wet water years, where the unmet demand decreases to 10,972 million cubic meters in 2038 and slightly increases to 12,488 million cubic meters by 2058. This reduction in unmet demand during very wet years suggests that parks and gardens may have a lower water deficit due to increased natural water availability or effective water management strategies that capitalize on periods of abundance. Despite the variable conditions, the demand for water in parks and gardens remains notably stable during normal and dry conditions, pointing to a potential optimization or a fixed demand threshold within this sector.

6.5 Conclusion

This study produced a forecast of the unmet water demands in the Toowoomba Region for the years 2038 and 2058. The Water Evaluation and Planning System (WEAP) model was constructed, incorporating the major water user sectors of the region, as well as the sources of water supply. Three different future climate scenarios were considered: the normal water year, the very dry water year, and the very wet water year. The study showed that among the nine major water users in the region, the Environmental Flow and Agriculture sectors ranked as the 1st and 2nd sectors with the highest unmet water demand. Due to data constraints, in this particular chapter, agriculture was represented by cotton, fruits, vines, vegetables, and pastures. The inclusion of Environmental Flow in this study as one of the user sectors was considered a novelty due to limited literature addressing the projection of its future water demand. Remarkably, the results revealed that the unmet water demand of Environmental Flow was far greater than the aggregated unmet water demands of all other eight sectors.

Considering the outcome of this study, the Toowoomba Region is facing the problem of maintaining reliable water supplies to meet growing demands, and this challenge will continue to worsen due to land use and climate changes. With the Bold

Ambition 2038 of the region, where agriculture is the priority industry, the integration of both demand and supply-side management is pivotal for sustainable water resources development.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The main goal of this study was to investigate the major water user sectors and the significant drivers of their usage in the Toowoomba Region. It also aimed to predict the future land use of the Toowoomba Region by 2038 and 2058, considering the following factors: distance from roads, anthropogenic disturbances, elevation, slope, rainfall, and temperature. Moreover, this study was designed to simulate the 2038 and 2058 water supply and demand of each sector. It also simulated the environmental flow to find out whether the demand for water would be satisfied in consideration of climate scenarios. To achieve these goals, three specific objectives detailed in Chapter 1 were addressed in Chapters 4 through 6. This last chapter presents the significance of the study and its implications, as well as offering recommendations for future research works.

7.2 Summary and Conclusions

The first objective of this study is to estimate the water consumption of various sectors (e.g., residential, agriculture, livestock, mining, industrial, institutional, energy generation, parks and gardens, and the human population) in the Toowoomba Region. This goal was effectively met through a comprehensive analysis that identified the major consumers and quantified water consumption patterns.

The study records the highest water consumption during the normal years of 2004-2005, followed by a sharp decline during the drought years of 2006-2009. Notably, an extreme drop in consumption across all sectors is observed during the severely dry years of 2006-2007. Despite a slight population growth of approximately 1.1% from 2004 to 2013, a downward trend in residential water consumption (-4.3%) is noted. This decrease is largely due to the diminishing supply of surface water, indicating the study's success in correlating water consumption with various factors.

The research uncovers strong positive correlations between water consumption in various sectors and factors such as population, water price, rainfall, and access charges. For instance, livestock consumption shows a positive correlation with population, water price, rainfall, and access charge. Similarly, residential consumption is positively correlated with surface water supply and treated water. The regression analysis further highlights the key determinants of water usage in each sector. In the Residential Sector, surface water and annual access charge are dominant factors (R^2 = 79.5%), while in the Commercial Sector, surface water stands as the only dominant factor (R^2 = 83%).

Moreover, the agriculture, livestock, and mining sectors are significantly influenced by factors like water price and December temperature. The agriculture sector is influenced by Tier 1A water consumption charge and December temperature (R^2 = 96.7%). Livestock consumption correlates with the annual access charge and rainfall (R^2 = 86.7%). The mining sector's water usage is influenced by the Toowoomba population and December temperature (R^2 = 89.6%).

In conclusion, the study successfully met its first objective. All results and discussions are stated in Chapter 4. By analyzing and correlating water consumption with various socio-economic and climatic factors across different sectors in the Toowoomba Region, it provided a comprehensive understanding of water usage patterns. This information is crucial for effective water resource management in the region.

Transitioning to the second objective, the study aims to provide projections of the potential land use changes in the Toowoomba Region for the years 2038 and 2058. In pursuit of this objective, the study employed Multi-Layer Perceptron and Markov Chain Analysis to predict future land use scenarios in Toowoomba. This approach utilized historical data from 1999 to 2018, with LULC map images aiding in the study of LULC change characteristics, modeling transitional potential, and projecting future patterns under three different scenarios. Throughout the study period, agriculture emerged as the dominant land use, witnessing notable overall expansions from 1999 to 2018.

Regarding future projections, the Base Scenario (1999-2018 Data) forecasts an expansion of croplands and mining areas, while anticipating a decline in areas designated for animal and livestock production, likely due to competition for land and water resources. The First Alternative Scenario (1999-2010 Data) suggests the persistence of all categories by 2038 and 2058, with an observed expansion in agriculture and a reduction in infrastructural areas. Meanwhile, the Second Alternative Scenario (2010-2018 Data) predicts a lower degree of change compared to other scenarios, with key classes either decreasing or maintaining their 2018 areas by 2038 and 2058.

In conclusion, the study successfully met its second objective by providing detailed projections of land use changes in the Toowoomba Region for 2038 and 2058. These projections are stated in detail in Chapter 5, and are derived from a blend of historical data analysis and advanced modeling techniques, offering critical insights for future planning and development in the region.

Moving to the third objective, the study aims to estimate the future water demand in the Toowoomba Region in relation to its land use under a range of climate change scenarios for the years 2038 and 2058. Chapter 6 presents detailed results on unmet water demands in the Toowoomba Region for these years, considering three different climate scenarios: normal water year, very dry water year, and very wet water year. The study's comprehensive approach analyzes the monthly average unmet water demands for different sectors under these varied climatic conditions.

In very dry years, the highest unmet water demand occurs in summer, particularly in January, with significant variations across different sectors. Conversely, during very wet years, the unmet demand is more evenly distributed throughout the months, though the agriculture sector still exhibits the highest demand.

The Environmental Flow demonstrates substantial unmet demand in all scenarios, highlighting the importance of considering ecological water needs in water management strategies. Similarly, the agriculture sector consistently shows significant unmet demands across all scenarios, with a notable increase during the summer months.

Livestock, ranking third in unmet water demand, is affected by factors such as the water footprint from animal feed production.

The Residential Sector faces consistent challenges across various timeframes and scenarios, with an expected increase in unmet demand driven by factors like population growth and climatic conditions. The Commercial and Industrial Sectors exhibit varying degrees of unmet demand, influenced by aspects such as surface water availability, economic activity, and water restrictions. Furthermore, the Institutional Sector experiences fluctuations in unmet demand, with temperature acting as a key contributing factor.

In conclusion, the study successfully meets its third objective, indicating significant unmet water demands in the Toowoomba Region across all sectors and scenarios, thus underscoring the challenge of water scarcity. It identifies Environmental Flow and Agriculture as the sectors with the highest unmet demands, emphasizing the need for integrated water resource management strategies. The study further underscores the impact of climatic variations on water demand and highlights the critical need for considering both demand and supply-side management to ensure sustainable water resource development in the region.

7.3 Limitations

This study, while providing valuable insights into water usage and land use in the Toowoomba Region, is subject to certain limitations. These must be acknowledged to accurately understand the context and scope of its findings. The key limitations, based on the provided information, are as follows:

- Coal Mining Area Exclusion: The coal mining area was not specified in the Toowoomba Region’s available land use maps of 2006, 2010, and 2018; hence, it is not included in this study.

- Fair Market Price Analysis: Due to time constraints, the study did not test the explanatory power of fair market price.

- Geographical Limitation: The study is confined to the Toowoomba Region. This geographical limitation means the results may not be representative of or applicable to other regions with different climatic, hydrological, or socio-economic conditions.

- Focus on Quantitative Analysis: The study emphasizes the quantitative aspects of surface water and groundwater supply, potentially overlooking qualitative aspects such as water quality, ecological impacts, and socio-cultural factors related to water use.

- Limited Water User Sectors: Although the study considers a range of water user sectors, its findings might not fully represent all possible water users, particularly those not included in the study.

- Agricultural Focus: The study's first technical chapter considers only irrigated cotton, fruits, pastures, and vegetables in agriculture. This narrow focus may not capture the full spectrum of agricultural water use, impacts, or issues associated with different crops and farming practices.

- Exclusion of Other Irrigated Agricultural Crops: The study did not include other irrigated agricultural crops due to time constraints. This exclusion limits the study’s ability to provide a comprehensive view of agricultural water use.

- Method of Measuring Water Usage: The study measures water usage based on allocation and consumption rather than virtual water concepts. This approach may overlook the broader water footprint of products and activities, especially in terms of indirect water use.

7.4 Recommendations

The recommendations from this study emphasize the need for more comprehensive and detailed analyses in future research concerning water consumption and land use, particularly in the Toowoomba Region. Key recommendations include:

- Inclusion of Coal Mining Water Demand: Future studies should incorporate the coal mining water demand, which was previously omitted due to its absence in the land use maps of 2006, 2010, and 2018.

- Expanded Sample Data: It is advised to increase the number of sample data cases, such as historical consumption per sector, to enable a more detailed statistical analysis. This should encompass all available historical and current data for each sector.

- Independent Land Cover Mapping: For a more uniform dataset, independently producing land cover maps for change analysis is recommended. This process should involve actual image processing and supervised image classification using cloud-free resolution satellite imagery.

- Exploration of Fair Market Price: Future land use studies should examine the fair market price alongside commonly used socio-economic and natural environmental factors, such as accessibility, spatial configuration, political restrictions, topography, and potential productivity.

- Inclusion of Human Population Data: Including human population data in future studies could help understand its impact on agricultural and infrastructural changes.

- Employment of Advanced Analytical Models: The use of the Binary Logistic Regression Model (BLRM) is recommended for modeling land use changes with binary or categorical dependent variables. Additionally, the combination of Cellular Automata and Markov Chain Model (CA_Markov) should be explored to predict and simulate future land use changes more accurately.

- Comprehensive Water Evaluation and Planning: Employing various iterations of water demand and supply in the WEAP model is recommended for a more comprehensive water evaluation and planning analysis, aiming to minimize unmet water demand.

- Extended Timeframe Analysis: Future studies could extend the analysis beyond 2058 to assess long-term trends in water consumption and land use.

- In-Depth Sector-Specific Studies: Focused research on individual sectors, especially those with high water demands like agriculture and environmental flow, is suggested for detailed insights into specific consumption patterns and management strategies.

- Impact of Climate Change: Further studies should address the detailed impacts of climate change on water availability and land use, incorporating recent climate models and projections.

- Technological and Policy Interventions: Investigating the effectiveness of technological solutions and policy interventions in managing water resources and land use could be valuable. This includes research on water-saving technologies, sustainable agricultural practices, and urban planning strategies.

- Socio-Economic Factors: Future studies should dig deeper into socio-economic factors affecting water consumption and land use, such as economic development, lifestyle changes, and demographic shifts.

- Integrated Water Resource Management (IWRM) Strategies: Developing and implementing comprehensive IWRM strategies in the Toowoomba Region, considering both demand and supply-side factors, would be beneficial.

REFERENCES

Acworth, R. I., Rau, G. C., Cuthbert, M. O., Leggett, K., & Andersen, M. S. (2021). Runoff and focused groundwater-recharge response to flooding rains in the arid zone of Australia. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-020-02284-x

Addis, T. B. (2023). Temporal variations in extreme rainfall events and their impacts on agricultural water demand in the Rift Valley, Ethiopia. *Journal of Hydrology*, 52.

Agarwal, S., Patil, J. P., Goyal, V. C., & Singh, A. (2019). Assessment of Water Supply–Demand Using Water Evaluation and Planning (WEAP) Model for Ur River Watershed, Madhya Pradesh, India. *Journal of The Institution of Engineers (India): Series A*, *100*(1), 21–32. https://doi.org/10.1007/s40030-018-0329-0

Aldwaik, S. Z., & Pontius, R. G. (2012). Intensity analysis to unify measurements of size and stationarity of land changes by interval, category, and transition. *Landscape and Urban Planning*, *106*(1), 103–114. https://doi.org/10.1016/j.landurbplan.2012.02.010

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050: the 2012 revision. *ESA Working Paper*, *12*(12), 146. www.fao.org/economic/esa

Alfarra, A., Kemp-Benedict, E., Hötzl, H., Sader, N., & Sonneveld, B. (2012). Modeling Water Supply and Demand for Effective Water Management Allocation in the Jordan Valley. In *Journal of Agricultural Science and Applications (JASA) JASA* (Vol. 1, Issue 1). www.j-asa.org

Allan, T. (2020). *The concept of virtual water*. https://www.eni.com/en-IT/low-carbon/concept-of-virtual-water.html#:~:text=Virtual water is the water,produce a ton of beef

Amakdouf, H., El Mallahi, M., Zouhri, A., Tahiri, A., & Qjidaa, H. (2018). Classification and recognition of 3d image of charlier moments using a multilayer perceptron architecture. *Procedia Computer Science*, *127*, 226–235. https://doi.org/10.1016/j.procs.2018.01.118

Ansari, A., & Golabi, M. H. (2019). Prediction of spatial land use changes based on LCM in a GIS environment for Desert Wetlands – A case study: Meighan Wetland, Iran. *International Soil and Water Conservation Research*, *7*(1), 64–70. https://doi.org/10.1016/j.iswcr.2018.10.001

Arbués, F., García-Valiñas, M. Á., & Martínez-Espiñeira, R. (2003). Estimation of residential water demand: A state-of-the-art review. *Journal of Socio-Economics*, *32*(1), 81–102. https://doi.org/10.1016/S1053-5357(03)00005-2

Arfanuzzaman, M., & Atiq Rahman, A. (2017). Sustainable water demand management in the face of rapid urbanization and groundwater depletion for social–ecological resilience building. *Global Ecology and Conservation*, *10*, 9–22. https://doi.org/10.1016/j.gecco.2017.01.005

Armenteras, D., Murcia, U., González, T. M., Barón, O. J., & Arias, J. E. (2019). Scenarios of land use and land cover change for NW Amazonia: Impact on forest intactness. *Global Ecology and Conservation*, *17*. https://doi.org/10.1016/j.gecco.2019.e00567

Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, *14*(1), 31–52. https://doi.org/10.1016/j.gloenvcha.2003.10.006

Arnell, N. W. (1999). Climate change and global water resources. *Global Environmental Change*, *9*(SUPPL.), S31–S49. https://doi.org/10.1016/S0959-3780(99)00017-5

Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability*, *2*(2), 95–96. https://doi.org/10.1007/s42398-019-00078-w

Arranz, R. (2006). *Future water demands and resources in the Olifants Catchment, South Africa: A scenario analysis approach using the WEAP model*. Colorado State University.

Ashton, D., Oliver, M., Hooper, S., Mackinnon, D., & Mallawaarachchi, T. (2009). Irrigated agriculture in the Murray-Darling Basin: a farm level analysis by region and industry. In *Issues insights 09.4* (Issue June). http://www.abare.gov.au/publications_html/ins/insights_09/a4.pdf

Australia's Science Channel. (2019). *New satellites show worrying views of droughts and ice loss*. https://australiascience.tv/new-satellites-show-worrying-view-of-droughts-and-ice-loss/

Australian Academy of Science. (2011). *Stressed ecosystem: Better decisions for Australia's future*. Australian Academy of Science. https://www.science.org.au/events/thinktank/thinktank2011/documents/recommendations.pdf

Australian Building Codes Board. (2015). *Climate Zone Map: Queensland*. https://www.abcb.gov.au/Resources/Tools-Calculators/Climate-Zone-Map-Queensland

Australian Bureau of Statistics. (2019). *3218.0 - Regional Population Growth, Australia, 2017-18*. https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02017-18

Australian Bureau of Statistics. (2020). *Water Account, Australia, 2018-19 financial year*. https://www.abs.gov.au/statistics/environment/environmental-management/water-account-australia/latest-release

Australian Institute for Disaster and Resilience. (2016). *Drought, Queensland and New South Wales*. https://knowledge.aidr.org.au/resources/environment-drought-queensland-and-new-south-wales/

Baker, B., Aldridge, C., & Omer, A. (2016). *Water: Availability and use*. https://www.researchgate.net/publication/324226678_Water_Availability_and_use

Bates, B., Kundzewicz, Z. W., Wu, S., & Palutikof, J. (2008). *Climate Change and Water* (B. Bates, Z. W. Kundzewicz, S. Wu, & J. Palutikof (eds.); 2008th ed.). Intergovernmental Panel on Climate Change.

Berbel, J., & Esteban, E. (2019). Droughts as a catalyst for water policy change. Analysis of Spain, Australia (MDB), and California. *Global Environmental Change*, *58*(April 2018), 101969. https://doi.org/10.1016/j.gloenvcha.2019.101969

Boretti, A., & Rosa, L. (2019). Reassessing the projections of the World Water Development Report. *Npj Clean Water*, *2*(1), 1–6. https://doi.org/10.1038/s41545-019-0039-9

Botterill, L. C. (2005). Late Twentieth Century Approaches to Living with Uncertainty: The National Drought Policy. In L. C. Botterill & D. A. Wilhite (Eds.), *From Disaster Response to Risk Management: Australia's National Drought Policy* (pp. 51–64). Springer Netherlands. https://doi.org/10.1007/1-4020-3124-6_5

Botterill, L. C., & Hayes, M. J. (2012). Drought triggers and declarations: Science and policy considerations for drought risk management. *Natural Hazards*, *64*(1), 139–151. https://doi.org/10.1007/s11069-012-0231-4

Bui, K. T. T., Tien Bui, D., Zou, J., Van Doan, C., & Revhaug, I. (2018). A novel hybrid artificial intelligent approach based on neural fuzzy inference model and particle swarm optimization for horizontal displacement modeling of hydropower dam. *Neural Computing and Applications*, *29*(12), 1495–1506. https://doi.org/10.1007/s00521-016-2666-0

Bui, T. D., Bui, K. T. T., Bui, Q. T., Doan, C. Van, & Hoang, N. D. (2017). Hybrid Intelligent Model Based on Least Squares Support Vector Regression and Artificial Bee Colony Optimization for Time-Series Modeling and Forecasting Horizontal Displacement of Hydropower Dam. In the *Handbook of Neural Computation* (pp. 279–293). Elsevier Inc. https://doi.org/10.1016/B978-0-12-811318-9.00015-6

Bureau of Meteorology. (2011). *Annual Australian Climate Statement 2010*. http://www.bom.gov.au/climate/current/annual/aus/2010/

Bureau of Meteorology. (2019). *Queensland in 2018*. http://www.bom.gov.au/climate/current/annual/qld/archive/2018.summary.shtml

Bureau of Meteorology. (2021a). *Annual climate statement 2020*. http://www.bom.gov.au/climate/current/annual/aus/#tabs=Rainfall

Bureau of Meteorology. (2021b). *Previous droughts*. http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml

Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organization. (2018). *State of the Climate 2018*.

Campbell, B. M., Beare, D. J., Bennett, E. M., Hall-Spencer, J. M., Ingram, J. S. I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J. A., & Shindell, D. (2017). Agriculture production as a major driver of the earth system exceeds planetary boundaries. *Ecology and Society*, *22*(4). https://doi.org/10.5751/ES-09595-220408

Chen, X. Z. (2021). Future water demand projection for universities: A case study in the United States. *Environmental pollution*.

Chiew, F., & Prosser, I. (2011). Water and Climate. In *Water: Science and Solutions for Australia* (pp. 29–46). https://doi.org/10.4324/9781315070261-8

Cho, J., Barone, V. A., & Mostaghimi, S. (2009). Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed. In *Agricultural Water Management* (Vol. 96, Issue 1, pp. 1–11). Elsevier. https://doi.org/10.1016/j.agwat.2008.07.005

Chung, C., & Salas, J. D. (2000). Drought Occurrence Probabilities and Risks of Dependent Hydrologic Processes. *Journal of Hydrologic Engineering*, *5*(3), 259–268. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:3(259)

Clark, D. (2020). *Graziers join calls for Queensland Government to stop spiking coal and embrace renewable future* - ABC News. https://www.abc.net.au/news/2020-10-11/queensland-cattle-graziers-end-coal-embrace-renewables-climate/12735320

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences Second Edition* (2nd Edition). Lawrence Erlbaum Associates.

Commonwealth of Australia. (2000). *Bureau of Meteorology Annual Report 1999-2000*. https://parlinfo.aph.gov.au/parlInfo/search/display/display.w3p;query=Id:%22publications/tabledpapers/12610%22;src1=sm1

Commonwealth of Australia. (2019). *Improving implementation of the Murray-Darling Basin Plan: Joint Basin government response to the Productivity Commission inquiry report: Murray-Darling Basin Plan: Five-year assessment*.

Commonwealth Scientific and Industrial Research Organization. (2008a). *Water Availability in the Condamine-Balonne. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project* (Issue June). https://www.clw.csiro.au/publications/waterforahealthycountry/mdbsy/pdf/condamine-report.pdf

Commonwealth Scientific and Industrial Research Organization. (2008b). *Water Availability in the Murray-Darling Basin. Summary of a report from CSIRO to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. https://www.clw.csiro.au/publications/waterforahealthycountry/mdbsy/pdf/WaterAvailabilityInTheMDB-ExecSummary.pdf

Commonwealth Scientific and Industrial Research Organization. (2010). *Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI)*.

Commonwealth Scientific and Industrial Research Organization. (2012). *Climate and water availability in South-Eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI)* (Vol. 41). www.geca.org.au/standardsregister.htm.

Coombes, P. J., Frost, A., Kuczera, G., O’loughlin, G., & Lees, S. (2002). *Rainwater Tank Options for Stormwater Management in the Upper Parramatta River Catchment*. https://search.informit.org/doi/10.3316/informit.319196726048110

Crabb, P. (1997). *Impacts of anthropogenic activities, water use and consumption on water resources and flooding / Peter Crabb* (A. E. Australia & A. D. of the Environment (eds.)). Central Queensland University Publishing Unit [for Environment Australia, Dept. of the Environment].

Dahal, V., Shakya, N. M., & Bhattarai, R. (2016). Estimating the Impact of Climate Change on Water Availability in Bagmati Basin, Nepal. *Environmental Processes*, *3*(1), 1–17. https://doi.org/10.1007/s40710-016-0127-5

Dehghanipour, A. H., Schoups, G., Zahabiyoun, B., & Babazadeh, H. (2020). Meeting agricultural and environmental water demand in endorheic irrigated river basins: A simulation-optimization approach applied to the Urmia Lake basin in Iran. *Agricultural Water Management*, *241*, 106353. https://doi.org/10.1016/j.agwat.2020.106353

Deo, R. C., Byun, H. R., Adamowski, J. F., & Begum, K. (2017). Application of effective drought index for quantification of meteorological drought events: a case study in Australia. *Theoretical and Applied Climatology*, *128*(1–2), 359–379. https://doi.org/10.1007/s00704-015-1706-5

Department of Agriculture, Water and the Environment. (2020). *About my region – Toowoomba Queensland*. https://www.agriculture.gov.au/abares/research-topics/aboutmyregion/qld-toowoomba

Dissanayake, S., Asafu-Adjaye, J., & Mahadeva, R. (2017). Addressing climate change cause and effect on land cover and land use in South Asia. *Land Use Policy*, *67*(April), 352–366. https://doi.org/10.1016/j.landusepol.2017.06.003

Dong, N., You, L., Cai, W., Li, G., & Lin, H. (2018). Land use projections in China under global socioeconomic and emission scenarios: Utilizing a scenario-based land-use change assessment framework. *Global Environmental Change*, *50*(November 2017), 164–177. https://doi.org/10.1016/j.gloenvcha.2018.04.001

Donley, E. E., Naiman, R. J., & Marineau, M. D. (2012). Strategic planning for instream flow restoration: a case study of potential climate change impacts in the central Columbia River basin. *Global Change Biology*, *18*(10), 3071–3086. https://doi.org/https://doi.org/10.1111/j.1365-2486.2012.02773.x

Droogers, P., Immerzeel, W. W., Terink, W., Hoogeveen, J., Bierkens, M. F. P., Van Beek, L. P. H., & Debele, B. (2012). Hydrology and Earth System Sciences Water resources trends in the Middle East and North Africa towards 2050. *Hydrol. Earth Syst. Sci*, *16*, 3101–3114. https://doi.org/10.5194/hess-16-3101-2012

du Plessis, A. (2019). Water as an inescapable risk. *Current and Future Water Scarcity and Stress*, 13–25. https://doi.org/10.1007/978-3-030-03186-2

Durán-Sánchez, A., Álvarez-García, J., & del Río-Rama, M. de la C. (2018). Sustainable water resources management: A bibliometric overview. *Water (Switzerland)*, *10*(9), 1–19. https://doi.org/10.3390/w10091191

Duzkale, S. B. (2019). Climate change impact on evapotranspiration and irrigation water requirement of cotton crop in north-west India. *Theoretical and Applied Climatology*, 1009-1023.

Eastman, J. R. (2016a). *TerrSet Geospatial Monitoring and Modeling System Manual*. *4*(1), 64–75.

Eastman, J. R. (2016b). *TerrSet Geospatial Monitoring and Modeling System Tutorial*. 634.

Exon, N. F. (1976). Geology of the Surat Basin in Queensland. Record 166. In *Geoscience Australia*. http://pid.geoscience.gov.au/dataset/ga/77

Fader, M., Shi, S., Von Bloh, W., Bondeau, A., & Cramer, W. (2016). Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrol. Earth Syst. Sci*, *20*, 953–973. https://doi.org/10.5194/hess-20-953-2016

Fard, M. D., & Sarjoughian, H. S. (2021). A RESTful framework design for componentizing the water evaluation and planning (WEAP) system. *Simulation Modelling Practice and Theory*, *106*, 102199. https://doi.org/10.1016/j.simpat.2020.102199

Farrell, R. (2018). *Australia Livestock and Products Annual 2018*.

Fernandez-Saez, L. G.-S.-S. (Journal of Cleaner Production). Water consumption in tourist destinations. *The role of water scarcity and tourist perception*, 262.

Findell, K. L., Berg, A., Gentine, P., Krasting, J. P., Lintner, B. R., Malyshev, S., Santanello, J. A., & Shevliakova, E. (2017). The impact of anthropogenic land use and land cover change on regional climate extremes. *Nature Communications*, *8*(1), 1–9. https://doi.org/10.1038/s41467-017-01038-w

Fischer, G., Tubiello, F. N., Van Velthuizen, H., & Wiberg, D. A. (2007). *Climate change impacts on irrigation water requirements: Effects of mitigation, 1990-2080*. https://doi.org/10.1016/j.techfore.2006.05.021

Flörke, M., Schneider, C., & McDonald, R. I. (2018). Water competition between cities and agriculture driven by climate change and urban growth. *Nature Sustainability, 1*(1), 51–58. https://doi.org/10.1038/s41893-017-0006-8

Foley, M. (2019). *"Drier than Millennium drought": satellite shows toll of big dry*. The Land. https://www.theland.com.au/story/6216925/drier-than-millennium-drought-satellite-shows-toll-of-big-dry/

Food and Agriculture Organization. (2009). *Global agriculture towards 2050*.

Food and Agriculture Organization. (2017). *Water for Sustainable Food and Agriculture - A report produced for the G20 Presidency of Germany*. www.fao.org/publications

Food and Agriculture Organization. (2019). *Water Scarcity – One of the greatest challenges of our time*. http://www.fao.org/fao-stories/article/en/c/1185405/

Fuentes, I., van Ogtrop, F., & Vervoort, R. W. (2020). Long-term surface water trends and relationship with open water evaporation losses in the Namoi catchment, Australia. *Journal of Hydrology*, *584*(December 2019), 124714. https://doi.org/10.1016/j.jhydrol.2020.124714

Garrick, D. E., Hanemann, M., & Hepburn, C. (2020). Rethinking the economics of water: An assessment. *Oxford Review of Economic Policy*, *36*(1), 1–23. https://doi.org/10.1093/oxrep/grz035

Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. W. (2018). Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin, Ethiopia. *Science of the Total Environment*, *619–620*, 1394–1408. https://doi.org/10.1016/j.scitotenv.2017.11.191

Gebremeskel, G., & Kebede, A. (2018). Estimating the effect of climate change on water resources: Integrated use of climate and hydrological models in the Werii watershed of the Tekeze river basin, Northern Ethiopia. *Agriculture and Natural Resources*, *52*(2), 195–207. https://doi.org/10.1016/j.anres.2018.06.010

Ghimire, M., Boyer, T. A., Chung, C., & Moss, J. Q. (2016). Estimation of Residential Water Demand under Uniform Volumetric Water Pricing. *Journal of Water Resources Planning and Management*, *142*(2), 04015054. https://doi.org/10.1061/(asce)wr.1943-5452.0000580

Gibson, L., Münch, Z., Palmer, A., & Mantel, S. (2018). Future land cover change scenarios in South African grasslands – implications of altered biophysical drivers on land management. *Heliyon*, *4*(7). https://doi.org/10.1016/j.heliyon.2018.e00693

Gidey, E., Dikinya, O., Sebego, R., Segosebe, E., & Zenebe, A. (2017). Cellular automata and Markov Chain (CA_Markov) model-based predictions of future land use and land cover scenarios (2015–2033) in Raya, northern Ethiopia. *Modeling Earth Systems and Environment*, *3*(4), 1245–1262. https://doi.org/10.1007/s40808-017-0397-6

Giri, S., Qiu, Z., & Zhang, Z. (2018). Assessing the impacts of land use on downstream water quality using a hydrologically sensitive area concept. *Journal of Environmental Management*, *213*, 309–319. https://doi.org/10.1016/j.jenvman.2018.02.075

Gogtay, N. J., & Thatte, U. M. (2017). Principles of Correlation Analysis. *The Journal of the Association of Physicians of India*, *65*(3), 78–81.

Gonzales, P., & Ajami, N. (2017). Social and Structural Patterns of Drought-Related Water Conservation and Rebound. *Water Resources Research*, *53*(12), 10619–10634. https://doi.org/10.1002/2017WR021852

Gorguner, M., & Kavvas, M. L. (2020). Modeling impacts of future climate change on reservoir storages and irrigation water demands in a Mediterranean basin. *Science of the Total Environment*, *748*, 141246. https://doi.org/10.1016/j.scitotenv.2020.141246

Grafton, R. P. (2019). Water in a changing World: The big picture, 2030 and beyond. *Australian Journal of Water Resources*, 1-13.

Grafton, R. Q. (2017). Editorial-Water Reform and Planning in the Murray-Darling Basin, Australia. *Water Economics and Policy*, *3*(3), 1–18. https://doi.org/10.1142/S2382624X17020015

Grafton, R. P. (2021). Climate Change and Water Management in Australian Agriculture. n A Focus on Queensland. *Resources Policy*, 75.

Grafton, R. Q., & Wheeler, S. A. (2018). Economics of Water Recovery in the Murray-Darling Basin, Australia. *Annual Review of Resource Economics*, *10*(March), 487–510. https://doi.org/10.1146/annurev-resource-100517-023039

Hall, J., & Murphy, C. (2010). Vulnerability Analysis of Future Public Water Supply Under Changing Climate Conditions: A Study of the Moy Catchment, Western Ireland. *Water Resources Management*, *24*(13), 3527–3545. https://doi.org/10.1007/s11269-010-9618-8

Hamad, R., Balzter, H., & Kolo, K. (2018). Predicting land use/land cover changes using a CA-Markov model under two different scenarios. *Sustainability (Switzerland)*, *10*(10), 1–23. https://doi.org/10.3390/su10103421

Hamlat, A., Errih, M., & Guidoum, A. (2013). Simulation of water resources management scenarios in western Algeria watersheds using WEAP model. *Arabian Journal of Geosciences*, *6*(7), 2225–2236. https://doi.org/10.1007/s12517-012-0539-0

Harbor, J. M. (1994). A Practical Method for Estimating the Impact of Land-Use Change on Surface Runoff, Groundwater Recharge and Wetland Hydrology. *Journal of the American Planning Association*, *60*(1), 95–108. https://doi.org/10.1080/01944369408975555

Harma, K. J., Johnson, M. S., & Cohen, S. J. (2012). Future Water Supply and Demand in the Okanagan Basin, British Columbia: A Scenario-Based Analysis of Multiple, Interacting Stressors. *Water Resources Management*, *26*(3), 667–689. https://doi.org/10.1007/s11269-011-9938-3

Hart, B. T., Bond, N. R., Byron, N., Pollino, C. A., & Stewardson, M. J. (2021). Introduction to the Murray–Darling Basin system, Australia. In *Murray-Darling Basin, Australia* (pp. 1–17). Elsevier. https://doi.org/10.1016/b978-0-12-818152-2.00001-2

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Heberger, M. (2012). Australia's Millennium Drought: Impacts and Responses. In P. H. Gleick (Ed.), *The World's Water: The Biennial Report on Freshwater Resources* (Issue January 2012, pp. 97–125). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-59726-228-6_5

Heinke, J., Lannerstad, M., Gerten, D., Havlík, P., Herrero, M., Notenbaert, A. M. O., Hoff, H., & Müller, C. (2020). Water Use in Global Livestock Production—Opportunities and Constraints for Increasing Water Productivity. *Water Resources Research*, *56*(12), 0–2. https://doi.org/10.1029/2019WR026995

Hemphill, J. F. (2003). Interpreting the magnitudes of correlation coefficients. *The American Psychologist*, *58*(1), 78–79. https://doi.org/10.1037/0003-066x.58.1.78

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djanlante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., & Zhou, G. (2018). Impacts of 1.5°C of Global Warming on Natural and Human Systems. In V. Masson-Delmotte,

P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.*

Hoffman, C., Melesse, A. M., & McClain, M. E. (2011). Geospatial Mapping and Analysis of Water Availability, Demand, and Use Within the Mara River Basin. In the Nile *River Basin* (pp. 359–382). Springer Netherlands. https://doi.org/10.1007/978-94-007-0689-7_18

Hogeboom, R. J. (2020). The Water Footprint Concept and Water's Grand Environmental Challenges. *One Earth*, *2*(3), 218–222. https://doi.org/10.1016/j.oneear.2020.02.010

Höllermann, B., Giertz, S., & Diekkrüger, B. (2010). Benin 2025—Balancing Future Water Availability and Demand Using the WEAP 'Water Evaluation and Planning' System. *Water Resources Management*, *24*(13), 3591–3613. https://doi.org/10.1007/s11269-010-9622-z

Hopkinson, C. S., & Vallino, J. J. (1995). The relationships among man's activities in watersheds and estuaries: A model of runoff effects on patterns of estuarine community metabolism. *Estuaries*, *18*(4), 598–621. https://doi.org/10.2307/1352380

Hua, Y., & Cui, B. (2018). Environmental flows and its satisfaction degree forecasting in the Yellow River. *Ecological Indicators*, *92*, 207–220. https://doi.org/10.1016/j.ecolind.2017.02.017

Huang, J., Yu, H., Guan, X., Wang, G., & Guo, R. (2016). Accelerated dryland expansion under climate change. *Nature Climate Change*, *6*(2), 166–171. https://doi.org/10.1038/nclimate2837

Huang, Y., Chang, Q., & Li, Z. (2018). Land use change impacts on the amount and quality of recharge water in the loess tablelands of China. *Science of the Total Environment*, *628–629*, 443–452. https://doi.org/10.1016/j.scitotenv.2018.02.076

Huang, Z., Hejazi, M., Li, X., Tang, Q., Vernon, C., Leng, G., Liu, Y., Döll, P., Eisner, S., Gerten, D., Hanasaki, N., & Wada, Y. (2018). Reconstruction of global gridded monthly sectoral water withdrawals for 1971-2010 and analysis of their spatiotemporal patterns. *Hydrology and Earth System Sciences*, *22*(4), 2117–2133. https://doi.org/10.5194/hess-22-2117-2018

Hudson, M., Martin, B., Hagan, T., & Demuth, H. B. (2010). *Neural Network Toolbox™ 7 User's Guide*. The MathWorks, Inc. www.mathworks.com

Hughes, L. (2011). Climate change and Australia: key vulnerable regions. *Regional Environmental Change*, *11*(1), 189–195. https://doi.org/10.1007/s10113-010-0158-9

Hurlimann, A., & Dolnicar, S. (2010). When public opposition defeats alternative water projects - The case of Toowoomba Australia. *Water Research*, *44*(1), 287–297. https://doi.org/10.1016/j.watres.2009.09.020

Hussain, H. A., Men, S., Hussain, S., Chen, Y., Ali, S., Zhang, S., Zhang, K., Li, Y., Xu, Q., Liao, C., & Wang, L. (2019). Interactive effects of drought and heat stresses on morpho-physiological attributes, yield, nutrient uptake and oxidative status in maize hybrids. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-40362-7

Inglezakis, V. J., Poulopoulos, S. G., Arkhangelsky, E., Zorpas, A. A., & Menegaki, A. N. (2016). *Chapter 3 - Aquatic Environment* (S. G. Poulopoulos & V. J. B. T.-E. and D. Inglezakis (eds.); pp. 137–212). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-62733-9.00003-4

Intergovernmental Panel on Climate Change. (1996). Climate Change 1995: The Science of Climate Change. In J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, & K. Maskell (Eds.), *Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*.

Intergovernmental Panel on Climate Change. (2001). Climate Change 2001: The Scientific Basis. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, & C. A. Johnson (Eds.), *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1016/S1058-2746(02)86826-4

Intergovernmental Panel on Climate Change. (2007a). Climate Change 2007: Impacts, Adaptation and Vulnerability. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1016/B978-008044910-4.00250-9

Intergovernmental Panel on Climate Change. (2007b). Climate Change 2007: The Physical Science Basis. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Vol. 59, Issue 8). https://doi.org/10.1256/wea.58.04

Intergovernmental Panel on Climate Change. (2014). Climate Change 2014 Mitigation of Climate Change. In *Climate Change 2014 Mitigation of Climate Change*. https://doi.org/10.1017/cbo9781107415416

Intergovernmental Panel on Climate Change. (2018). Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.*

Islam, K., Rahman, M. F., & Jashimuddin, M. (2018). Modeling land use change using Cellular Automata and Artificial Neural Network: The case of Chunati Wildlife Sanctuary, Bangladesh. *Ecological Indicators*, *88*(December 2017), 439–453. https://doi.org/10.1016/j.ecolind.2018.01.047

Jaramillo, F. N. (2021). Effects of Environmental flows on hydrological alteration and reliability of water demand. *Journal of Hydrology*.

Jayarathna, L., Rajapaksa, D., Managi, S., Athukorala, W., Torgler, B., Garcia-Valiñas, M. A., Gifford, R., & Wilson, C. (2017). A GIS based spatial decision support system for analysing residential water demand: A case study in Australia. *Sustainable Cities and Society*, *32*, 67–77. https://doi.org/10.1016/j.scs.2017.03.012

Jazouli, A. El, Barakat, A., Khellouk, R., Rais, J., & Baghdadi, M. El. (2019). Remote sensing and GIS techniques for prediction of land use land cover change effects on soil erosion in the high basin of the Oum Er Rbia River (Morocco). *Remote Sensing Applications: Society and Environment*, *13*(May 2018), 361–374. https://doi.org/10.1016/j.rsase.2018.12.004

Johannsen, I. M., Hengst, J. C., Goll, A., Höllermann, B., & Diekkrüger, B. (2016). Future of water supply and demand in the Middle Drâa Valley, Morocco, under climate and land use change. *Water (Switzerland)*, *8*(8). https://doi.org/10.3390/w8080313

Joseph, N., Preetha, P. P., & Narasimhan, B. (2021). Assessment of environmental flow requirements using a coupled surface water-groundwater model and a flow health tool: A case study of Son River in the Ganga basin. *Ecological Indicators*, *121*, 107110. https://doi.org/10.1016/j.ecolind.2020.107110

Kattel, G. R. (2019). State of future water regimes in the world's river basins: balancing the water between society and nature. *Critical Reviews in Environmental Science and Technology*, *49*(12), 1107–1133. https://doi.org/10.1080/10643389.2019.1579621

Kaushal, S. S., Gold, A. J., & Mayer, P. M. (2017). Land use, climate, and water resources-global stages of interaction. *Water (Switzerland)*, *9*(10), 815. https://doi.org/10.3390/w9100815

Kavzoglu, T., & Mather, P. M. (2003). The use of backpropagating artificial neural networks in land cover classification. *International Journal of Remote Sensing*, *24*(23), 4907–4938. https://doi.org/10.1080/0143116031000114851

Keenan, T. D., & Cleugh, H. A. (2011). *Climate Science Update: A Report to the 2011 Garnaut Review* (T. D. Keenan & H. A. Cleugh (eds.); CAWCR Technical Report No. 036).

Kerr, A., Hall, H., & Kozub, S. (2002). *Doing Statistics with SPSS*. SAGE Publications.

Khastagir, A., & Jayasuriya, N. (2010). Optimal sizing of rain water tanks for domestic water conservation. *Journal of Hydrology, 381*(3–4), 181–188. https://doi.org/10.1016/j.jhydrol.2009.11.040

Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in Life Science*, *8*(1), 23–39. https://doi.org/10.1080/21553769.2014.933716

Kiem, A. S. (2013). Drought and water policy in Australia: Challenges for the future illustrated by the issues associated with water trading and climate change adaptation in the Murray-Darling Basin. *Global Environmental Change*, *23*(6), 1615–1626. https://doi.org/10.1016/j.gloenvcha.2013.09.006

Kirby, M. (2011). Irrigation. In I. P. Prosser & Editors (Eds.), *Water: Science and Solutions for Australia* (pp. 105–118). CSIRO Publishing. https://www.publish.csiro.au/ebook/chapter/9780643103283_Chapter_8

Koech, R., & Langat, P. (2018). Improving irrigation water use efficiency: A review of advances, challenges and opportunities in the Australian context. *Water (Switzerland), 10*(12). https://doi.org/10.3390/w10121771

Koukoulas, S. (2015). *What will happen to Australia when the mining boom ends?* In The Black. https://www.intheblack.com/articles/2015/04/01/what-will-happen-to-australia-when-the-mining-boom-ends

Koutroulis, A. G., Papadimitriou, L. V., Grillakis, M. G., Tsanis, I. K., Warren, R., & Betts, R. A. (2019). Global water availability under high-end climate change: A vulnerability-based assessment. *Global and Planetary Change*, *175*(January), 52–63. https://doi.org/10.1016/j.gloplacha.2019.01.013

Krugman, P. (2009). *Empire of Carbon*. The New York Times. https://www.nytimes.com/2009/05/15/opinion/15krugman.html

Kumar, S., Radhakrishnan, N., & Mathew, S. (2014). Land use change modelling using a Markov model and remote sensing. *Geomatics, Natural Hazards and Risk*, *5*(2), 145–156. https://doi.org/10.1080/19475705.2013.795502

Kumaraswamy, S., & Shetty, P. K. (2016). Critical abiotic factors affecting implementation of technological innovations in rice and wheat production: A review. *Agricultural Reviews*, *37*(4), 268–278. https://doi.org/10.18805/ag.v37i4.6457

Lake, P. S., & Bond, N. R. (2007). Australian futures: Freshwater ecosystems and human water usage. *Futures*, *39*(2–3), 288–305. https://doi.org/10.1016/j.futures.2006.01.010

Leong, W. K., & Lai, S. H. (2017). Application of Water Evaluation and Planning Model for Integrated Water Resources Management: Case Study of Langat River Basin, Malaysia. *IOP Conference Series: Materials Science and Engineering*, *210*(1). https://doi.org/10.1088/1757-899X/210/1/012024

Li, C., Jiang, T. T., Luan, X. B., Yin, Y. L., Wu, P. T., Wang, Y. B., & Sun, S. K. (2021). Determinants of agricultural water demand in China. *Journal of Cleaner Production*, *288*, 125508. https://doi.org/10.1016/j.jclepro.2020.125508

Li, G., Zhang, F., Jing, Y., Liu, Y., & Sun, G. (2017). Response of evapotranspiration to changes in land use and land cover and climate in China during 2001–2013. *Science of the Total Environment*, *596–597*, 256–265. https://doi.org/10.1016/j.scitotenv.2017.04.080

Li, Jing, Rodriguez, D., & Tang, X. (2017). Effects of land lease policy on changes in land use, mechanization and agricultural pollution. *Land Use Policy*, *64*, 405–413. https://doi.org/10.1016/j.landusepol.2017.03.008

Li, Jingsi, Fei, L., Li, S., Xue, C., Shi, Z., & Hinkelmann, R. (2020). Development of “water-suitable” agriculture based on a statistical analysis of factors affecting irrigation water demand. *Science of the Total Environment*, *744*, 140986. https://doi.org/10.1016/j.scitotenv.2020.140986

Li, W., & Cui, X. (2014). A Special Issue on Plant Stress Biology: From Model Species to Crops. *Molecular Plant*, *7*, 755–757. https://doi.org/10.1093/mp/ssu040

Liliane, T. N., & Charles, M. S. (2020). Factors Affecting Yield of Crops. In *Agronomy - Climate Change and Food Security*. IntechOpen. https://doi.org/10.5772/intechopen.90672

Liping, C., Yujun, S., & Saeed, S. (2018). Monitoring and predicting land use and land cover changes using remote sensing and GIS techniques—A case study of a hilly area, Jiangle, China. *PLoS ONE*, *13*(7), 1–23. https://doi.org/10.1371/journal.pone.0200493

Liu, J. E. (2021). Characterization of water use in university buildings considering occupancy patterns and building types. *Resources Conservation and Recycling*.

Liu, Jianwei, Zhang, C., Kou, L., & Zhou, Q. (2017). Effects of Climate and Land Use Changes on Water Resources in the Taoer River. *Advances in Meteorology*, *2017*, 1–13. https://doi.org/10.1155/2017/1031854

Liu, Jiyuan, Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., & Chi, W. (2014). Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. *Journal of Geographical Sciences*, *24*(2), 195–210. https://doi.org/10.1007/s11442-014-1082-6

Liu, Junguo, Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., Alcamo, J., & Oki, T. (2017). Water scarcity assessments in the past, present, and future. In *Earth's Future* (Vol. 5, Issue 6, pp. 545–559). John Wiley and Sons Inc. https://doi.org/10.1002/2016EF000518

Liu, Y., Chen, B., Wei, W., Shao, L., Li, Z., Jiang, W., & Chen, G. (2020). Global water use is associated with energy supply, demand and international trade of China. *Applied Energy*, *257*, 113992. https://doi.org/10.1016/j.apenergy.2019.113992

Loaiciga, H. A., & Leipnik, R. B. (1996). Stochastic renewal model of low-flow streamflow sequences. *Stochastic Hydrology and Hydraulics*, *10*(1), 65–85. https://doi.org/10.1007/BF01581794

Loh, M., & Coghlan, P. (2003). Domestic Water Use Study: In Perth, Western Australia 1998-2001. In *Hydro 2000: Interactive Hydrology; …* (Issue March).

http://search.informit.com.au/documentSummary;dn=254857076293546;res=IELENG

Lohani, V. K., & Loganathan, G. V. (1997). An Early Warning System for Drought Management Using the Palmer Drought Index 1. *JAWRA Journal of the American Water Resources Association*, *33*(6), 1375–1386. https://doi.org/https://doi.org/10.1111/j.1752-1688.1997.tb03560.x

Maduku, D. K. (2020). Water conservation campaigns in an emerging economy: how effective are they? *International Journal of Advertising*, *0*(0), 1–21. https://doi.org/10.1080/02650487.2020.1780060

Maliehe, M., & Mulungu, D. M. M. (2017). Assessment of water availability for competing uses using SWAT and WEAP in South Phuthiatsana catchment, Lesotho. *Physics and Chemistry of the Earth*, *100*, 305–316. https://doi.org/10.1016/j.pce.2017.02.014

Mallawaarachchi, T., Auricht, C., Loch, A., Adamson, D., & Quiggin, J. (2020). Water allocation in Australia’s Murray–Darling Basin: Managing change under heightened uncertainty. *Economic Analysis and Policy*, *66*, 345–369. https://doi.org/10.1016/j.eap.2020.01.001

Martinez, J. L., Raiber, M., & Cox, M. E. (2015). Assessment of groundwater-surface water interaction using long-term hydrochemical data and isotope hydrology: Headwaters of the Condamine River, Southeast Queensland, Australia. *Science of the Total Environment*, *536*, 499–516. https://doi.org/10.1016/j.scitotenv.2015.07.031

Mead, N., & Aravinthan, V. (2009). Investigation of household water consumption using a smart metering system. *Desalination and Water Treatment*, *11*(1–3), 115–123. https://doi.org/10.5004/dwt.2009.850

Megahed, Y., Cabral, P., Silva, J., & Caetano, M. (2015). Land cover mapping analysis and urban growth modelling using remote sensing techniques in the greater Cairo region-Egypt. *ISPRS International Journal of Geo-Information*, *4*(3), 1750–1769. https://doi.org/10.3390/ijgi4031750

Mehboob, M. S., & Kim, Y. (2021). Effect of climate and socioeconomic changes on future surface water availability from mountainous water sources in Pakistan's Upper Indus Basin. *Science of the Total Environment, 769*, 144820. https://doi.org/10.1016/j.scitotenv.2020.144820

Mehran, A., AghaKouchak, A., Nakhjiri, N., Stewardson, M. J., Peel, M. C., Phillips, T. J., Wada, Y., & Ravalico, J. K. (2017). Compounding Impacts of Human-Induced Water Stress and Climate Change on Water Availability. *Scientific Reports*, *7*(1), 1–9. https://doi.org/10.1038/s41598-017-06765-0

Mekonnen, M. &. (2020). Four billion people are facing severe water scarcity. *Science Advances*, 6 (39).

Meyer, W. B., & Turner, B. L. (1992). Human Population Growth and Global Land-Use/Cover Change. *Annual Review of Ecology and Systematics*, *23*(1), 39–61. https://doi.org/10.1146/annurev.es.23.110192.000351

Middlemis, H., Walker, G., Peeters, L., Hayes, P., & Moore, C. (2019). Groundwater modelling uncertainty Implications for decision-making. In *Summary, report of the national groundwater modelling uncertainty workshop* (Issue July 2017). https://doi.org/10.25957/5ca5641defe56

Modarres, R. (2007). Streamflow drought time series forecasting. *Stochastic Environmental Research and Risk Assessment*, *21*(3), 223–233. https://doi.org/10.1007/s00477-006-0058-1

Mounir, Z. M., Ma, C. M., & Amadou, I. (2011). Application of Water Evaluation and Planning (WEAP): A Model to Assess Future Water Demands in the Niger River (In Niger Republic). *Modern Applied Science*, *5*(1), 38–49. www.ccsenet.org/maswww.ccsenet.org/mas

Mu, J. E., Sleeter, B. M., Abatzoglou, J. T., & Antle, J. M. (2017). Climate impacts on agricultural land use in the USA: the role of socio-economic scenarios. *Climatic Change*, *144*(2), 329–345. https://doi.org/10.1007/s10584-017-2033-x

Müller, D. (2016). Research frontiers in land use science. *Journal of Land Use Science*, *11*(6), 619–622. https://doi.org/10.1080/1747423X.2016.1242924

Nair, S., & Timms, W. (2020). Freshwater footprint of fossil fuel production and thermal electricity generation and water stresses across the National Electricity Market (NEM) region of Australia. *Journal of Cleaner Production*, *267*, 122085. https://doi.org/10.1016/j.jclepro.2020.122085

Nover, D. M., Dogan, M. S., Ragatz, R., Booth, L., Medellín-Azuara, J., Lund, J. R., & Viers, J. H. (2019). Does More Storage Give California More Water? *Journal of the American Water Resources Association*, *55*(3), 759–771. https://doi.org/10.1111/1752-1688.12745

Nyquist, S. (2016). Energy 2050: Insights from the ground up. *McKinsey & Company*, 1–3.

OECD. (2012). *OECD Environmental Outlook to 2050: The Consequences of Inaction*. http://www.oecd-ilibrary.org/environment/oecd-environmental-outlook-to-2050_9789264122246-en

OECD. (2019). *Environmental Outlook 2060.* OECD.

Owuor, S. O., Butterbach-Bahl, K., Guzha, A. C., Rufino, M. C., Pelster, D. E., Díaz-Pinés, E., & Breuer, L. (2016). Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments. *Ecological Processes*, *5*(1). https://doi.org/10.1186/s13717-016-0060-6

Parsa, V. A., Yavari, A., & Nejadi, A. (2016). Spatio-temporal analysis of land use/land cover pattern changes in Arasbaran Biosphere Reserve: Iran. *Modeling Earth Systems and Environment*, *2*(4), 1–13. https://doi.org/10.1007/s40808-016-0227-2

Parveen, S., Basheer, J., & Praveen, B. (2018). A Literature Review on Land Use Land Cover Changes. *International Journal of Advanced Research*, *6*(7), 1–6. https://doi.org/10.21474/ijar01/7327

Pearce, T. D., Rodríguez, E. H., Fawcett, D., & Ford, J. D. (2018). How is Australia adapting to climate change based on a systematic review? *Sustainability (Switzerland), 10*(9). https://doi.org/10.3390/su10093280

Perlmutter, D. D., & Rothstein, R. L. (2010). The Challenge of Climate Change: Which Way Now? In *The Challenge of Climate Change: Which Way Now?* John Wiley and Sons. https://doi.org/10.1002/9781444328523

Pham, B. T., Nguyen, M. D., Bui, K. T. T., Prakash, I., Chapi, K., & Bui, D. T. (2019). A novel artificial intelligence approach based on Multi-layer Perceptron Neural Network and Biogeography-based Optimization for predicting coefficient of consolidation of soil. *Catena*, *173*, 302–311. https://doi.org/10.1016/j.catena.2018.10.004

Pham, B. T., Tien Bui, D., Prakash, I., & Dholakia, M. B. (2017). Hybrid integration of Multilayer Perceptron Neural Networks and machine learning ensembles for landslide susceptibility assessment at Himalayan area (India) using GIS. *Catena*, *149*, 52–63. https://doi.org/10.1016/j.catena.2016.09.007

Pham, T. D., Bailey, G., & Spurr, R. (2013). *The positive and negative effects of the mining boom – A technical paper*.

Phillips, K. (2016). *The mining boom that changed Australia - Rear Vision* -. ABC Radio National. https://www.abc.net.au/radionational/programs/rearvision/the-mining-boom-that-changed-australia/7319586

Pontius, R. G., Shusas, E., & McEachern, M. (2004). Detecting important categorical land changes while accounting for persistence. *Agriculture, Ecosystems and Environment*, *101*(2–3), 251–268. https://doi.org/10.1016/j.agee.2003.09.008

Prosser, I. (2011). Current water availability and use. In I. P. Prosser (Ed.), *Water: Science and Solutions for Australia* (pp. 1–16). CSIRO PUBLISHING. https://www.publish.csiro.au/ebook/chapter/9780643103283_Chapter_1

Prosser, I. V. (2020). Impact Seasonal rainfall Variability on Irrigation Water use in Southeast Queensland. *Water Resources Management*, 2107-2122.

Puy, A., Lo Piano, S., & Saltelli, A. (2020). Current Models Underestimate Future Irrigated Areas. *Geophysical Research Letters*, *47*(8), e2020GL087360. https://doi.org/10.1029/2020GL087360

Qin, Y., Mueller, N. D., Siebert, S., Jackson, R. B., AghaKouchak, A., Zimmerman, J. B., Tong, D., Hong, C., & Davis, S. J. (2019). Flexibility and intensity of global water use. *Nature Sustainability*, *2*(6), 515–523. https://doi.org/10.1038/s41893-019-0294-2

Radcliffe, J. C., & Page, D. (2020). Water reuse and recycling in Australia — history, current situation and future perspectives. *Water Cycle*, *1*, 19–40. https://doi.org/10.1016/j.watcyc.2020.05.005

Rahman, M. G. (2019). Seasonal Variations in Urban Demand: A Case Study of Brisbane, Australia. *Water Resources Management*, 407-424.

Rahman, R., & Zafarullah, H. (2020). Impact of climate change on human health: adaptation challenges in Queensland, Australia. *Climate Research*, *80*(1), 59–72. https://www.int-res.com/abstracts/cr/v80/n1/p59-72/

Rahmati, O., Falah, F., Dayal, K. S., Deo, R. C., Mohammadi, F., Biggs, T., Moghaddam, D. D., Naghibi, S. A., & Bui, D. T. (2020). Machine learning approaches for spatial modeling of agricultural droughts in the south-east region of Queensland Australia. *Science of the Total Environment*, *699*, 134230. https://doi.org/10.1016/j.scitotenv.2019.134230

Rea, W., Reale, M., & Brown, J. (2011). Long memory in temperature reconstructions. *Climatic Change*, *107*(3), 247–265. https://doi.org/10.1007/s10584-011-0068-y

Riebsame, W. E., Meyer, W. B., & Turner, B. L. (1994). Modeling Land Use and Cover as Part of Global Environmental Change. In K. D. Frederick & N. J. Rosenberg (Eds.), *Assessing the Impacts of Climate Change on Natural Resource Systems* (pp. 45–64). Springer Netherlands. https://doi.org/10.1007/978-94-011-0207-0_3

Roberts, P. (2005). 2004 Residential End Use Measurement Study. *Yarra Valley Water*, *June*, 1–77.

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T., & Woznicki, S. A. (2017). Climate change and livestock: Impacts, adaptation, and mitigation. In *Climate Risk Management* (Vol. 16, pp. 145–163). Elsevier B.V. https://doi.org/10.1016/j.crm.2017.02.001

Romano, Giovanni, Abdelwahab, O. M. M., & Gentile, F. (2018). Modeling land use changes and their impact on sediment load in a Mediterranean watershed. *Catena*, *163*(December 2017), 342–353. https://doi.org/10.1016/j.catena.2017.12.039

Romano, Giulia, Salvati, N., & Guerrini, A. (2016). An empirical analysis of the determinants of water demand in Italy. *Journal of Cleaner Production*, *130*, 74–81. https://doi.org/10.1016/j.jclepro.2015.09.141

Rosegrant, M. W., Cai, X., & Cline, S. A. (2002). *World Water and Food to 2025: Dealing with Scarcity*. www.ifpri.org

Rostam, K. K. (2019). Water footprint of crop production in India. *Environmental Science and Pollution Research*, 9807-9823.

Russel, Z. (2017). *Darling Downs embraces renewables to become a diverse economic powerhouse*. Ministerial Media Statements. https://statements.qld.gov.au/statements/81901

Sadowski, Ł., Hoła, J., Czarnecki, S., & Wang, D. (2018). Pull-off adhesion prediction of variable thick overlay to the substrate. *Automation in Construction*, *85*, 10–23. https://doi.org/10.1016/j.autcon.2017.10.001

Sahin, O., Bertone, E., & Beal, C. D. (2017). A systems approach for assessing water conservation potential through demand-based water tariffs. *Journal of Cleaner Production*, *148*, 773–784. https://doi.org/10.1016/j.jclepro.2017.02.051

Saidan, M. N. (2020). Estimation of industrial water demand and reclamation in Jordan: A cross-sectional analysis. *Water Resources and Industry*, *23*, 100129. https://doi.org/10.1016/j.wri.2020.100129

Sankarasubramanian, A., Vogel, R. M., & Limbrunner, J. F. (2001). Climate elasticity of streamflow in the United States. *Water Resources Research*, *37*(6), 1771–1781. https://doi.org/https://doi.org/10.1029/2000WR900330

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., & Dennehy, K. F. (2005). Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology*, *11*(10), 1577–1593. https://doi.org/https://doi.org/10.1111/j.1365-2486.2005.01026.x

Schneider, L. C., & Gil Pontius, R. (2001). Modeling land-use change in the Ipswich watershed, Massachusetts, USA. *Agriculture, Ecosystems and Environment*, *85*(1–3), 83–94. https://doi.org/10.1016/S0167-8809(01)00189-X

Schneider, P., Sander, B. O., Wassmann, R., & Asch, F. (2019). Potential and versatility of WEAP model (Water Evaluation and Planning System) for hydrological assessments of AWD (Alternate Wetting and Drying) in irrigated rice. *Agricultural Water Management*, *224*, 105559. https://doi.org/10.1016/j.agwat.2019.03.030

Scully, J. (2020). *'Overwhelming interest' for Queensland's renewable energy zones*. PV Tech. https://www.pv-tech.org/overwhelming-interest-for-queenslands-renewable-energy-zones/

Şen, Z. (1976). Wet and Dry Periods of Annual Flow Series. *Journal of the Hydraulics Division*, *102*(10), 1503–1514. https://doi.org/10.1061/JYCEAJ.0004634

Şen, Z. (1977). Run-sums of annual flow series. *Journal of Hydrology*, *35*(3), 311–324. https://doi.org/https://doi.org/10.1016/0022-1694(77)90009-9

Senent-Aparicio, J., George, C., & Srinivasan, R. (2021). Introducing a new post-processing tool for the SWAT+ model to evaluate environmental flows. *Environmental Modelling and Software*, *136*, 104944. https://doi.org/10.1016/j.envsoft.2020.104944

Shiferaw, H., Bewket, W., Alamirew, T., Zeleke, G., Teketay, D., Bekele, K., Schaffner, U., & Eckert, S. (2019). Implications of land use/land cover dynamics and Prosopis invasion on ecosystem service values in Afar Region, Ethiopia. *Science of the Total Environment*, *675*, 354–366. https://doi.org/10.1016/j.scitotenv.2019.04.220

Shindell, D. T. (2016). Crop yield changes induced by emissions of individual climate-altering pollutants. *Earth's Future*, *4*(8), 373–380. https://doi.org/10.1002/2016EF000377

Singer, P., Helic, D., Taraghi, B., & Strohmaier, M. (2014). Detecting memory and structure in human navigation patterns using Markov chain models of varying order. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0102070

Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., Voll, E., McDonald, A., Lefebvre, P., & Schlesinger, P. (2006). Modelling conservation in the Amazon basin. *Nature*, *440*(7083), 520–523. https://doi.org/10.1038/nature04389

Soni, D. (2018). *Introduction to Markov Chains - Towards Data Science*. https://towardsdatascience.com/introduction-to-markov-chains-50da3645a50d

Southward, J. (2019). *Increase in infrastructure could be the boom Toowoomba needs*. Australian Institute of Company Directors. https://aicd.companydirectors.com.au/membership/company-director-magazine/2019-back-editions/october/infrastructure-in-toowoomba

State of Queensland. (2010). *CoalPlan 2030: Laying the foundations of a future*.

State of Queensland. (2011). *Surat Basin Regional Planning Framework*. http://www.statedevelopment.qld.gov.au/resources/plan/surat-basin-regional/planning-framework.pdf

State of Queensland. (2013). *Darling Downs Regional Plan*. State of Queensland. https://www-010.clevvi.com.au/fileadmin/user_upload/darling-downs-regional-plan.pdf

State of Queensland. (2018). Queensland agriculture snapshot 2018. *Queensland Government*, 1–56.

https://www.daf.qld.gov.au/__data/assets/pdf_file/0007/1383928/State-of-Agriculture-Report.pdf

State of Queensland. (2019). *Climate change in the Eastern Downs region Version 1* (pp. 1–8). https://www.qld.gov.au/__data/assets/pdf_file/0027/68337/eastern-downs-climate-change-impact-summary.pdf

State of Queensland Water Commission. (2010). *South East Queensland Water Strategy*. 162.

Stockholm Environment Institute. (2015). *Water Evaluation and Planning System USER GUIDE for WEAP 2015*. http://www.weap21.orghttp//www.sei-us.org

Stockholm Environment Institute. (2016). Water Evaluation and Planning System. *Water Evaluation and Planning System Tutorial*, *August*, 1–202.

Stonestrom, D. A., Scanlon, B. R., & Zhang, L. (2009). Introduction to special section on Impacts of Land Use Change on Water Resources. *Water Resource. Res*, *45*, 0–00. https://doi.org/10.1029/2009WR007937

Stuchte, W. e. (2019). City- level water loss: a global assessment. *Environmental Science and Technology*, 9405-9415.

Subiyanto, S., & Suprayogi, A. (2019). Modeling And Spatial Analysis of Change Settlement and Fair Market Land Price Using Markov Chain Model in Banyumanik District. *KnE Engineering*, *2019*, 278–290–278–290. https://doi.org/10.18502/keg.v4i3.5866

Sun, S. K., Li, C., Wu, P. T., Zhao, X. N., & Wang, Y. B. (2018). Evaluation of agricultural water demand under future climate change scenarios in the Loess Plateau of Northern Shaanxi, China. *Ecological Indicators*, *84*, 811–819. https://doi.org/10.1016/j.ecolind.2017.09.048

Sundara Kumar, K., Udaya Bhaskar, P., & Padmakumari, K. (2015). Application of Land Change Modeller for Prediction of Future Land Use Land Cover A Case Study of

Vijayawada City. *International Journal of Advanced Technology in Engineering and Science*, *3*(1), 773–783.

Suppiah, R., Hennessy, K. J., Whetton, P. H., McInnes, K., Macadam, I., Bathols, J., Ricketts, J., & Page, C. M. (2007). Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. *Australian Meteorological Magazine*, *56*(3), 131–152. http://www-pcmdi.llnl.gov/ipcc/

Sutrin, P. (2019). *14 Renewable & Sustainable Projects in the Toowoomba Region*. Proven Energy. https://www.provenenergy.com.au/renewable-toowoomba-projects/

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-70816-2

Tena, T. M., Mwaanga, P., & Nguvulu, A. (2019). Hydrological modelling and water resources assessment of Chongwe River Catchment using WEAP model. *Water (Switzerland), 11*(4). https://doi.org/10.3390/w11040839

Thom, B., Cane, J., Cox, R., Farrell, C., Hayes, P., Kay, R., Kearns, A., Low Choy, D., McAneney, J., McDonald, J., Nolan, M., Norman, B., Nott, J., & Smith, T. (2010). *National Climate Change Adaptation Research Plan for Settlements and Infrastructure*. National Climate Change Adaptation Research Facility.

Thornton, P. K. (2010). Livestock production: Recent trends, future prospects. In *Philosophical Transactions of the Royal Society B: Biological Sciences* (Vol. 365, Issue 1554, pp. 2853–2867). https://doi.org/10.1098/rstb.2010.0134

Tien Bui, D., Tuan, T. A., Klempe, H., Pradhan, B., & Revhaug, I. (2016). Spatial prediction models for shallow landslide hazards: a comparative assessment of the efficacy of support vector machines, artificial neural networks, kernel logistic regression, and logistic model tree. *Landslides*, *13*(2), 361–378. https://doi.org/10.1007/s10346-015-0557-6

Toowoomba Region. (2020). *Where our water comes from*. http://www.tr.qld.gov.au/environment-water-waste/water-supply-dams/dams-bores/13244-where-our-water-comes-from

Toowoomba Regional Council. (2013). *Toowoomba Sustainable Agriculture and Rural Activity Study*.

Toowoomba Regional Council. (2014). *Toowoomba Regional Council Demographic Projections* (Issue December). https://www.tr.qld.gov.au/component/edocman/local-government-infrastructure-plan-lgip-demographic-projections-2011-2031/download

Toowoomba Regional Council. (2016). *Agriculture Profile 2016*. Toowoomba Regional Council.

Toowoomba Regional Council. (2017a). *Toowoomba Region Annual Report 2016-2017*. https://doi.org/10.1007/s00234-016-1748-0

Toowoomba Regional Council. (2017b). *Toowoomba Region Economic Profile March 2017* (pp. i–33). Toowoomba Regional Council.

Toowoomba Regional Council. (2018). *Bold Ambitions 2038: Toowoomba Region Economic Development Strategy (May 2018)* (Issue May, pp. 1–38). Toowoomba Regional Council. http://www.tr.qld.gov.au/testcat/toowoomba-region-economic-development-strategy/viewdocument

Toowoomba Regional Council. (2019). *Toowoomba Region Corporate Plan 2019 - 2024* (pp. 1–23). Toowoomba Regional Council. http://www.tr.qld.gov.au/component/edocman/corporate-plan-2019-2024/download

Tortajada, C., González-Gómez, F., Biswas, A. K., & Buurman, J. (2019). Water demand management strategies for water-scarce cities: The case of Spain. *Sustainable Cities and Society*, *45*(April 2018), 649–656. https://doi.org/10.1016/j.scs.2018.11.044

Touch, T., Oeurng, C., Jiang, Y., & Mokhtar, A. (2020). Integrated Modeling of Water Supply and Demand Under Climate Change Impacts and Management Options in the

Tributary Basin of Tonle Sap Lake, Cambodia. *Water*, *12*(9), 2462. https://doi.org/10.3390/w12092462

Towler, B., Firouzi, M., Underschultz, J., Rifkin, W., Garnett, A., Schultz, H., Esterle, J., Tyson, S., & Witt, K. (2016). An overview of the coal seam gas developments in Queensland. In *Journal of Natural Gas Science and Engineering* (Vol. 31, pp. 249–271). Elsevier B.V. https://doi.org/10.1016/j.jngse.2016.02.040

Turner, A., White, S., Chong, J., Dickinson, M. A., Cooley, H., & Donnelly, K. (2016). Managing drought: Learning from Australia. In *Alliance for Water Efficiency, Institute for Sustainable Futures, University of Technology Sydney, Pacific Institute*. https://pacinst.org/wp-content/uploads/2016/02/Managing-Drought-Report-2016-02-23-FINAL-US-Letter.pdf

Turner, K., Georgiou, S., Clark, R., Brouwer, R., & Burke, J. (2004). Economic valuation of water resources in agriculture - From the sectoral to a functional perspective of natural resource management. In *FAO (Food and Agriculture Organization of the United Nations)* (Vol. 27). Food and Agriculture Organization. https://doi.org/10.1016/j.proenv.2011.09.187

United Nations, Department of Economic and Social Affairs, P. D. (2019). *World Population Prospects 2019, Online Edition. Rev. 1*. https://population.un.org/wpp/Download/Standard/Population/

United Nations. (2015). *UN projects world population to reach 8.5 billion by 2030, driven by growth in developing countries*. https://www.un.org/sustainabledevelopment/blog/2015/07/un-projects-world-population-to-reach-8-5-billion-by-2030-driven-by-growth-in-developing-countries/

United Nations. (2018). *Water Scarcity*. https://doi.org/10.4135/9781412974592.n151

USGS. (2019). How Much Water is There on Earth? *Water Science School*, 1–6. https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science_center_objects=0#qt-science_center_objects

Vanham, D., Hoekstra, A. Y., Wada, Y., Bouraoui, F., de Roo, A., Mekonnen, M. M., van de Bund, W. J., Batelaan, O., Pavelic, P., Bastiaanssen, W. G. M., Kummu, M., Rockström, J., Liu, J., Bisselink, B., Ronco, P., Pistocchi, A., & Bidoglio, G. (2018). Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 “Level of water stress.” *Science of the Total Environment*, *613–614*(September 2017), 218–232. https://doi.org/10.1016/j.scitotenv.2017.09.056

Varun, N. M., Praveen, K. R., & Kshitij, M. (2014). Prediction of land use changes based on land change modeler (LCM) using remote sensing: A case study of Muzaffarpur (Bihar), India. *Journal of the Geographical Institute Jovan Cvijic, SASAZbornik Radova Geografskog Instituta Jovan Cvijic, SANU*, *64*(1), 111–127. https://doi.org/10.2298/ijgi1401111m

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human Domination of Earth’s Ecosystems. *Science*, *277*(5325), 494 LP – 499. https://doi.org/10.1126/science.277.5325.494

Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284

Vörösmarty, C., Lettenmaier, D., Leveque, C., Meybeck, M., Pahl-Wostl, C., Alcamo, J., Cosgrove, W., Grassl, H., Hoff, H., Kabat, P., Lansigan, F., Lawford, R., & Naiman, R. (2004). Humans transforming the global water system. *Eos, Transactions American Geophysical Union*, *85*(48), 509–514. https://doi.org/https://doi.org/10.1029/2004EO480001

Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., Satoh, Y., Van Vliet, M. T. H., Yillia, P., Ringler, C., Burek, P., & Wiberg, D. (2016). Modeling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches. *Geoscientific Model Development*, *9*(1), 175–222. https://doi.org/10.5194/gmd-9-175-2016

Wada, Yoshihide, Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., Stacke, T., Tessler, Z., & Schewe, J. (2013). Multimodel projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, *40*(17), 4626–4632. https://doi.org/https://doi.org/10.1002/grl.50686

Walshaw, H. e. (2021). Quantifying urban leakage by combining pressure and flow data: 10 UK studies. *Urban Water Journal*, 926-938.

Wang, F., Ge, Q., Yu, Q., Wang, H., & Xu, X. (2017). Impacts of land-use and land-cover changes on river runoff in Yellow River basin for the period of 1956–2012. *Chinese Geographical Science*, *27*(1), 13–24. https://doi.org/10.1007/s11769-017-0843-3

Wang, W., Zhang, C., Allen, J. M., Li, W., Boyer, M. A., Segerson, K., & Silander, J. A. (2016). Analysis and prediction of land use changes related to invasive species and major driving forces in the state of Connecticut. *Land*, *5*(3), 25. https://doi.org/10.3390/land5030025

Wei, Y., Langford, J., Willett, I. R., Barlow, S., & Lyle, C. (2011). Is irrigated agriculture in the Murray Darling Basin well prepared to deal with reductions in water availability? *Global Environmental Change*, *21*(3), 906–916. https://doi.org/10.1016/j.gloenvcha.2011.04.004

Wigley, T. M. L., & Jones, P. D. (1985). Influences of precipitation changes and direct CO2 effects on streamflow. *Nature*, *314*(6007), 149–152. https://doi.org/10.1038/314149a0

Wilhite, D. A., Hayes, M. J., Knutson, C., & Smith, K. H. (2000). Planning For Drought: Moving From Crisis to Risk Management 1. *JAWRA Journal of the American Water Resources Association*, *36*(4), 697–710. https://doi.org/https://doi.org/10.1111/j.1752-1688.2000.tb04299.x

Williams, A., Mushtaq, S., Kouadio, L., Power, B., Marcussen, T., McRae, D., & Cockfield, G. (2018). An investigation of farm-scale adaptation options for cotton production in the face of future climate change and water allocation policies in southern Queensland, Australia. *Agricultural Water Management*, *196*, 124–132. https://doi.org/10.1016/j.agwat.2017.10.026

Windle, J., & Rolfe, J. (2014). Assessing the trade-offs of increased mining activity in the Surat Basin, Queensland: Preferences of Brisbane residents using nonmarket valuation techniques. *Australian Journal of Agricultural and Resource Economics*, *58*(1), 111–129. https://doi.org/10.1111/1467-8489.12025

World Economic Forum. (2010). *Mining & Metals Scenarios to 2030*.

World Economic Forum. (2011). Water security: the water-food-energy-climate nexus. In D. Waughray (Ed.), *Choice Reviews Online* (Vol. 49, Issue 02). https://doi.org/10.5860/choice.49-1001

World Wildlife Fund. (2012). *Water Scarcity*. https://www.worldwildlife.org/threats/water-scarcity

Wu, L., Zhang, X., Hao, F., Wu, Y., Li, C., & Xu, Y. (2020). Evaluating the contributions of climate change and human activities to runoff in typical semi-arid area, China. *Journal of Hydrology*, *590*, 125555. https://doi.org/10.1016/j.jhydrol.2020.125555

WWAP (UNESCO World Water Assessment Programme). (2019). The United Nations World Water Development Report 2019: Leaving no one behind. *UNESCO Digital Library*, 55, 201.

Xiang, X., Svensson, J., & Jia, S. (2017). Will the energy industry drain the water used for agricultural irrigation in the Yellow River basin? *International Journal of Water Resources Development*, *33*(1), 69–80. https://doi.org/10.1080/07900627.2016.1159543

Yang, L., Feng, Q., Yin, Z., Wen, X., Si, J., Li, C., & Deo, R. C. (2017). Identifying separate impacts of climate and land use/cover change on hydrological processes in the upper stream of Heihe River, Northwest China. *Hydrological Processes*, *31*(5), 1100–1112. https://doi.org/https://doi.org/10.1002/hyp.11098

Yang, Y., McVicar, T. R., Donohue, R. J., Zhang, Y., Roderick, M. L., Chiew, F. H. S., Zhang, L., & Zhang, J. (2017). Lags in hydrologic recovery following an extreme drought: Assessing the roles of climate and catchment characteristics. *Water Resources Research*, *53*(6), 4821–4837. https://doi.org/10.1002/2017WR020683

Yao, J., Liu, H., Huang, J., Gao, Z., Wang, G., Li, D., Yu, H., & Chen, X. (2020). Accelerated dryland expansion regulates future variability in dryland gross primary production. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-15515-2

Yates, D., Purkey, D., Sieber, J., Huber-Lee, A., Galbraith, H., West, J., Herrod-Julius, S., Young, C., Joyce, B., & Rayej, M. (2009). Climate Driven Water Resources Model of the Sacramento Basin, California. *Journal of Water Resources Planning and Management*, *135*(5), 303–313. https://doi.org/10.1061/(ASCE)0733-9496(2009)135:5(303)

Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005). WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model. *Water International*, *30*(4), 487–500. https://doi.org/10.1080/02508060508691893

Yevjevich, V. M. (1969). An objective approach to definitions and investigations of continental hydrologic droughts. *Journal of Hydrology*, *7*(3), 353. https://doi.org/https://doi.org/10.1016/0022-1694(69)90110-3

Young, M. D. (2014). Designing water abstraction regimes for an ever-changing and ever-varying future. *Agricultural Water Management*, *145*, 32–38. https://doi.org/10.1016/j.agwat.2013.12.002

Zeppel, H. (2011). Planning for Climate Change by Queensland Coastal Councils. *20th Anniversary NSW Coastal Conference*. www.coastalconference.com

Zhang, Hong, Wang, B., Liu, D. L., Zhang, M., Feng, P., Cheng, L., Yu, Q., & Eamus, D. (2019). Impacts of future climate change on water resource availability of eastern Australia: A case study of the Manning River basin. *Journal of Hydrology*, *573*, 49–59. https://doi.org/10.1016/J.JHYDROL.2019.03.067

Zhang, Hong, Wang, B., Liu, D. L., Zhang, M., Leslie, L. M., & Yu, Q. (2020). Using an improved SWAT model to simulate hydrological responses to land use change: A case study of a catchment in tropical Australia. *Journal of Hydrology*, *585*(March), 124822. https://doi.org/10.1016/j.jhydrol.2020.124822

Zhang, Hongxue, Chang, J., Gao, C., Wu, H., Wang, Y., Lei, K., Long, R., & Zhang, L. (2019). Cascade hydropower plants operation considering comprehensive ecological water demands. *Energy Conversion and Management*, *180*, 119–133. https://doi.org/10.1016/j.enconman.2018.10.072

Zhang, X. L. (2022). Environmental Flow requirements largely reshape global surface water scarcity assessment. *Environmental Research Letters*.

Zhang, X., Dong, Q., Costa, V., & Wang, X. (2019). A hierarchical Bayesian model for decomposing the impacts of human activities and climate change on water resources in China. *Science of the Total Environment*, *665*, 836–847. https://doi.org/10.1016/j.scitotenv.2019.02.189

Zhang, Z. Y. (2020). Future industrial water demand and water scarcity risk in China under shared socio-economic climate scenarios. *Resources, Conservation and Recycling.*

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J. L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., … Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(35), 9326–9331. https://doi.org/10.1073/pnas.1701762114

Zhao, X., Pu, J., Wang, X., Chen, J., Yang, L. E., & Gu, Z. (2018). Land-use spatio-temporal change and its driving factors in an artificial forest area in Southwest China. *Sustainability (Switzerland)*, *10*(11), 1–19. https://doi.org/10.3390/su10114066

Zubaidi, S. L., Hashim, K., Ethaib, S., Al-Bdairi, N. S. S., Al-Bugharbee, H., & Gharghan, S. K. (2020). A novel methodology to predict monthly municipal water demand based on weather variables. *Journal of King Saud University - Engineering Sciences*. https://doi.org/10.1016/j.jksues.2020.09.01

APPENDICES

Table A.1. Residential Category.

Code	Description	Definition
2	Single Unit Dwelling	Land used primarily as a site for a dwelling in an urban area and generally less than 5,000 square metres.
02A	Single Unit Dwelling/Home Occupation	Land used primarily as a site for a dwelling with minor home occupation activity in an urban area and generally less than 5,000 square metres.
3	Multi Dwellings or Flats	The use of a parcel of land for two or more self-contained residential dwellings or flats but not group or strata title and in an urban area.
5	Large Home Site Dwelling	Land used primarily as a site for a dwelling, generally between 5,000 square metres and 10 hectares (inclusive) and not used for a bonafide rural activity.
8	Building Format Plan Primary Use Only	A residential parcel of land surveyed on a Building Format Plan which may include Common Property and which has attached to it a Community Management Statement in an urban area.
10	Combined Dwelling and Shops	Combined dwelling/multi dwelling and shops i.e. residential flats with shops but not registered on a Building Unit Plan or Group Title Plan.

Table A.2. Commercial Category.

Code	Description	Definition
7	Guest House/Private Hotel	An accommodation building where room only or room and meals are provided and have shared facilities (not a motel) in an urban area.
9	Body Corporate in any strata titled scheme	Body Corporate in any strata titled scheme (community titles, group titles or building units).
11	Shop Single	Shop with or without attached accommodation and may include provision for car parking.

12	Shopping Group (7 - 9 Shops)	Seven to nine shops and may include provision for car parking.
13	Shopping Group (2 - 6 Shops)	Two to six shops and may include provision for car parking.
14	Shops – Main Retail (Central Business District)	Shops located in the main inner city/town commercial area (central business district).
15	Shops – Secondary Retail (Fringe Central Business)	Shops located on the fringe of a central business district of city/town commercial areas.
16	Drive In Shopping Centre	Drive In Shopping Centre including regional, sub regional and neighbourhood centres and having ten or more shops.
17	Restaurant/Function Centre	Restaurant including fast food outlets e.g. Kentucky Fried Chicken, McDonalds or function centre.
22	Car Park	An area of land which has been prepared to accommodate vehicles either below or at ground level or on suspended concrete floors.
23	Retail Warehouse	Isolated large showroom, warehouse used for retail purposes.
24	Sales Area Outdoors (Dealers, Boats, Cars etc)	Dealers, Boats, Cars, etc.
25	Professional Offices	Building with professional offices, finance, banks, lending agents and brokers which are predominantly offices.
26	Funeral Parlour	Funeral Parlour.
28	Warehouse and Bulk Stores	Warehouse and Bulk Stores not used for retail purposes.
30	Service Station	Predominantly used for fuel retailing which includes fuelling area, associated fuel storage area, associated retail shop and associated parking area. If predominantly servicing repairs see Land Use Code 36A.

Table A.2. Commercial Category (cont).

34	Cold Stores - Ice works	Cold Stores - Ice works.
42	Hotel/Tavern	Premises licensed by Licensing Commission as hotel or tavern for the sale of liquor including casino.
43	Motel	Building predominantly used for

		overnight accommodation of persons plus vehicle.
44	Nursery (Plants)	Retail of plants and associated garden material.
45	Theatre Cinema	Theatre or Cinema
47	Licensed Club	Any club with liquor licence/non sporting e.g. R.S.L. (not including clubs with attached sporting/recreation facilities).
48	Sports Club/Dance Facility	All sporting/dance/fitness/health/bowling clubs with or without a liquor licence run as a business.
52	Cemetery (Include Crematoria)	Cemetery (Include Crematoria).
56	Show Ground, Race Course, Airfield	Airfield (including Toowoomba Airport) parking, no maintenance. If maintenance see Code 36A or Code 36B.

Table A.3. Mining Category.

Code	Description	Definition
40A	Extractive (Quarry)	Any industry which extracts quarry material from the ground.
40B	Extractive (Mining)	Any industry which extracts mining material from the ground.
40C	Gas or Oil Extraction	Any industry which extracts gas or oil from the ground.

Table A.4. Parks and Gardens Category.

Code	Description	Definition
49	Caravan Park	Caravan Park
57	Parks, Gardens	Parks, Gardens - including undeveloped parkland.

Table A.5. Institutions Sector.

Code	Description	Definition
18	Special Tourist Attraction	Any development with special recreation, historical or residential features which attracts a large number of people (includes tourist village).
21	Residential Institution (Non-Medical Care)	Aged People’s Homes not predominantly medical care.
27	Hospital, Convalescent,	Hospital, aged people’s home, nursing

	Home (Medical Care) (Private)	home, convalescent home. Predominantly medical care.
41	Child Care excluding Kindergarten	Facility for safe keeping of below school age children.
50	Other Club Non-Business	Boy Scouts/Girl Guides etc. not run as a business. Memorial Halls, Q.C.W.A., School of Arts etc. Sporting Clubs not run as a business including sports fields/area tennis courts etc.
51	Church/Facilities	Churches, places of worship, church halls, etc.
55	Library	Library
58	Educational include Kindergarten	University, Tertiary, State and Private, residential colleges/school and non-residential school, kindergarten.
92	Defence Force Establishment	Defence Force Establishment.
96	Public Hospital	Public Hospital.
97	Welfare Home/Institution	Child/adult welfare institution.
99	Community Protection Centre	Ambulance Centre, Fire Station, State Emergency Service and Headquarters, Air Sea Rescue Station, Coast Guard.

Table A.6. Industrial Sector.

Code	Description	Definition
31	Oil Depot and Refinery	Fuel dumps or storage and oil refineries.
33	Outdoor Storage Area/Contractors Yard	Builders/contractors yard, outdoor storage area (not retail or hardware) or area for parking heavy equipment/materials.
35	General Industry or Medium Industry	Industrial premises that are not Light Industry A – Land Use Code 36A, or Light Industry B – Land Use Code 36B, Heavy Industry – Land Use Code 37A or Abattoir – Land Use Code 37B
36A	Light Industry A	Light/service industries e.g. vehicle workshops, bicycle repairs, furniture assembly/repairs/restoration, electrical goods repairs/maintenance, locksmiths, lawn mower repairs or upholstering or car washes.
36B	Light Industry B	Light manufacturing industries e.g. bread making, clothing manufacturing, dry cleaning, glass cutting or implement/machinery assembly.

37A	Heavy Industry	Industry from where a deal of offensive noise, odour, dust, etc. emanates that is not Abattoir – Land Use Code 37B. Refer to Toowoomba Planning Scheme under the term high impact industry and noxious and hazardous industries.

Table A.7. Livestock Category.

Code	Description	Definition
64	Cattle Grazing Breeding	Concentration of the growing and selling of young stock – includes stud breeding.
85	Pigs	The breeding and/or growing and/or fattening of pigs in an open range or feedlot environment.
86	Horses	The breeding and/or growing of horses including for stud purposes, including predominantly stables.
87	Poultry	Includes breeding, plus the growing for meat and/or egg production either in a controlled environment or by open runs.

Table A.8. Changes in cotton prices from 1974-2018.

Year	Australian Base Price	Change in Price
	for raw cotton (Ac/kg)	for raw cotton (Ac/kg)
1974-75	90	
1975-76	117	27
1976-77	166	49
1977-78	135	-31
1978-79	156	21
1979-80	179	23
1980-81	188	9
1981-82	157	-31
1982-83	191	34
1983-84	225	34
1984-85	210	-15
1985-86	169	-41
1986-87	222	53
1987-88	233	11
1988-89	192	-41
1989-90	250	58
1990-91	246	-4
1991-92	194	-52
1992-93	196	2
1993-94	240	45
1994-95	285	45
1995-96	263	-22
1996-97	235	-28
1997-98	249	14
1998-99	227	-21
1999-00	199	-28
2000-01	251	53
2001-02	194	-58
2002-03	225	32
2003-04	226	0
2004-05	167	-59
2005-06	178	11
2006-07	177	-1
2007-08	191	14

2008-09	193	2
2009-10	205	12
2010-11	377	172
2011-12	225	-152
2012-13	199	-26
2013-14	229	29
2014-15	199	-30
2015-16	226	28
2016-17	257	30
2017-18	256	-1

Source: Revised from ABARES, 2018 downloaded 6/6/18 www.agriculture.gov.au**.**