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The Effect of Urbanization, Population growth and Climate Change on the WEF Nexus Using an Input-Output Analysis and Econometric Modelling Framework: A Case Study on Water-stressed Countries

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DECLARATION

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the Research Project contains no material previously published or written by another person except where due reference is made in the Research Project itself.

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TABLE OF CONTENTS

LIST OF TABLES:

LIST OF FIGURES:

Abstract

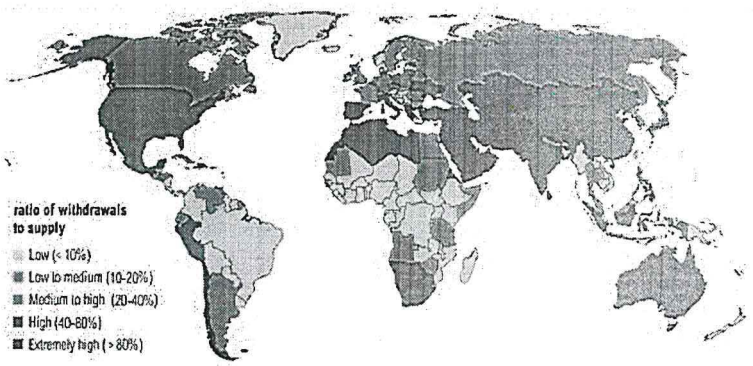
The efficient allocation and consumption of resources has been of interest to the economics academic community for many years, and this is mainly attributable to the fact that, resources are a part of our everyday lives. This paper focuses on three main resources for human development: the water, energy and food resources, and their sustainability in today's economic systems. We utilize two modelling techniques in this paper, the panel data approach seeks to investigate the impact of urbanization, population growth and climate change on water demand, and the input-output modelling approach seeks to investigate the interlinkages that exist between the WEF sectors of China, Mexico, South Africa, and Spain. Results from the paper suggest that urbanization and population growth are the significant variables that contribute to water demand, whereas the WEF Nexus interlinkages of the four countries exhibit strong linkages between the water, energy, and food sectors. Results of this paper are relevant to policymakers that are interested in improving either the water, energy, or food sectors without destroying the other sectors.

CHAPTER 1: INTRODUCTION

1.1 Background of the study

In a world of scarce resources, the potential for "running out" is always expected. Thomas Malthus strongly defended the theory that population growth was a sufficient condition for the decline of resource availability, and ultimately, the fall of humankind (Malthus, 1798). The 9.7 billion global population projection by 2050 (United Nations, 2019), the increasing global urbanisation rate of 2.11% per year over the last 2 centuries (Ritchie & Roser, 2019) and the growth of economies and in turn their carbon emissions, all provide reasonable evidence for the increased stress on resources and their availability to vulnerable groups. FAO data indicates that the current global population without access to basic clean drinking water stands at 10%, however, future global demand for water is projected to increase by 20-30% by 2050 (FAO, 2019). Thus, due to the fact that water is a closed system, the increased water demand and the negative effect of climate change on the quantity and quality of available water resources, can be expected to increase the threat levels on water security for poorer and vulnerable communities around the world. Figure 1 is a projected scenario of water stressed countries by the year 2040, calculated by taking the projected water supply per country, divided by the projected water withdrawals.

Figure 1: Water stressed countries: 2040 projections



Source: Aqueduct World Resources Institute (WRI, 2015)

The water scarcity issue is one of significant importance, attributable to the high dependence of other sectors on water resources as explained later in this chapter. Other than the high demand for water, climate change is one of the major contributors to the depletion of water resources such as lakes and rivers. The issue is so critical that in 2008, Goldman Sachs termed water to be "the next petroleum" of the 21st century

(Goldman Sachs Group, 2008), resulting in an influx of investment by private players into municipal water supply organisations, as well as hedge fund managers entering into the water sector, to make "bets" on substantial profits when water resources become increasingly scarce in the future.

With regards to food security, the prevalence of severe food insecurity in the global population was 8.7% in 2017 (World Bank, 2017), and this is expected to worsen under harsher climate conditions in the future. Furthermore, despite the recent developments in energy production, the global access to clean energy for cooking still stands at a surprisingly low 59%, where 54% of Sub-Saharan Africa does not even have access to electricity (Ritchie, 2019). In addition to this, the complex interlinkages that exist between these three industries (water, energy and food) increase the difficulty which economies face with regards to reaching holistic and sustainable development.

Various papers suggest that a new approach to dealing with the three sectors should be adopted (Giampietro, et al., 2013), known as the water, energy and food (WEF) nexus approach, which takes into consideration the interlinkages. The approach identifies the synergies and tradeoffs that exist between the sectors, and can be used to advise policy makers on how to take advantage of opportunities, and how to avoid maladaptive practices. However, a majority of countries currently neglect this approach with regards to the governance of the three sectors, leading to preventable inefficienies, and an overall poor environmental performance. This has been blamed on the limited research on the topic, specifically with regards to quantitative analysis and the creation of tools that can be used by these policy makers for decision making.

With the already low access to these three resources, the climate-change-strain on them, and the poor knowledge and application of the nexus approach into policy strategy, it is inevitable that the pressure from the aforementioned factors will potentially lead us into a world where wars emerge over basic resources (Starr, 1991). However, the focus of this study is four water stressed countries: China, Mexico, South Africa and Spain, which have all experienced water crises in the last decade.

1.1.1 Factors affecting water resources.

China

Over the last 50 years, China's fresh-water resources have depleted due to the strain imposed mainly by the rapid industrialisation of the nation and its high population growth, amongst other factors. The North of China has faced severe challenges with regards to water access since all the water reservoirs in the country are located in the southern part of China (rivers Yangtze, Han, Pearl and Yellow). This has been a major problem for the country since these water-stressed zones (including major cities like Beijing) account for 50% of power generation in China, 46% of industrial production, 41% of population and 38% of agricultural output, where 62% of water consumption is attributable to agriculture in the country.

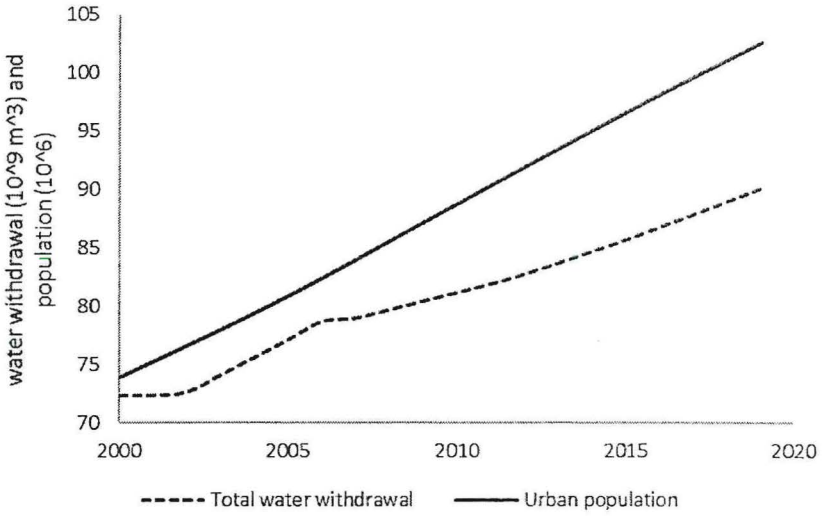
To combat the challenges of water scarcity in the north of China, the government implemented the South to North Water Diversion projection in 2002 that aimed to transport 44.8billion m^3 per year at a total cost of USD 62Bn. However, various factors hinder the success of the project, such as the depletion of water resources attributable to climate change as well as severe pollution, where 40% of surface water fail to comply with safety standards, and where 20% is too toxic even for household or agricultural purposes (thus approximately 60% of total surface water resources is deemed unsafe). Other factors that hinder the project's success is the high level of water usage inefficiency compared to other countries, where China uses 2x more water than its peers to produce the same output. Thus, water resources are expected to continue depleting drastically until the country manages to implement policies that improve water quality, water usage efficiency, reduce water consumption by sectors such as agriculture, and adaptation policies that combat the effects of climate change onto water resources.

Mexico

Mexico city's water resources have been a challenge for many years, where 70% of water is supplied by aquifers beneath the city, and where the remainder is supplied by the Guatemala system. The issues that contribute to water scarcity include high levels of non-revenue water (30%-45% lost every year) due to the poor piping system around the city, climate change that has dried up lakes over the years, and the intense floods that pollute clean water reserves during the rainy seasons. The population growth has also contributed to the increased strain on water resources, as seen in figure 2 where

total water withdrawal increases with urbanisation despite the capped water resources available (533 trillion m^3 every year) that continue to decline as aquifers are drained beyond their natural ability to recharge.

Figure 2: Mexico's total water withdrawal and urbanisation from 2000 to 2019



Source: Aquastat Food and Agricultural Organization of the United Nations

Currently, the government has failed to implement any sound regulations to promote sustainability of the water resources due to the already complex process of solving the country's low water access levels (especially for poorer communities), as well as the huge investment and over-complicated restructuring of the cities to accommodate more efficient water systems that will preserve water (Gutierrez, 2019).

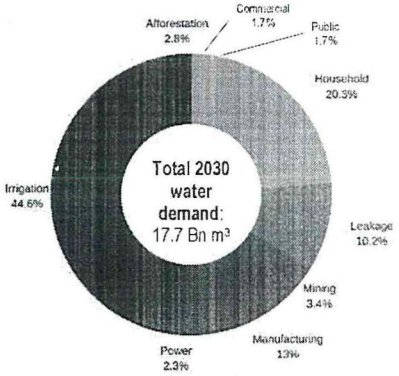
South Africa

In May 2016, a three-month water crisis was announced in the Western Cape, where Cape Town is the major city. This was due to the three-year long period of intermittent droughts that gradually depleted the water resources in the country, and the high levels of water consumption in the area. The water crisis extended to 2018 where major dams in the Western Cape (Theewaterskloof dam) were operating at approximately 10% capacity. Analysts predicted that the city would run out of municipal water resources by March 2018, and was termed "Day Zero", which would make Cape Town the first major city in the world to officially "close their taps".

The high levels of water consumption can be attributed to three main participants in the economy: households, agricultural systems and industries, where the share of

water withdrawals in the country were 63%, 11% and 26% in 2015 respectively (Ritchie & Roser, 2018). Figure 3 depicts a projected scenario of the share of water demand between different water users, illustrating that South Africa's demand for water (17.7 Bn m3) is projected to surpass water supply (13.9 Bn m^3) in 2030 by 3.8 billion cubic metres when taking into consideration climate change impacts.

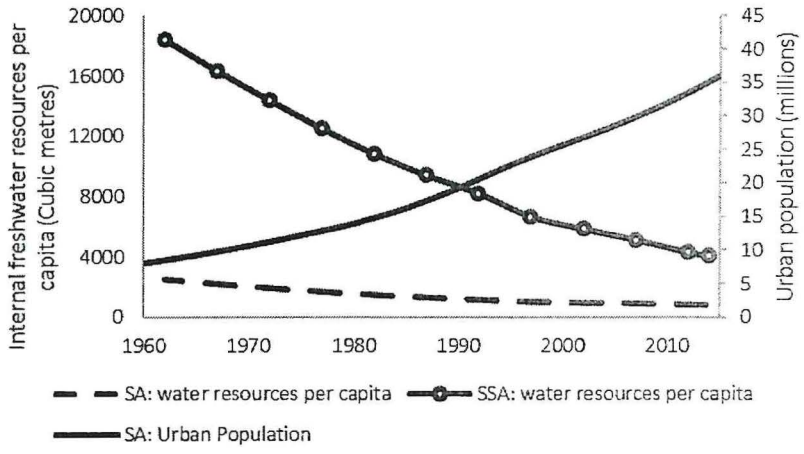
Figure 3: Estimated share of water demand (%): 2030 South Africa



Source: National Water Resource Strategy, McKinsey analysis (McKinsey, 2004)

As a result, the Malthusian theory can be exhibited here, where the availability of water resources will never sustain under an economy with an exponentially increasing population and demand on water. The effect of urbanization on water resources available to individuals is depicted in figure 4, where both Sub-Saharan and South African renewable water resources per capita figures have been declining since 1960, while population and urbanisation grew.

Figure 4: Renewable internal freshwater resources per capita vs. Urban population

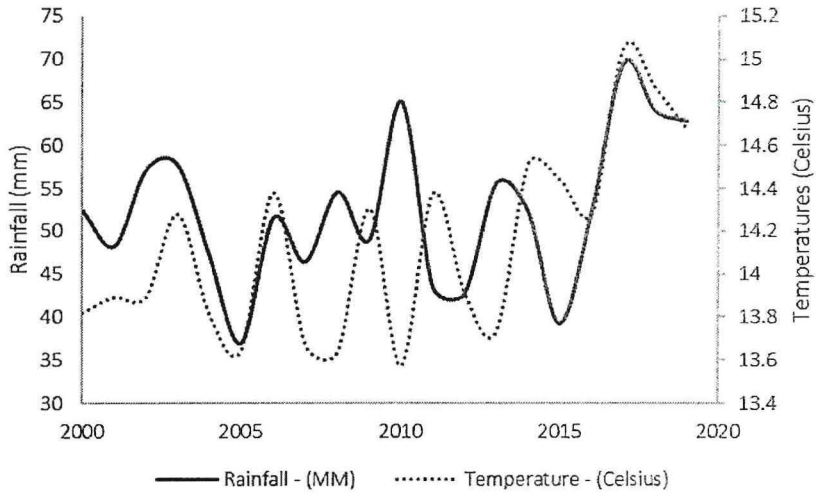


Source: World Development Indicators

Spain

In 1986, Spain joined the European Union, and this presented opportunities for farmers, where the EU's common agricultural policy allowed farmers to take advantage of subsidies and favourable trade conditions for agricultural products. As a result, over the years Spain's agricultural industry grew, as more land was used for agriculture and this inevitably led to the over-exploitation of ground water resources for irrigation purposes. Thus, water resources have faced challenges with regards to water quality, where irresponsible agriculture has increased the levels of contaminants in the surface water, rendering the water unsafe for consumption. Other factors that deplete water resources in the country include illegal water extraction for farming purposes, as well as climate change that induces long periods of drought and irregular hydrological patterns as seen in figure 5 in various regions of the country, which further contribute to the drilling of illegal boreholes. Unfortunately, the government's response to illegal water extraction ("water theft") and illegal farming is weak, where irrigation practices regulation is poorly implemented across the country.

Figure 5: Rainfall and temperature trends in Spain from 2000-2019



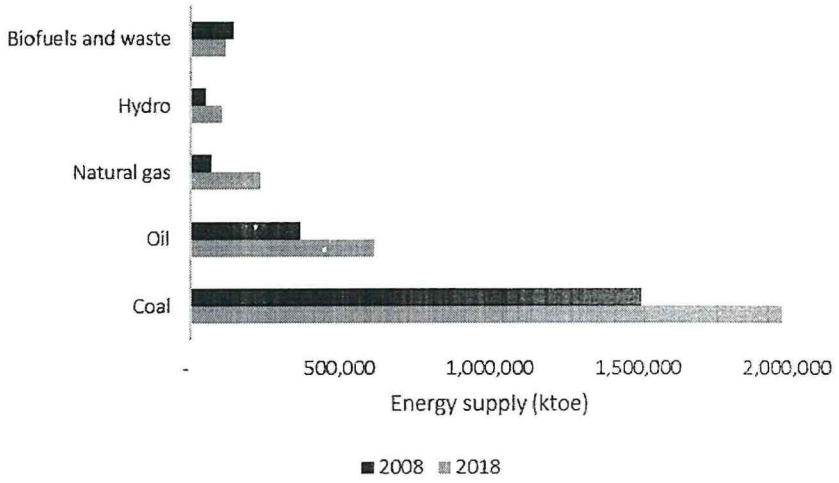
Source: World bank Climate Change Knowledge Portal

1.1.2 Factors affecting energy resources.

China

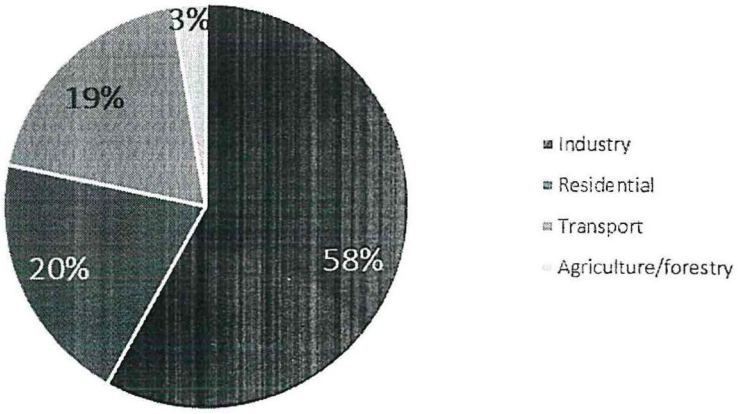
China's energy sector has rapidly grown since the start of the industrial revolution in 1988, and the continued pressure on the country to maintain and improve its economic status as a global giant impose added strains on the energy sector. Figure 6 depicts the growth of energy supply from different sources, where coal is seen to be the largest source of energy, which is water-intensive and explains the 22% of water consumption by the industrial sector as of 2016 (Wang, Bian, & Hao, 2015). Other factors that contribute to the increased energy supply include rapid urbanisation, where the growth and modernisation of cities require massive amounts of energy to sustain. Policymakers have recently embarked on developing policies to promote the use of electricity, natural gas and wind/solar energy in the attempt to decarbonise the energy supply of the country (IEA, 2021).

Figure 6: Sources of China's energy (2008 and 2018)



Currently, energy is consumed mainly by the industrial sector, followed by households and then transport as seen in figure 7. Agriculture also uses energy, and this highlights the interlinkage between the energy and food sector, however, the sector's consumption of energy is insignificant compared to other sectors.

Figure 7: China's Total Final Consumption by Sector (2018)



Mexico

According to IEA, Mexico's energy supply mainly constitutes of oil (48% of total energy supply) and natural gas (41%) as of 2019. The high levels of oil are attributed not only to the increased need by households and industries in the country, but also to the increased production of crude oil for export purposes to the US and other countries. In addition to this, the natural gas supply is attributed to the large existing gas reserves and the cheap gas imports from Texas as a result of favourable bi-lateral agreements between US and Mexico (Camba, Lenero, & Scott, 2019). The country's transport sector consumes the most energy followed by the industrial and residential sectors. With growing populations and increased urbanisation, the inevitable increase in energy consumption can be expected to strain Mexico's gas reserves, and strain production of oil for export purposes.

In 2013, the Mexican government implemented energy reforms that sought to privatise the energy sector in order to increase competition, innovation, and ultimately, increase energy use efficiency in the country (Camba, Lenero, & Scott, 2019).

South Africa

The energy sector in South Africa has been growing steadily over the past 4 decades, with a CAGR of 2.7% (IEA, Africa Energy Outlook 2019: World Energy Outlook special report, 2019). Data from IEA (2019) suggests that South Africa's primary energy consumption has been growing slower than Africa in general, which had a

CAGR of 3.9%, but faster than that of the World, which had a CAGR of 2.5% from 1965 to 2018. This can be attributed to the increased demand from the population growth, as well as the increased industrial and mining activities in the country.

Table 1 indicates that the energy sector in the country has been, and is projected to still be coal dependent. This brings about WEF nexus issues due to the high levels of water-dependency of coal production, as well as the emissions caused that are expected to impact the environment negatively in the long run through climate change. It should be noted that despite the 1086 operational dams in the country, South Africa relies mostly on thermal and other renewable energy sources (bioenergy, low carbon) to satisfy its energy demands. As a result, the effect of depleting water resources due to the aforementioned factors (climate change, population growth, urbanisation) is hypothesised only to affect the production of power plants that use water for cooling purposes.

Table 1: South Africa's energy demands (projected to 2040 under IEA scenario)

Energy Demand (*USD billion Mtoe*)	2010	2018	2030	2040
Coal	110	99	82	68
Oil	18	19	25	30
Gas	4	4	5	8
Hydro	0.18	0.06	0.24	0.48
Solar PV	0	0	2	4
Other low carbon	3	5	8	17
Bioenergy	7	7	10	13

Source: IEA database (IEA, 2019)

Spain

Spain's energy sector is considered to be the most ambitious compared to its European peers when it comes to the revolution towards clean energy. The country submitted its National Energy and Climate Plan 2030, which highlighted plans to increase the

consumption of renewable energy to 42% by 2030. This move is in line with recent government policies designed to address climate change risks across the country, especially with respect to energy production. Currently, the country's production of energy from coal has reduced by 25% over the past 3 decades, and natural gas and wind/solar have increased by over 500% and 30,000% respectively from 1990 to 2019.

1.1.3 Factors affecting food resources.

China

China's increasing population has inevitably imposed a strain on available food in the country, where the China's food production index has increased by 190% since 1990 according to the World Bank database. As a result, this has caused the country to sustain food consumption trends through imports from countries such as Canada. In 2017, the country's food imports value grew by 647% from 2003, while exports grew by only 195% over the same period. Hence, policymakers have begun to design solutions to reduce the dependency of the nation on food imports (China Power, 2017).

Furthermore, the water shortages explained in section 1.1.1 and the heavy agricultural production in the North of China have resulted in a situation of low food security in the country. The increased intensity of climate change on the country's land is also expected to adversely affect food production over time.

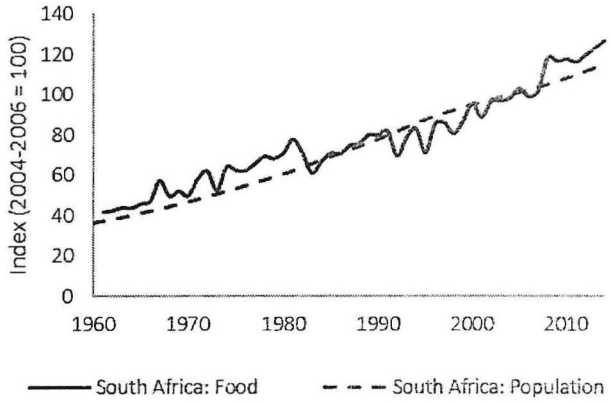
Mexico

According to the World Bank database, Mexico's food production has increased by 92% since 1990, while total population only grew by 51% over the period. Evidently, this suggests that investment into the food sector is attributable to increasing food consumption patterns, as well as the favourable bilateral trade agreement with USA that allow Mexico to export agricultural produce without incurring any tariff costs. The contribution of the agricultural sector to the economy is not without consequences, where the country's agricultural sector water withdrawal as a percentage of total water withdrawal in 2017 was 76% according to Aquastat FAO database, while contribution to GDP in the same year was only 3.4%. As a result, this leads to inefficiency of the economy to transform water resources into value added agricultural output at the expense of water insecurity.

South Africa

Figure 9 illustrates the trends of population and food production over time in both Sub-Saharan Africa and in South Africa itself. The indexed data suggests that the changes in food production have being varying over the years, with short term fluctuations likely attributable to the effect of climate change on agricultural yields. Furthermore, over the period, population growth has been consistently sloping upwards, increasing pressure on the food sector to meet demands.

Figure 8: Food production and Population indexed trends (South Africa)



Source: WorldBank database

The future of food security in South Africa is also threatened by various factors other than population growth. The three-year long drought in 2016 brought light to the dependency of the food sector on the water sector, hence, food security is largely dependent on water security. The country's highest water-consuming sector is agriculture, and this is highlighted in three major ways. The first way is because cereals such as wheat and barley are water-intensive crops, as a result, the low cost of water results in farmers using inefficient irrigation techniques due to the low incentive to invest in more expensive, efficient irrigation systems. Secondly, the wine industry in South Africa is one of the largest sectors in the country, where more than 92,000 hectares of land are managed by approximately 3,000 farmers currently, and where wine production is water intensive as well. Finally, the livestock industry affects water resources as well, where approximately 6,000 litres of water are spent on one cow a day. These 6,000 litres are accounted for in the fodder used in animal feed, and as a result, it took more water to feed a cow than to feed a household during the water crisis in 2018, where households were limited to 50 litres a day.

Spain

As explained in 1.1.1, the country's membership allows the country to benefit from favourable subsidies and trade laws within the EU, and this has contributed to the increased agricultural production. However, food production increased only by 25% over the period 1990-2016, which is low in comparison to other countries in this study. Despite the slow growth in food production, population has increased by 21% over the same period, consequently implying that the country's food production is growing faster than the population itself, which brings to question the sustainability water resources and land quality in the long run. The country also suffers from the same problem as Mexico, where contribution of agriculture to GDP is only 2.8% (2016) despite the high levels of water withdrawals for agricultural purposes (67%).

This discussion brings light to the interlinkages that exist between the sectors, and sets the tone for the rest of the paper where we emphasize the need for a WEF nexus approach to be adopted for the sustainable development of the three sectors, and of the country as a whole.

1.2 Problem Statement

Climate change has become a global challenge, where major contributors to greenhouse gas emissions include; energy consumption, as well as agricultural systems (WRI, 2016). The various weather anomalies attributable to changes in hydrological cycles, such as wildfires, droughts and floods, have had an adverse impact on water resources. In addition to this, climate change contributes to many forms of water pollution (Murdoch, Baron, & Miller, 2000), affecting both the quantity and quality of water resources. This is expected to lead to a global water crisis in the near future, with over 30 countries being projected to become "water-stressed" by 2040 (Maddocks, Young, & Reig, 2015). Furthermore, the decrease in water resources is also expected to be driven by growing global populations, hence, heightening the consumption of energy, food and water by the economy. As a result, both the climate-induced depletion of water resources, and the increased water demand by the households, and the food and energy sectors are hypothesised to have an effect on the overall level of water, energy and food resources, due to the existence of industry interlinkages: the water, energy and food (W-E-F) nexus.

Extensive literature exists on the nexus in relation to the effects of the energy and food sectors on production of WEF resources. Khan and Hanjra (2009) found that food production has significant water and energy footprints in all levels: local, national, and global. Ringler, et al. (2016) analysed the effects of energy price changes on global water and energy security using general and partial equilibrium models, and found that increases in energy prices due to carbon taxes are expected to decrease food security globally. Bazilian et al. (2011) revealed that the intensity of food-related water usage was significant in developing countries. Various frameworks have been developed to quantitatively assess the interlinkages between the WEF industries (Karnib, 2017; Bazilian, et al., 2011; Giampietro, et al., 2013), and have been applied to various countries. However, there is no extensive quantitative literature that addresses the impact on the WEF nexus from the perspective of urbanisation, population change and climate change as key drivers, which would provide insights on the potential impact of climate change on the water, energy and food production. Furthermore, there is currently only one paper that assesses the WEF nexus using econometric modelling. This proposed study will fill this gap by examining the relationship between temperatures, rainfall, and the WEF industries of China, Mexico, South Africa and Spain, and differentiates itself from past studies by combining the two modelling frameworks, panel data analysis and the input-output model framework (Karnib, 2017), to capture the effect of climate change on water, and hence, on the WEF resources, which is often neglected from other WEF-related studies.

1.3 Research Objectives

General objective:

To identify the general effect of urbanisation, population change and climate change on water, energy and food resources.

The Specific Objectives are:

1. To analyse the effects of population growth, urbanisation and climate change on water demand in the four countries.
2. To investigate the interlinkages and footprints between the WEF sectors
3. To investigate the impact of population growth, urbanisation and climate change on the WEF nexus.

1.4 Research Questions

a) How does urbanisation, population growth and climate change affect water demand in the four countries?
b) How do the WEF sectors relate with each other?
c) How does urbanisation, population growth and climate change affect the WEF nexus?

1.5 Significance of the Study

In this paper, we will specifically focus on the impact of climate change, urbanisation and population growth on water resources, and the implications on the WEF nexus in the context of our four countries, by applying quantitative tools proposed by other authors in this field that assess the synergies and trade-offs within the interlinkages. Recent studies on the topic managed to capture different aspects of the WEF nexus, however, none have been quantitatively analysed in depth with respect to climate change and water resources. This is due to the fact that data in the area is limited and there is a lack of a unified methodology in the literature. However, understanding the WEF nexus is of critical importance, due to the fact that policies that are developed with regards to water, energy and food sectors are at risk of being more harmful than helpful to the nexus, and hence, to the sustainability of the economy's growth and development. This raises the need for more quantitative assessments on the nexus that use minimal data, due to the importance of the research outcomes for various stakeholders: academics, policy makers and the private sector.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

The objective of this section is to explore the existing literature that have been chosen and analysed in relation to this research topic. First, we start off with a discussion on the existing theoretical literature that underpin the foundation of general concepts in the study area. Then, we discuss the empirical literature on the topic, focussing primarily on the models used by the authors. This section will be split into four categories: the three sectors; water, energy and food; and then into the fourth category, the WEF nexus conceptual framework as a whole. Throughout this section, we convey the need for more quantitative analyses in the WEF nexus literature community, justifying the case for the importance of this study to the research community. Papers were chosen based on their methodologies and on the jurisdiction of the studies.

2.1 Theoretical literature

The theories that encompasses the climate change and resource-scarcity arena are: (1) Anthropogenic global warming, (2) Malthusian theory of population growth and (3) Theory of Sustainability. These three theories supplement each other as seen in the following discussions.

3.1.1 Anthropogenic Global Warming Theory (AGW)

This theory is a scientific theory which states that rising temperatures around the world are caused by emissions of greenhouse gases (GHG) as a result of human activities. The theory is based on the greenhouse effect phenomenon, whereby gases such as methane and carbon dioxide contribute to the already existing greenhouse gas layer in the atmosphere that regulates the electromagnetic waves trapped on the earth. The thicker this layer becomes, the warmer the atmosphere gets. As a result, the increase in greenhouse gas emissions by human activities directly contributes to the rising temperatures on the planet, commonly referred to as global warming, and subsequently, leads to other long-term and short-term changes in climate conditions: climate change and climate variability. Despite the notion that the contribution of human activities to the amount of greenhouse gases is small this, the AGW theory states that human-related GHG emissions increase the effect of the already existing gases in the atmosphere by approximately 4 times (Bast, 2010).

Furthermore, water vapor is also considered to be a greenhouse gas, and contributes a significant amount to the greenhouse effect (approximately 36-90%). The rising

temperatures on the planet lead to various consequences with regards to water; higher evapotranspiration, melting glaciers and higher evaporation from water bodies, leading to occasional sporadic rains and torrential rains that deplete the state of the environment and human living standards, due to excess erosion and infrequent flooding. This brings about issues such as agricultural failure, and consequently, famines caused by droughts, severe weather patterns that threaten the standards of living and economic growth of countries, and the spread of diseases that diminish the health of individuals affected by these catastrophes.

Hence, the AGW theory provides the basis of theoretical proof for the existence of climate change, where further studies will be analysed in the empirical literature section to justify the theory and its implications.

3.1.2 Malthusian theory of population growth

Many of the issues relating to the effect of population growth on the sustainability of lifestyles were captured by Paul Ehrlich in his book: "Population Bomb", and who shared the same view as Thomas Malthus who first introduced the theory of population growth in 1798 (Malthus T. R., 1798). The theory states that the exponential growth of global population increases pressure on the agricultural sector based on the assumption that food supply growth is arithmetic. However, the theory was later repudiated due to the advancements in technology and the scientific revolutions that changed the global food sector, and increased food availability around the world despite the exponential population growth. However, despite these advancements, humanity has not escaped the general trap of the effect of population density on non-renewable resources. Bretschger (2020) explicitly links the implications of population growth and climate change on future economies. He states that a potential new version of the Malthusian theory may be considered: "The New Malthusian", where growing economies and their carbon emissions contribute to the depletion of the atmosphere's absorption capacity (as opposed to the traditionally proposed variable by Thomas Malthus; the agricultural sector), and hence, presenting a similar problem as was experienced in the late 1700's (Bretschger, 2020). He states that as long as economic growth is hinged onto emissions; economies will become more vulnerable as climate change intensifies.

To assess the effect of population growth on climate change and variability, the integrated assessment model can be used. However, one of the assumptions of the

integrated assessment model is that productivity and population growth rates should marginally diminish. Kelly and Kolstad (2001) investigate the significance of this assumption for the abatement of greenhouse gases as generally assumed in integrated assessment models. Results showed that climate change and population growth have a bi-causality relationship, where an increase in population growth was observed to have negative consequences on the state of the atmosphere, and where climate change was also hypothesised to have a negative effect on the incentives of economies (especially developing economies) to support high population growth rates (Kelly & Kolstad, 2001). The former observation provides evidence for the Malthusian theory in the context of climate change.

3.1.3 Theory of Sustainability

The theory of sustainability is a broad concept encompassing elements of human rights, justice and climate and resource policy. The literature community lacks a common agreed upon definition of the theory, however, Jenkins (2009) defines two versions of sustainability. Strong sustainability refers to actively preserving components of ecological systems such as a species or the preservation of ecosystems. Weak sustainability on the other hand refers to the attempt to generate enough benefits such that the discounted value of the future benefits is equal to the value today, leaving future generations in a similar state as us, or put simply, "leaving them no worse-off than we are" today (Jenkins, 2009). He outlines three potential models for sustainability; economic models (such as the Solow model), ecological models (which is the focus of this study) and political models (concerned with aspects of human dignity, justice and human rights). The ecological models for sustainability necessitate the need for biological and ecological goods to be sustained, these include both natural resources and other species that reside within ecological systems that must also be maintained.

The AGW theory of climate change directly threatens the existence of these ecological systems and their goods, implying that one way to achieve sustainability of ecological models is to tackle the problem of climate change. However, Ekardt (2015) emphasizes that sustainability from an ecological perspective is also a broad concept that must take into consideration multiple resources when being assessed (Ekardt, 2015), giving weight to the significance of achieving sustainability of the water-energy-food nexus, which considers three of the most important natural resources for

human development. He further states that the current failure of society to achieve sustainability of these ecological models is hinged on external factors such as politics and economics, where geopolitical tensions inhibit development, and where the success of sustainability is also dependent on the preferences and mindsets of consumers who drive the demand-side of the sustainability equation. He also brings light to the fact that achieving sustainability successfully not only implies enhancing efficiency of resource systems, but also requires societies to detach themselves from the "growth paradigm", where pressures on available resources increase due to the inevitability of population growth, and therefore, leading to unsustainable consumption. This relationship connects the theory of sustainability and the Malthusian theory of population growth. Hence, unless policies and innovations are designed in a truly adaptability sense (adapting to climate change) as well as catering to the challenges of continuous population growth (especially in the developing nations), then all actions taken to mitigate climate change and to achieve sustainability will be inherently maladaptive.

2.2 Empirical literature

2.2.1 Factors Affecting Water Resources

Brown, Hammill and Mcleman (2007) claim that climate change may be considered as a security threat in Africa. This is backed by the increased vulnerability of African communities to natural events such as droughts, as well as the diminishing of water resources accessible to sustainably support these societies. Furthermore, the degradation of land contributes to the lower levels of food security in the continent, where security analysts predict that the threat on food and water security may be the catalyst that leads to tensions between African nations, and eventually, conflict over these resources (Starr, 1991). In 2012, the World Bank published a report that analysed the severity of the effect of climate change on water resources. In this report, Assaf et al. (2012) provide evidence that support the notion that observations of climate change impacts will differ in various geographic regions. They predict that areas such as North Africa will experience decreased runoff by approximately 50%, while other areas in the continent, such as East Africa, will experience an increase in their runoff by the same amount. They also state that the prevalence of recent drought years in Eastern Africa due to climate variability may potentially lead to a large-scale famine in this

part of Africa (Assaf, et al., 2012). This conclusion contributes to the implications of the future climatic state in case study as well, and is relevant to research question 1.

Ternus et al. (2011) follow with an analysis of the effects of urbanisation on the water quality of the Uruguay River basin in Brazil. Water samples were collected from springs and river mouths of different tributaries running across rural and urban towns. These samples were collected and sent to a laboratory for tests, such as pH tests, oxygenation tests and temperature tests. Other data consisted of land use and types of vegetation, which were collected from field observations. The data consisted of bi-monthly data points accumulated between the time period of March 2005 to August 2006. Results revealed that tributaries running through urban towns had higher concentrations of organic content as a result of human activities, such as the use of agricultural fertilizers in farming, which increased levels of water pollutants, namely; chemical oxygen demand (COD), phosphorus and nitrogen. Furthermore, forest-covered land that was cleared to make room for vegetation fields to feed the growing urban population resulted in higher levels of river contamination. This provides evidence for the negative effect of urbanisation on water quality, and hence, on the availability of clean, unpolluted water resources for human use (Ternus, Souza-Franco, Anselmini, Mocellin, & Magro, 2011). Furthermore, this is relevant to our research question 2.

Singh, Mishra, Chowdhary and Khedun (2014) discuss in vast detail the potential impacts of climate variability over time, onto surface water resources. Their study is theoretically underpinned on the AGW theory. They explain how climate change impacts will mostly be felt by the hydrological system, where carbon emissions will either lessen evapotranspiration capacity, or lead to heavy/torrential rainfall and snowmelt, thus resulting in phenomena such as droughts, excess runoff and floods (Singh, Mishra, Chowdhary, & Khedun, 2014). One of the popular methods of analysing the effect of climate change on water resources is the impact assessment methodology. This entails building a hydrologic model, by first defining various scenarios regarding climate change indicators, and thereafter, simulating the behaviour of water resources change in a closed system, such as a river basin, using generation technology (Nan, Bao-hui, & Chun-kun, 2011). Gosain, Rao and Basuray (2006) used this methodology to assess the predicted impacts of climate change onto the hydrological systems of Indian river basins. To simulate the complex hydrological

process of Indian river basins, the authors employ a version of a water balance model called the soil and water assessment tool (SWAT). The data used in the study include; weather data (such as rainfall, temperatures, humidity, solar radiation), soil layers, land cover and use layers (applied to the in-built GIS software in the SWAT model) as well as general terrain data. They simulate two scenarios, a controlled climate scenario and a green-house gas (GHG) scenario, where the GHG scenario consist of analysing the impact of predicted weather patterns on output variables such as soil moisture, runoff and evapotranspiration. Their drought and flood analysis showed that under their GHG scenario, some parts of the country were projected to have intense drought occurrences, while others were simulated to have severe floods, and where both river basins (Krishna and Mahanandi basins) were predicted to have lower levels of runoff in the future (Gosain, Rao, & Basuray, 2006). These results are consistent with studies in other geographic locations (Abbaspour, Faramarzi, Ghasemi, & Yang, 2009), where climate change is seen to have different impacts on different geographic locations. However, the estimated lower runoff in both rivers implies that the negative effect of climate change on the hydrological system is expected to reduce the amount of surface water resources, resulting in lower living standards and increasing strain onto other sectors that are water dependent, and is relevant to our research question 1.

2.2.2 Factors Affecting Energy Resources

Isingoma (2009) emphasizes the hypothesised negative effect of warm years attributable to climate change on the energy sector in Africa, which is also a hypothesis inexplicitly underpinned by the new Malthusian theory and the sustainability theory. He states that most African countries' electricity sectors depend largely on hydro-power due to the existence of hydroelectric hubs located across the continent (Singh, Gowa, Lund, & Mabirizi, 2017). This presents challenges for African economies as climate change gradually depletes available water resources for hydroelectric power plants, leading to a predicted increase in unmet energy-demands in the future. This will not only affect standards of living for future generations, but will also have adverse implications for economic growth and development (Isingoma, 2009).

Vliet et al. (2016) assessed the impacts of droughts and years with higher average temperatures from a more global perspective, using a hybrid hydrological-electricity modelling framework. They integrated water related impacts of climate change into the model to capture the effect of lower water supply on electricity sectors around the

world. The hybrid model assessed this impact by analysing annual and monthly meteorological data (temperatures, precipitation, evapotranspiration), streamflow, water temperatures and power plant characteristics (types of cooling systems used, fuel sources, water usage for cooling), from the period 1981-2010. They reported that power plant utilisation rates significantly reduced in most regions around the world, for both thermoelectric power plants (3.8%) and hydropower plants (5.2%) during drought periods due to the lower levels of water resources available for power plant-cooling purposes (Vliet, Sheffield, Wiberg, & Wood, 2016). This is in line with the complementarities theory that requires sectors to work together optimally, therefore, if the water sector is running at lower capacity (due to drought years), then the electricity sector is expected to suffer due to its water-dependency. This sheds light on the importance for economies to develop adaptation policies that take advantage of other sources of energy that are climate-change resilient, such as solar and wind energy (Fant, Schlosser, & Strzepek, 2015).

The limitations of the hydrological models and the hybrid hydrological-electricity models are built on the fact that the heterogeneity in hydraulic characteristics and water temperatures leads to uncertainties and hence, bias, in the structure and parametrisation of the model, specifically the hydrological and water temperature components of the model.

2.2.3 Factors Affecting Food Resources

Jones and Thornton (2003) investigate future potential impacts of climate change on agricultural systems in developing countries, with a special interest in small-scale farmers. The authors utilise regression models in conjunction with a third-order Markov rainfall model (MarkSim tool) and a maize-crop simulator (CERES-Maize model) to forecast potential 2055 scenarios. Data included daily rainfall data, climate data (precipitation, temperature), soils maps and land-cover data over the period 1920-1990 for countries in Africa and Latin America. They concluded that alleviation of poverty common in small-scale farmers will be challenging in a future that is plagued by climate change. This is because their results predicted a high negative effect of climate change onto subsistence farmlands consisting of maize, as well as a general decrease of maize yields in 2055 by 10%. Furthermore, the authors suggest that these impacts are expected to be felt more severely by other crops that are not as temperature-resilient as the maize crop (Jones & Thornton, 2003). These results are

consistent with Arndt, Farmer, Strzepek and Thurlow (2012) who investigate the forecasted impacts of climate change on the agricultural sector in Tanzania using General Circulation Models (GCM) (Arndt, Farmer, Strzepek, & Thurlow, 2012). The GCM methodology is an extension of a series of models that use an economic model known as the IIASA-Basic Linked System (BLS), which is used to assess the economic impacts of climate change in this case (Schmidhuber & Tubiello, 2007).This implies that climate change is expected to result in serious challenges in food security, over and above the current levels of food insecurity African countries face today. This study is based on the sustainability theory, and is relevant to our case study as well, and to the analysis of research question 1.

Schmidhuber and Tubiello (2007) compare the results of different studies that use BLS based economic models, and they state that all models (B1 SRES, A2 SRES, GCM) report similar results with regards to the quantitative effect of climate change on the number of undernourished people, where undernourished people are expected increase by 5-26% by 2080, hence increasing food insecurity. However, the problem of this study, as well as with most of these economic models is that they isolate the effects of climate change while ignoring other socio-economic components of the complex dynamics of food security, such as stability of food production, availability and access of food to individuals, as well as food utilization. Where *food stability* refers to the variability of food production (yields) contingent on the ever-increasing variability of climate fluctuations. *Food availability* refers to the availability of sufficient quantities of food produce, which is expected to be adversely affected by the changing agro-ecological conditions. *Food access* refers to the ability of consumers to purchase enough food that is of quality. And finally, *food utilization* refers to the capacities in which individuals are able to consume food and benefit from it in the context of health. The challenge that researchers face today is that these socio-economic development factors are difficult to quantify, and hence, most studies tend to qualitatively discuss these issues. The authors state that the effects of socio-economic development on food security is significantly larger than that of climate change, and that the combined impact is expected to be of a higher magnitude than previously reported in studies.

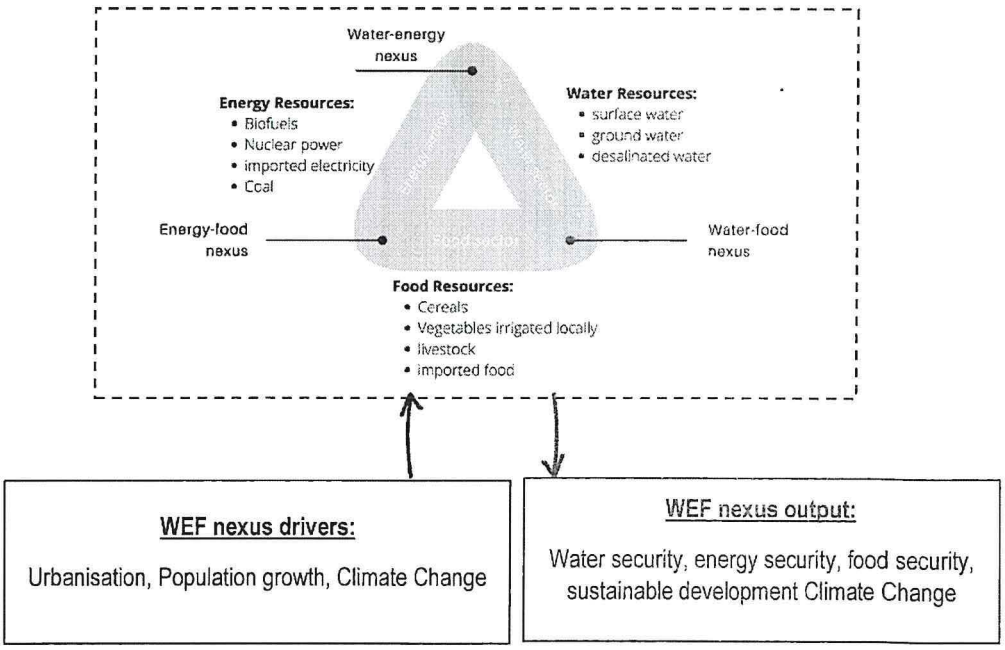
With regards to urbanisation as a driving factor affecting food security, some papers written in the late 20th century held the view that urbanisation would have a positive effect on food consumption, specifically with respect to animal products (Rae A. ,

1998). And this hypothesis was attributed to the fact that urbanisation brought about income and expenditure growth, thus, individuals would be able to consume more animal products as they moved into urban areas and earned higher wages as compared to those who remained in rural areas.

However, the argument quickly shifted as more researchers became more interested in the effects of urbanisation on other agricultural produce such as cereals. Matuschke (2008) investigated how rapid urbanisation would impact food security in developing nations, specifically with regards to countries in Sub-Saharan Africa and South and East Asia. In his assessment, he managed to capture all four dimensions of food security as defined by The Food and Agriculture Organization of the United Nations; food availability, access, safety and stability. He adopted food density maps in 2005, and compared them to projected maps in 2050 (as informed by UN estimates), where food density maps provide insights on which areas are expected to have high demand pressure on food resources as a result of population size and urbanisation. As a result, his datasets included population, urbanisation, population densities and availability of food for 2005. However, he states that food density maps are not popular in the research community due to their heavy reliance on large datasets that may be unavailable in most parts of the developing world, and their inherent bias based on projection assumptions. Despite these limitations, results were still consistent with other papers discussed here, where food density levels grew for all developing countries over the period 2005-2050, implying that food insecurity levels are likely to increase as a result of increased strain on the food sector by an increasing urban population (Matuschke, 2009). Consequently, this is theoretically underpinned by the new Malthusian theory, and is relevant to research question 1 and to our case study.

2.3 Conceptual Framework

Figure 9: WEF conceptual framework with key drivers



After discussing all the individual sectors, we can establish a framework that recognizes the interlinkages between all the three industries. As mentioned before, there exists individual relationships between the sectors, for instance, the energy-water nexus as described in section 2.2. The nexus approach recognizes all these interlinkages, from where sound adaptation strategies can be developed by policy makers for sustainable development of the three sectors. It should be noted that failure of adaptation activities to take advantage of the synergies prevalent in the nexus, may lead to a situation called "maladaptation". IPCC defines maladaptation as:

> *"actions, or inaction that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future"* (Noble, et al., 2014)

Hoff (2011) first coined the term for the WEF nexus, referring to it as the "an approach that integrates management and governance across sectors and scales" in the pursuit for water, energy and food security. Most literature on the topic use similar key terms to describe the "WEF nexus" such as; complex interdependencies, linkages as well as trade-offs and feedbacks between the WEF systems (Galaitsi, Veysey, & Huber-Lee, 2018).

Fan, Lin and Hu (2019) identified a significant causal relationship between urbanisation and the Water-Energy-Food Nexus, where less urbanised areas in China were observed to be more sustainable than urbanised areas, and where this sustainability was subjected more to the water market forces, and less to the food production in the areas. They used a simultaneous equation model to investigate the complex interlinkages between the sectors, and the overall sustainability of the system, which is the first of its kind in terms of methodology in this study area. They explain the hypothesis of the effect of population growth onto WEF resources, which is in line with the Malthusian theory, where an increase in population growth is expected to inevitably increase demand-induced pressure onto existing WEF resource systems, resulting in unsustainable development of future economies (Fan, Lin, & Hu, 2019) (Willis, et al., 2016). The researchers further state that the needs of future and current populations can only be met by increasing the productivity of the current WEF sectors, in-order to combat the increased vulnerability of societies due to climate-change and water-stress- related issues. Some of the modelling techniques defined in the empirical section will be based on the study.

Nair et al. (2014) conducted a global analysis to investigate the link between the water and energy markets, and proposed a framework designed to fill in the gap observed in literature, a holistic and integrated framework for the water-energy nexus (Nair, George, Malanoa, Arora, & Nawarathna, 2014). They explain the vital dependence of global energy security on water-resources, and vice-versa, where global water withdrawals used in industrial related activities (including power plant cooling) were approximately 21% as at 2015, and were highly concentrated in high-income countries such as Spain and Estonia (96%) (Ritchie & Roser, 2018).

The need for a nexus approach inherently supports both the complementarity and sustainability theories, where the interlinkages that exist between WEF sectors necessitate the need for these same sectors to work together towards sustainable development in all economies. IEA (2018) supported this notion by stating that the SDGs related to water and energy present synergies that can be better managed and optimally utilized by policy makers to present opportunities, and give various examples of how potential synergies can be tapped into through the consideration of water supply options in government-led rural electrification projects (IEA, 2018).

2.4 Overview of the Literature

In overall, the literature presented in this review provide evidence for the need for a nexus approach towards tackling both the sustainable development problem, and the climate change problem. As demonstrated, WEF nexus literature consists of multiple reported methodologies that widen the scope of study, most of which tend to be qualitative as opposed of quantitative, emphasizing on physical systems' modelling, governance systems and supported policy and decision making empirical studies, where no single approach can considered as the unified and holistic methodology in this field of research. As previously mentioned, there is limited research done on the quantitative effects of climate change onto the nexus, and where most of the nexus related studies focus only on the interlinkages between the energy and water sector. Due to the complexity of the nexus and the drivers that must be taken into consideration, many researchers have found it challenging to develop holistic frameworks for their methodologies. For the purpose of this study, we will bridge this literature gap by employing the new approach to WEF nexus modelling, the econometric analysis methodology as borrowed from Fan, Lin and Hu (2019), as well as the input-output analysis framework as described in the empirical model section, to quantitatively evaluate the effect of urbanisation, population change and climate change on the WEF nexus in the four countries.

CHAPTER 3: METHODOLOGY

3.0 Introduction

The aim of this chapter is to introduce the methodology to be used in the analysis of the effect of urbanisation, population change and climate change on water resources, and the resulting impacts on the total water, energy and food resources as a result of the complex interlinkages that exist between the three industries. First the chapter will delve into the theoretical models that underpin a majority of the analyses, and then the second part of the chapter will derive the empirical models that will be used in the study in late chapters.

3.1 Research Design

This study establishes the impact of urbanisation, population change and climate change on the WEF nexus in our four countries by using both econometric modelling (panel data analysis) and input-output analysis techniques (Karnib (2017); Leontief (1986)). To observe the effects of urbanisation, population change and climate change on WEF nexus, we focus primarily on the urbanisation, population change and climate change effect on the water sector, using panel data analysis. The variable, water demand, is used as a dependent variable for the panel data model, while variables: population, urbanisation, food security, energy security, water security, incomes and climate change are used as explanatory variables. As for the nexus model, we will use WEF final demand variables as outputs and WEF resources as inputs in the input-output analysis framework. This paper adds onto the framework proposed by Karnib (2017) by including the effect of climate change on water resources, and assessing the impact on the coefficients of the WEF nexus model.

3.2 Theoretical Model

3.2.1 Climate change theoretical model

The theoretical model underpinning the climate econometric analysis in this study is derived from Hsiang (2016). Climate change is a phenomenon that also affects the short-term weather patterns of a given geographic location. In his paper, Hsiang (2016) states that the climate change variable is a vector of other weather-related random variables collected over time. Hence, the climate change (x_{it}) variable can be expressed as:

$$x_{it} = [temperature_{it}, rainfall_{it}, wind_{it}, cloudcover_{it}, \ldots.] \quad (3.1)$$

However, we can also express equation 3.1 as a joint probability distribution function (Hsiang, 2016) defined as:

$$x_{it} = \omega(C_{iT}) \quad \forall\, t \in T \tag{3.2}$$

Where;

C_{iT} is a vector of all the estimated weather factors/parameters statistically affected by climate change.

$\omega(C_{iT})$ represents the probability distribution function that captures the actual weather patterns that occur conditional on the characteristics of the climate defined in C_{iT}.

To capture the effect of climate change on water, we employ a multivariate econometric model (Fan, Lin, & Hu, 2019):

$$Y_{it} = \alpha + \beta x_{it} + \delta z_{it} + \varepsilon_{it} \tag{3.3}$$

Where;

Y_{it} is the dependent variable for cross-section i at time t.

x_{it} is a climate change variable defined in equation 3.2

z_{it} represents a vector of other explanatory variables that might be related to x_{it} for cross-section i at time t.

3.2.2 WEF nexus theoretical model

This WEF nexus analysis section uses the input-output theory (inter-industry analysis) developed by Leontief (1986), which employs the use of matrices to quantitatively capture the interdependencies that exist between sectors (Leontief, 1986). We apply the modified input-output model known as the Q-model as borrowed from Karnib (2016), where the sum of final demand for the water, energy and food resources (y) (by households, industries, agricultural units and the whole economy in general) and the inter-sectoral usage of the three sectors (Z) (or the quantities used within the WEF interlinkages) equals the total quantity of available resources (x) (water, energy and food resources) in the balance-equation (Eqn. 3.7). The input-output analysis framework also considers the inflows and outflows of resources from the unit (the

country) that occur due to the dynamic socio-economic systems that exist today (Karnib, 2017).

$$Z + y = x \tag{3.7}$$

Where;

Z is the matrix for inter-sectoral usage,

y is the vector for the quantities of final demand,

x is the vector for total quantity of available resources.

The maximum amount of resources that a country can consume (either through final demand or through the interlinkages) is equals to the total amount of resources available to the country, and these resources can either be internally produced or externally produced and imported to the country. As a result, the relationship must net-off all imports and exports of WEF resources in order to derive at the total amount consumed by the country. In addition to this, the final demand quantities are driven by factors such as urbanization, population and climate change.

3.3 Empirical Model

3.3.1 Climate change and water demand

First, to capture the effect of climate change, we define a panel data model to estimate the effect of the three key drivers on water resources in the ecosystem:

$$WD_{i,t} = B_0 + B_1 POP_{i,t} + B_3 URB_{i,t} + B_4 SEC_{F_{i,t}} + B_5 SEC_{E_{i,t}} + B_6 SEC_{W_{i,t}} + B_7 INC_{i,t} + B_8 x_{it} + \mu_i + \varepsilon_{it} \tag{3.8}$$

Where;

WD is annual water demand

POP is total population in the country

URB is total urban population

SEC_W is water security index

SEC_F is a food security index

SEC_E is an energy security index

INC refers to household income, captured by GDP per capita

x_{it} is the climate change variable described in equation 3.2

ε_t is the error term that includes unobserved variables

The panel data modelling approach was chosen due to the insufficient time-series data on one individual country, thus, combining countries to form a panel is more practical. Furthermore, the panel data approach is adopted to contribute to the lack of holistic WEF-related models that use econometric analysis in the literature community. The reason for estimating only one model (Eqn 3.8) is because we assume that the three key drivers (urbanisation, population growth and climate change) will impact water resources directly, while other resources (energy and food) will be impacted indirectly. For the case of climate change, this is based on the assumption that agricultural lands are irrigated using surface water resources (lakes and rivers) or ground water resources (aquifers), and not from rain. As a result, only water resources are affected by rising temperatures and less rainfall, translated into evapotranspiration and low discharge/runoff, which in turn affect the yields of cereals harvested, and the amount of hydropower generated in the country.

3.3.2 The Q-model

Using the Q-model (Eq. 3.8) estimated by Karnib (2016), we can further the study by defining three simultaneous input-output balance equations which incorporate the interdependencies: water-energy, water-food, energy-water, energy-energy, energy-food, food-energy and food-food. The Z matrix in the Q-model that represents all the interdependencies that exist within the WEF nexus is replaced by the individual interdependencies, however, we omit the food for water and water for water interlinkages due to the insignificance of the relationships.

$$\sum_{j=1}^{n} z_{ij}^{w\_e} + \sum_{j=1}^{d} z_{ij}^{w\_f} + y_i^w = x_i^w \qquad i = 1,2,\ldots,h \qquad (3.9)$$

$$\sum_{j=1}^{h} z_{ij}^{e\_w} + \sum_{j=1}^{n} z_{ij}^{e\_e} + \sum_{j=1}^{d} z_{ij}^{e\_f} + y_i^e = x_i^e \qquad i = 1,2,\ldots,n \qquad (4.0)$$

$$\sum_{j=1}^{n} z_{ij}^{f\_e} + \sum_{j=1}^{d} z_{ij}^{f\_f} + y_i^f = x_i^f \qquad i = 1,2,\ldots,d \qquad (4.1)$$

Where:

h is the amount of water resources that exist internally, or inflows

d is the amount of food resources inflows

n is the amount of energy resources inflows

x_i^w is the total consumption of the i^{th} water resource

x_i^e is the total consumption of the i^{th} energy resource

x_i^f is the total consumption of the i^{th} food resource

y_i^w is the total demand for the i^{th} water resource

y_i^e is the total demand for the i^{th} energy resource

y_i^f is the total demand for the i^{th} food resource

$z_{ij}^{e\_w}$ is the consumption of energy resource i by the water resource j

$z_{ij}^{e\_f}$ is the consumption of energy resource i by the food resource j

$z_{ij}^{e\_e}$ is the consumption of energy resource i by the energy resource j

$z_{ij}^{w\_e}$ is the consumption of water resource i by the energy resource j

$z_{ij}^{w\_f}$ is the consumption of water resource i by the food resource j

$z_{ij}^{f\_e}$ is the consumption of food resource i by the energy resource j

$z_{ij}^{f\_f}$ is the consumption of food resource i by the food resource j

The following intensity coefficients described by Karnib (2016) are introduced into the three balance equations so as to convert the equations into an active inter-related system of WEF nexus resources which have an effect each other, both directly and indirectly:

$$b_{ij}^{e\_w} = \frac{z_{ij}^{e\_w}}{x_j^w} \qquad b_{ij}^{w\_f} = \frac{z_{ij}^{w\_f}}{x_j^f}$$

$$b_{ij}^{e\_e} = \frac{z_{ij}^{e\_e}}{x_j^e} \qquad b_{ij}^{f\_e} = \frac{z_{ij}^{f\_e}}{x_j^e}$$

$$b_{ij}^{e\_f} = \frac{z_{ij}^{e\_f}}{x_j^f} \qquad b_{ij}^{f\_f} = \frac{z_{ij}^{f\_f}}{x_j^f}$$

$$b_{ij}^{w\_e} = \frac{z_{ij}^{w\_e}}{x_j^e}$$

Where;

x_i^w is the total consumption of the j^{th} water resource

x_i^e is the total consumption of the j^{th} energy resource

x_i^f is the total consumption of the j^{th} food resource

As a result, the Q-model becomes:

$$\sum_{j=1}^{n} b_{ij}^{w\_e} x_j^e + \sum_{j=1}^{d} b_{ij}^{w\_f} x_j^f + y_i^w = x_i^w$$

$$i = 1,2,\ldots,h \qquad (4.2)$$

$$\sum_{j=1}^{h} b_{ij}^{e\_w} x_j^w + \sum_{j=1}^{n} b_{ij}^{e\_e} x_j^e + \sum_{j=1}^{d} b_{ij}^{e\_f} x_j^f + y_i^e = x_i^e$$

$$i = 1,2,\ldots,n \qquad (4.3)$$

$$\sum_{j=1}^{n} b_{ij}^{f\_e} x_j^e + \sum_{j=1}^{d} b_{ij}^{f\_f} x_j^f + y_i^f = x_i^f$$

$$i = 1,2,\ldots,d \qquad (4.4)$$

The new Q-model (equations 4.3, 4.3, 4.4) can now be reduced into simpler matrix representation:

$$Bx + y = x \qquad (4.5)$$

Where B can be treated as the technology matrix for the WEF nexus.

The block form of equation 4.5 can be written as:

$$\begin{bmatrix} 0 & B^{w\_e} & B^{w\_e} \\ B^{e\_w} & B^{e\_e} & B^{w\_f} \\ 0 & B^{f\_e} & B^{f\_f} \end{bmatrix} \begin{bmatrix} x_j^w \\ x_j^e \\ x_j^f \end{bmatrix} + \begin{bmatrix} y_i^w \\ y_i^e \\ y_i^f \end{bmatrix} = \begin{bmatrix} x_i^w \\ x_i^e \\ x_i^f \end{bmatrix} \qquad (4.6)$$

As a result, we can deduce the final input-output analysis equation by employing Leontief's inverse function (Miller & Blair, 2009), which is also referred to as the total requirements matrix, and is the inverse of the technology matrix B. .

$$L = \begin{bmatrix} 0 & B^{w\_e} & B^{w\_e} \\ B^{e\_w} & B^{e\_e} & B^{w\_f} \\ 0 & B^{f\_e} & B^{f\_f} \end{bmatrix}^{-1} \qquad (4.7)$$

$$L \begin{bmatrix} y_i^w \\ y_i^e \\ y_i^f \end{bmatrix} = \begin{bmatrix} x_i^w \\ x_i^e \\ x_i^f \end{bmatrix} \qquad (4.8)$$

Where equation 4.7 is the final input-output analysis equation (Karnib, 2017; Leontief, 1986) that explains the relationship between final demands for the WEF resources (y) and the total available units of WEF resources in the ecosystem (or the total amount of resources consumed) (x). The model can also be used to inform policy makers on the amount of internal resources (x) that are needed to sustainably satisfy final demand (y) in a given year.

And we can further derive equation (Karnib, 2017)that quantifies the impact of total demand on the WEF resources as:

$$\Delta Z = B\Delta\widehat{L}y \qquad (4.9)$$

Where equation 4.9 assesses the impact of a change in total demand on the intersectoral quantities exchanged.

By combining both models, we can analyse the direct, indirect and total effects of climate change on the total available WEF resources, where equation 3.8 will inform us on the relationship between climate change (precipitation and temperatures) and total water demanded (y_i^W from Eqn. 4.8). From this climate total effect, we can then arrive at a general impact of climate change on water demand over time (in percentage form). Afterwards, we can apply this impact of climate change to equation 4.9, where for example, if we arrive at a 15% impact of climate change on water demanded, we multiply that 15% to the right-hand side of equation 4.9 to generate the overall effect on the amount of intersectoral usage changes in the WEF nexus.

3.4 Definition of Variables

We start by defining the variables in the first model (panel data model) as seen in table 2. We then proceed to define the variables in the Q-model in table 4. The security indices were created from scratch using guidelines from Nhamo et. al (2020), Global Energy Institute and FAO and are described further in table 3.

Table 2: definition of variables

Variable	Definition	Scale of measurement	Expected relationship with dependent variable	Authors
Water Demand (WD)	This is the final demand for water resources in the economy, by households, industries and agriculture, both local and external. The proxy variable for this will be water withdrawals.	Continuous data across 4 countries (annual) measured in Cubic metres, collected from 2000 to 2019.	Positive	none
Urbanisation (URB)	This is the urbanisation rate of countries	Percentage, calculated from change in urban population data collected from 2000 to 2019.	Positive	Fan, Lin and Hu (2019)
Population growth (POP)	This is the population growth rate of the four countries.	Percentage growth rate, calculated from change in population data collected from 2000 to 2019.	Positive	none
Food security (SEC_F)	This is the food security index.	Discrete data measured by Scale of 1-5	Negative	Nhamo et al. (2020)
Energy security (SEC_E)	This is the energy security index.	Discrete data measured by Scale of 1-5	Positive/Negative	Nhamo et al. (2020)
Water security (SEC_W)	This is the water security index.	Discrete data measured by Scale of 1-5	Positive	Nhamo et al. (2020)

Table 3: WEF Security indices variables

Water security index	**Indicators**	**Data source**
Water access	Population with access to safe drinking water	World Bank Database
Water productivity	Proportion of agricultural output to water withdrawals	World Bank Database and AQUASTAT (FAO)
Environmental flows	Renewable water resources (RWR) minus environmental water requirements plus total water withdrawn	AQUASTAT (FAO)
Water availability	(RWR-Freshwater withdrawals)/RWR	AQUASTAT (FAO)
Energy security index		
Energy import exposure	Oil, natural gas and coal import proportion to exports	IEA
Energy use intensity	Energy consumption per capita and energy intensity	IEA
Environmental risk metrics	Carbon dioxide emissions, CO2 GDP intensity	IEA
Food security index		
Food affordability	Food production value, cereal import dependency ratio, value of imports	FAO and World Bank Database
Food availability	Per capita food supply variability, percent of arable land equipped for irrigation, Per capita food production variability	FAO and World Bank Database
Food quality and safety	Average dietary energy supply adequacy, prevalence of undernourishment, average protein supply	FAO and World Bank Database

The input variables used in the Leontief model (Q-model) are presented in table 4 and all variables are as defined by Karnib (2017).

Table 4:WEF Security indices variables

Water inflows	**Symbol**	**Scale of measurement**	**Data Source**
Total renewable surface water	W1	Cubic metres	AQUASTAT (FAO)
Total renewable ground water	W2	Cubic metres	AQUASTAT (FAO)
Desalinated water produced	W3	Cubic metres	AQUASTAT (FAO)
Treated municipal wastewater	W4	Cubic metres	AQUASTAT (FAO)
Energy inflows			
Imported oil products	E1	Tera-joules	IEA
Imported electricity	E2	Tera-joules	IEA
Imported natural gas	E3	Tera-joules	IEA
Electricity (fossil fuels)	E4	Tera-joules	IEA

Electricity (Nuclear)	E5	Tera-joules	IEA
Electricity (Renewable resources)	E6	Tera-joules	IEA
Food inflows			
Cereals	F1	Tonnes	FAO
Fruit	F2	Tonnes	FAO
Vegetables	F3	Tonnes	FAO
Livestock-eggs	F4	Tonnes	FAO
Livestock-meat	F5	Tonnes	FAO
Livestock-milk	F6	Tonnes	FAO
Aquaculture	F7	Tonnes	FAO
Imported agricultural products	F8	Tonnes	FAO
Imported livestock products-meat	F9	Tonnes	FAO
Imported livestock products-milk	F10	Tonnes	FAO
Imported livestock products-eggs	F11	Tonnes	FAO

3.5 Data Types and Sources

The data used in analysis of the first model in the study, the panel data model, are collected from the World Bank database, The World Bank Climate Change Knowledge Portal and the Aquastat database supported by the Food and Agricultural Organization of the United Nations (FAO).

The World Bank provides data on the GDP per capita, urban population, as well as total population (2000-2019). The World Bank Climate Change Knowledge Portal provides data on rainfall and temperatures from 1901 to 2016. And the Aquastat database provides further data on water consumption in the form of water withdrawals.

The data used in the analysis of the second model, the Q-model, are collected from Aquastat database, the FAO database and the IEA database. The Aquastat database will be used to collect data on water resources for two years (1995 and 2018), variables include surface water withdrawals, ground water withdrawals, imported and exported water, and desalination water production. The FAO database will be used to collect data on food resources, such as crop production, animal production, livestock production, cereals imports and livestock imports. The IEA database will be used to collect data on renewable energy production, electricity production, nuclear power production, imported electricity, coal production and natural gas production.

3.6 Data Analysis

3.6.1 Preliminary tests

i. Stationarity tests

These panel unit root tests will be performed to assess whether the variables in the model (Eqn 3.2) are stationary, and will inform us on which variables to use in the fixed/random effects model. This can be performed using the Fisher-type unit root test, where the hypothesis tests are described below:

$$H_0: unit\ root\ problem\ present$$

$$H_a: unit\ root\ problem\ absent$$

ii. Autocorrelation tests

These tests are used to investigate whether the panel cross-sections are correlated with each other. Evidence of autocorrelation will inform us on whether a dynamic panel data approach is more suitable than the static panel data model.

$$H_0: Autocorrelation\ is\ not\ significant$$

$$H_a: unAutocorrelation\ is\ significant$$

iii. Heteroskedasticity tests

These tests are used to investigate whether heteroskedastic robust standard errors are necessary in estimating the fixed/random effects model. The test can also inform us further on whether or not the dynamic panel data approach should be adopted.

$$H_0: panel\ data\ errors\ are\ homoskedastic$$

iv. Hausman test

The Hausman test is used to investigate whether the independent variables of the panel are correlated with the unobserved heterogeneity. This test will be used to choose between the fixed effects or random effects model for our first model.

$$H_0: Random\ effects\ model\ is\ suitable$$

$$H_a: endogeneity\ between\ regressors\ and\ unobserved\ heterogeneity\ exists,$$

$$Fixed\ effects\ model\ is\ more\ suitable$$

3.6.2 Diagnostic tests

v. Sargan and Hansen test.

These tests are used to check for validity of instruments used in the dynamic panel data model specified.

$$H_0: overidentification\ restrictions\ are\ valid$$

vi. Arellano-Bond serial correlation test.

This test is used to investigate whether serial correlation between first difference error terms exists in the model specified. There are two levels to the AR test, AR order 1 and AR order 2 tests. We shall focus on the results of the AR(2) test simply because its results are more relevant than the results of the first order AR test.

$$H_0: First\ difference\ errors\ are\ not\ serially\ correlated$$

CHAPTER 4: EMPIRICAL FINDINGS

4.0 Introduction

This chapter presents the findings of the study. The descriptive statistics for both models (equation 3.8 and 4.8) are presented in section 4.1, the diagnostic tests for the econometric model (equation 3.8) are presented in section 4.2, and the empirical results for the econometric analysis and the input-output analysis are presented in section 4.3.

4.1 Descriptive statistics

Table 6 displays the summary statistics for the variables in our first model, arranged by country. The table suggests that China has on average higher water consumption levels (logged) than the other countries, with low volatility relative to the rest of the panel, with a skewness of -0.4 and a kurtosis of 1.536 over the 2 decades (2000-2019). Spain's logged GDP per capita is higher than that of other countries, averaging at 10.173 and with a volatility of 0.25 which is relatively low compared to that of China which stands at 0.83. Spain also exhibits the skewness and kurtosis measures of logged GDP per capita of -1.4 and 3.6 respectively, which are relatively poor normality results compared to other countries in the panel.

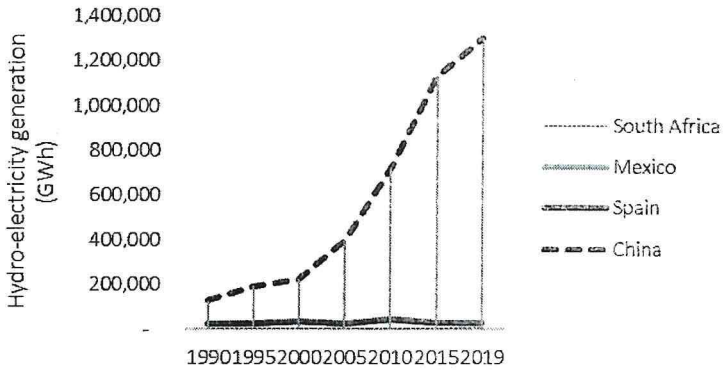
China's logged urban population is the highest at 20, and also recorded the highest volatility in urban population over the period (0.19) (with a skewness and kurtosis of -0.2 and 1.9 respectively. The high urban population can be attributable to the rapid increase in population in the country and the support of urbanisation by the economy. Our climate related variables over the last 18 years suggest that China's temperatures and rainfall volumes are rising more on average at 0.6% and 1.4% per year respectively, with skewness measures of -0.6 and 0.5 respectively, and kurtosis measures of 1.7 and 2.2 respectively. South Africa's rainfall is reducing annually by an average of 0.3% which is consistent with the research documented in chapter one, with skewness and kurtosis measures of 0.7 and 2.5. Spain and South Africa record the highest levels of volatility in rainfall change (both at 0.2), while China recorded the highest volatility in temperature change (0.047) over the 18-year period, with skewness and kurtosis measures of -0.6 and 1.7. South Africa experienced the highest maximum rainfall growth over the period while China experienced the highest maximum temperature increase over the period, which is consistent with the hypothesis that less developed nations will experience the adverse effects of climate

change more intensely.

Mexico has on average higher levels of water and energy security, while Spain has on average higher levels of food security than the rest of the panel in the study. The high levels of water security in China could be attributed to the high levels of water consumption. With regards to urban population, China has the highest average annual growth rate at 3.3%, followed by South Africa at 2.3%. China also has the highest volatilities in all three WEF security indices which suggests that these sectors may not be efficiently integrated in order to maximise on synergies and improve the security of the sectors.

Tables 6 also presents the summary statistics for the various input variables used in the estimation of the Q-model for the four countries. Results suggest that China has more water resources (surface water, ground water and treated municipal water) as compared to the other countries in this study, this may explain the higher generation of hydropower as seen in figure 10.

Figure 10:Hydro-electricity generation by country



With regards to the energy sector, China produces and imports 15 times more energy as compared to Mexico, 22 times more energy than South Africa and 19 times more energy than Spain; where approximately 76% of China's energy is supplied from fossil fuels, followed by renewable energy (19%). On the other hand, electricity generated using fossil fuels accounts for 93%, 69% and 48% of the total energy inflows in South Africa, Mexico and Spain, respectively. The food sectors of both Spain and China rely heavily on the local agricultural production of vegetables (57% and 96% respectively).

However, South Africa relies more on the local production of meat (54%), while Mexico relies on the local production of milk (43%).

These statistics give light to the potential interconnectedness of the three sectors in the four countries, where both the energy and food sectors are heavily reliant on sources that are water-dependent, namely; fossil fuel energy, vegetable crop production and livestock rearing for milk production).

Table 5: Descriptive statistics of variables used in both models.

		Mean	*Standard deviation*	*N*	*Skewness*	*Kurtosis*
China						
Log Water Demand	**logWD**	6.363	.034	20	-.387	1.536
Log GDP per capita	**logGDP**	8.196	.832	20	-.302	1.585
Log Urbanisation	**logUP**	20.271	.193	20	-.221	1.85
Temperature growth	**gTEMP**	1.006	.047	19	-.056	1.658
Rainfall growth	**gRAIN**	1.014	.096	19	.513	2.202
Water security index	**WI**	3.08	.379	20	.219	1.356
Energy security index	**EI**	3.228	.244	20	.105	1.996
Food security index	**FI**	3.03	.269	20	-.661	2.135
Total water inflows		*Mean*	*Standard deviation*	*N*	*Skewness*	*Kurtosis*
Total renewable surface water	**W1**	2,739.00	0.00	34	-	-
Total renewable groundwater	**W2**	828.80	0.00	34	-	-
Desalinated water produced	**W3**	0.01	0.00	34	-	-
Treated municipal wastewater	**W4**	3.56	0.02	34	2.24	5
Total Energy Inflows						
Imported oil products	**E1**	35,343.28	16,911.31	48	0.09	-1.38
Imported electricity	**E2**	325.88	205.84	48	-0.50	-2.66
Imported Natural gas	**E3**	15,685.41	26,729.9	48	2.15	4.67
Electricity (fossil fuels)	**E4**	2,157,373	1,438,118	48	0.65	-1.13
Electricity (Nuclear)	**E5**	68,172.93	77,145	48	1.98	4.06
Electricity (Renewable resources)	**E6**	547,418.42	468,975	48	1.53	2.06
Total Food Inflows						
Cereals	**F1**	17,283.90	3,443.86	58	1.412845	3.06
Fruit	**F2**	918,821.78	132,638	58	0.12507	0.06
Vegetables	**F3**	74,366,960	7,963,723	58	-0.53575	0.01
Livestock-Eggs	**F4**	393,797.31	97,704.36	58	0.608589	-3.33
Livestock-Meat	**F5**	794,508.93	248,672	58	1.278323	0.42

Livestock-Milk	**F6**	1,035,325.67	331,046	58	1.692483	2.56
Aquaculture	**F7**	1,033,902.93	189,166	58	0.52	0.72
Imported Agricultural products	**F8**	16,094.84	6,445.33	58	2.035815	4.19
Imported livestock-Meat	**F9**	135,474.71	51,633.61	58	2.224209	4.96
Imported livestock-Milk	**F10**	4,241.21	1,428.12	58	2.057449	4.27
Imported livestock-Eggs	**F11**	3,619.17	1,363.02	58	2.234723	4.99
Mexico						
Log Water Demand	**logWD**	4.389	.07	20	-.126	1.928
Log GDP per capita	**logGDP**	9.099	.138	20	-.367	1.808
Log Urbanisation	**logUP**	18.288	.104	20	-.083	1.757
Temperature growth	**gTEMP**	1.001	.016	19	4.115	17.978
Rainfall growth	**gRAIN**	1.013	.126	19	.656	2.826
Water security index	**WI**	3.749	.061	20	-1.794	4.682
Energy security index	**EI**	3.411	.154	20	-1.221	3.146
Food security index	**FI**	2.656	.11	20	-.197	2.284
Total water inflows		*Mean*	*Standard deviation*	*N*	Skewness	Kurtosis
Total renewable surface water	**W1**	402.90	0.00	34	-	-
Total renewable groundwater	**W2**	150.00	0.00	34	-	-
Desalinated water produced	**W3**	0.03	0.00	34	0.61	2.23
Treated municipal wastewater	**W4**	0.52	0.05	34	-2.08	-2.23
Total Energy Inflows						
Imported oil products	**E1**	14,020.65	2,027.74	48	1.10	0.64
Imported electricity	**E2**	59.59	8.57	48	0.82	1.35
Imported Natural gas	**E3**	6,783.96	1,564.40	48	1.87	1.81
Electricity (fossil fuels)	**E4**	129,999.52	11,949.54	48	-0.22	-1.41
Electricity (Nuclear)	**E5**	5,383.08	699.12	48	0.55	-0.66
Electricity (Renewable resources)	**E6**	31,869.45	1,611.22	48	1.24	-1.64
Total Food Inflows						
Cereals	**F1**	1,832.91	297.32	58	0.45	-0.14
Fruit	**F2**	245,088.17	22,678.88	58	-0.50	-1.52
Vegetables	**F3**	292,668.62	39,687.55	58	-0.45	-0.87
Livestock-Eggs	**F4**	1,259,659.14	407,325	58	1.68	1.68
Livestock-Meat	**F5**	2,665,611.72	986,107	58	1.75	1.75
Livestock-Milk	**F6**	3,624,559.09	1,315,603	58	1.94	1.94
Aquaculture	**F7**	56,057.55	9,422.69	58	0.77	0.45
Imported Agricultural products	**F8**	35,338.05	11,309.57	58	-0.26	-0.26
Imported livestock-Meat	**F9**	135,474.71	51,633.61	58	2.22	1.49

Imported livestock-Milk	**F10**	23,731.79	7,612.01	58	-0.19	-0.19
Imported livestock-Eggs	**F11**	5,612.52	2,223.63	58	2.24	2.24
South Africa						
Log Water Demand	**logWD**	2.734	.155	20	.872	2.673
Log GDP per capita	**logGDP**	8.577	.332	20	-1.16	3.286
Log Urbanisation	**logUP**	17.269	.134	20	.031	1.762
Temperature growth	**gTEMP**	1.004	.014	19	-3.367	13.93
Rainfall growth	**gRAIN**	.997	.206	19	.656	2.509
Water security index	**WI**	2.691	.147	20	-1.09	3.186
Energy security index	**EI**	3.405	.195	20	.867	2.728
Food security index	**FI**	2.322	.124	20	-.206	1.839
Total water inflows		*Mean*	*Standard deviation*	*N*	Skewness	Kurtosis
Total renewable surface water	**W1**	49.55	0.00	34	-	-
Total renewable groundwater	**W2**	4.80	0.00	34	-	-
Desalinated water produced	**W3**	0.02	0.00	34	-	-
Treated municipal wastewater	**W4**	0.36	0.11	34	0.61	0.27
Total Energy Inflows						
Imported oil products	**E1**	-	-	48		
Imported electricity	**E2**	464.37	75.96	48	-1.19	-1.21
Imported Natural gas	**E3**	791.42	185.47	48	0.53	0.53
Electricity (fossil fuels)	**E4**	121,548.85	15,359.96	48	-0.68	-2.07
Electricity (Nuclear)	**E5**	6,939.56	879.84	48	0.81	-2.04
Electricity (Renewable resources)	**E6**	1,330.99	284.85	48	2.05	1.94
Total Food Inflows						
Cereals	**F1**	12,127.78	1,093.30	58	-0.25	-1.56
Fruit	**F2**	51,280.66	2,043.16	58	0.86	-1.93
Vegetables	**F3**	254,623.00	10,514.81	58	0.74	-0.25
Livestock-Eggs	**F4**	4,417,583.34	1,509,527	58	1.89	1.89
Livestock-Meat	**F5**	5,744,517.69	1,964,478	58	1.79	1.79
Livestock-Milk	**F6**	-	-	58	-	-
Aquaculture	**F7**	2,710.20	358.12	58	0.43	-0.57
Imported Agricultural products	**F8**	153,148.88	48,810.03	58	2.15	2.15
Imported livestock-Meat	**F9**	-	-	58	-	-
Imported livestock-Milk	**F10**	43,369.95	15,486.33	58	1.81	1.81
Imported livestock-Eggs	**F11**	5,901.55	2,272.31	58	2.12	2.12

Spain						
Log Water Demand	**logWD**	3.542	.066	20	-1.367	3.622
Log GDP per capita	**logGDP**	10.173	.247	20	-1.305	3.587
Log Urbanisation	**logUP**	17.377	.067	20	-.788	2.148
Temperature growth	**gTEMP**	1.002	.034	19	-2.54	10.566
Rainfall growth	**gRAIN**	1.021	.212	19	.337	1.984
Water security index	**WI**	2.977	.117	20	.043	1.466
Energy security index	**EI**	2.913	.034	20	-.621	3.989
Food security index	**FI**	3.21	.207	20	-.442	2.261
Total water inflows		*Mean*	*Standard deviation*	*N*	Skewness	Kurtosis
Total renewable groundwater	**W2**	29.90	0.00	34	-	-
Desalinated water produced	**W3**	0.12	0.01	34	-	-
Treated municipal wastewater	**W4**	0.39	0.02	34	2.00	2.18
Total Energy Inflows						
Imported oil products	**E1**	-	-	48		
Imported electricity	**E2**	578.24	71.13	48	-0.14	-0.72
Imported Natural gas	**E3**	13,244.22	1,846.7	48	-0.36	-0.03
Electricity (fossil fuels)	**E4**	96,513.08	6,394.3	48	0.29	-0.88
Electricity (Nuclear)	**E5**	41,940.88	3,302.1	48	-0.32	-2.17
Electricity (Renewable resources)	**E6**	47,450.18	3,982.3	48	1.70	1.13
Total Food Inflows						
Cereals	**F1**	15,557.07	2,651.9	58	1.64	0.90
Fruit	**F2**	104,677.98	5,983	58	-0.74	-0.93
Vegetables	**F3**	459,849.12	9,405	58	1.54	-1.64
Livestock-Eggs	**F4**	28,472.25	17,038.69	58	-	-
Livestock-Meat	**F5**	128,558.5	41,639.46	58	-	-
Livestock-Milk	**F6**	479,323.5	83,634.79	58	-	-
Aquaculture	**F7**	-	-	58	1.35	-1.70
Imported Agricultural products	**F8**	-	-	58	-	-
Imported livestock-Meat	**F9**	-	-	58	-	-
Imported livestock-Milk	**F10**	251,220.3	41,335.27	58	-	-
Imported livestock-Eggs	**F11**	-	0	58	1.90	2.15

4.2 Regression results

The results for the econometric model and the Q-model are discussed in "water demand panel data model" and "Q-model results", respectively. We start this section with preliminary tests for the econometric model before reporting the results of the model.

Stationarity tests

According to the stationarity panel tests (fisher type), we see that the only variables that need to be differenced are the temperature, water index and energy index variables. These are the variables that will be used to estimate our fixed/random effects models. Results are reported in table 8.

Table 6: Stationarity tests results

Variable	Integration order	p-value	Conclusion
Log(Water demand)	I(0)	0.0002	Stationary
Log(GDP per cap.)	I(0)	0.0086	Stationary
Log(Urban pop)	I(0)	0.0000	Stationary
Population	I(0)	0.0059	Stationary
Log(Temp) growth	I(0)	0.0051	Stationary
Log(Rain)	I(0)	0.0000	Stationary
Water index growth	I(0)	0.0015	Stationary
Energy index growth	I(0)	0.0000	Stationary
Food index	I(0)	0.0373	Stationary

Fixed and time-effects.

Based on the p-values for both the fixed and time effects tests, we reject the null hypothesis where all individual firm effects and time effects are zero, hence, we conclude that unobserved heterogeneity exists and that time effects are significant. As a result, a two-way fixed effects model may be more appropriate as specified in the equation below. Results are reported in table 9:

Table 7: Fixed and time effects test results

Dependent variable	Independent variables	p-value fixed effects	p-value time effects	Conclusion
Log(Water demand)	Log(GDP), Log(UP), POP, gTemp, gRain, gWI, gEI, FI	0.0000	0.0000	Use a two-way fixed effects model
Log(Water demand)	Log(GDP) log(UP) POP gTEMP gRAIN gIMPORT gEUSE gENV gWACCESS gWPROD gENVFLOW gWAVAIL gFOODAFF FOODAVAIL gFOODQS	0.0000	0.0000	Use a two-way fixed effects model

$$logWD_{i,t} = \beta_0 + \beta_1 logGDP_{i,t} + \beta_0 logUP_{i,t} + \beta_0 gTEMP_{i,t} + \beta_0 logRAIN_{i,t} + \beta_0 gWI_{i,t} + \beta_0 gEI_{i,t} + \beta_0 FI_{i,t} + \mu_i + \varepsilon_t + \epsilon_{i,t}$$

Hausman test

We use the Hausman test to confirm whether the fixed effects model is a more suitable model for our panel. Results are consistent with the fixed effects tests above and are presented in table 10.

Table 8: Hausman test results

Model	Dependent variables	Independent variables	p-value	Conclusion
Restricted	Log(Water demand)	Log(GDP), Log(UP), POP, gTemp, Log(Rain), gWI, gEI, FI	0.0000	Unobserved heterogeneity significant, FE model suitable
Unrestricted	Log(Water demand)	Log(GDP), Log(UP), POP, gTemp, Log(Rain), gIMPORT, gEUSE, gENV, gWACCESS, gWPROD, gENVFLOW, gWAVAIL, gFOODAFF, FOODAVAIL, gFOODQS	0.0000	Unobserved heterogeneity significant, FE model suitable

Auto-correlation and heteroskedasticity tests

The Woolridge test for serial correlation and the Wald test for heteroskedasticity indicate that a system GMM is the more appropriate dynamic panel data analysis technique to adopt, since both tests reject the null hypotheses. The results are presented table 6.

Table 9: serial correlation and heteroskedasticity tests

Model	Dependent variable	Independent variable	p-value serial correlation test	p-value heteroskedasticity test	Conclusion
Restricted	Log(Water demand)	Log(GDP), Log(UP), POP, gTemp, Log(Rain), gWI, gEI, FI	0.0001	0.0000	Panel is heteroskedastic and serially correlated, heteroskedastic-robust standard errors should be used in system GMM.
Unrestricted	Log(Water demand)	Log(GDP), Log(UP), POP, gTemp, Log(Rain), gIMPORT, gEUSE, gENV, gWACCESS, gWPROD, gENVFLOW, gWAVAIL, gFOODAFF, FOODAVAIL, gFOODQS	0.0002	0.0000	

4.2.1 Water-demand panel data model

The results presented in the tables 12 and 13 suggest that only a few variables have a statistically significant impact on the dependent variable (water demand) at the 5% significance level in both the restricted and unrestricted models. The LSDV results table (table 13) suggests that the unrestricted model better explains the variation in water demand while both models conclude that we reject the null hypothesis in favour of the group effect (F-

statistic). Comparing the results of the LSDV approach and the FE approach which both deal with unobserved heterogeneity, we observe that the number of significant variables remains relatively the same.

According to the FE table (table 12), the first model reports that for each unit increase in log GDP per capita leads to a decrease in water demand by 13.4%, holding all other factors constant. This is inconsistent with our assumption that incomes should lead to higher consumption of water. A one unit increase in urban population (logged) is expected to increase water demand by 120%, holding all other variables constant. This is consistent with our hypothesis that urbanisation contributes to water consumption. A unit increase in population is expected to decrease water demand by an economically insignificant amount. An increase in energy index growth is expected to increase water demand by 254% which is consistent with our assumption that energy security relies on the water sector as well. And finally, the only other significant variable is food index, where for each unit increase in food security, we expect water demand to decrease by 62% which is still consistent with our hypothesis about the relationship between the water and food industry, where food security depends on water resources.

As for our second model, a one unit increase in urban population and food availability index is expected to increase water demand by 100% and 26% respectively, ceteris paribus. These results are partially consistent with our hypothesis that urban population and food security are expected to increase water consumption. However, our hypothesis that climate change variables have a significant effect on water demand was poorly rejected by these results.

Table 10: Results from the Fixed-Effects Analyses Predicting water demand from climate related variables and other key economic and WEF sector variables:

	Restricted Model 1: log(Water demand) (within $R^2 = 0.6657$)			Unrestricted Model 2: log(Water demand) (within $R^2 = 0.7328$)		
Predictor	*b*	*SE b*	*p-value*	*b*	*SE b*	*p-value*
Log(GDP per capita)	-0.134*	0.0627	0.036	0.025	0.0168	0.629
Log(Urban Population)	1.204***	0.1048	0.000	1.007***	0.099	0.000
Population	-5.38e-10*	2.63e-10	0.044	-3.48e-11	2.14e-10	0.871
Temperature growth	0.0184	0.6895	0.979	-0.145	0.1080	0.2726
Log(Rain)	-0.0583	0.0424	0.2624	-0.0893	0.0548	0.2019
Water index growth	0.185	0.2504	0.5137	2.655	0.7136	0.338
Energy index growth	2.541*	1.238	0.044	1.158	0.6030	0.1505
Food index	0.616***	0.143	0.000	-0.143	0.1495	0.4089
Energy import risk index				-0.333	0.1619	0.1318

Energy use intensity index				-0.122	0.3320	0.7309
Energy environmental risk index				-0.319	0.2732	0.3275
Water access index				-0.624	0.7846	0.4847
Water productivity index				-0.440	0.1465	0.0575
Environmental flows index				-0.808	0.2241	0.367
Water availability index				-0.794	0.2808	0.0663
Food affordability index				0.0144	0.1493	0.9291
Food availability index				0.2620***	0.0553	0.000
Food quality and safety index				-0.238	0.4770	0.6522
Constant	-21.429***	2.059	0.000	-28.557***	7.3021	0.000
N	76			76		
Prob > F	0.0000			0.0000		

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 11: Results from the LSDV Analyses Predicting water demand from climate related variables and other key economic and WEF sector variables:

	Restricted Model 1: log(Water demand) (adj $R^2 = 0.9984$)			Unrestricted Model 2: log(Water demand) (adj $R^2 = 0.9985$)		
Predictor	*b*	*SE b*	*p-value*	*b*	*SE b*	*p-value*
Log(GDP per capita)	-0.072*	0.0327	0.072	-0.106*	0.0398	0.010
Log(Urban Population)	0.9135***	0.1030	0.000	1.036***	0.1120	0.000
Population	-8.61e-10	9.51e-10	-0.91	-1.87e-09*	8.88e-10	0.039
Temperature growth	-0.1591	0.2174	0.4664	-0.145	0.2258	0.5241
Log(Rain)	-0.0583	0.0591	0.3276	-0.1204*	0.0526	0.026
Water index growth	0.1852	0.2680	0.4927	2.655	1.7601	0.1372
Energy index growth	0.2011	0.3663	0.5853	1.158	1.0811	0.2886
Food index	-0.1716***	0.0488	0.0001	-0.143	0.0897	0.1164
Energy import risk index				-0.333	0.2703	0.2232
Energy use intensity index				-0.122	0.3719	0.7450
Energy env. risk index				-0.319	0.3832	0.4089
Water access index				-0.624	2.3486	0.7915
Water productivity index				-0.440	0.3989	0.275
Environmental flows index				-0.808	0.6147	0.194
Water availability index				-0.342*	0.1528	0.029
Food affordability index				0.0144	0.1807	0.937

Food availability index				-0.0708**	0.0214	0.002
Food quality and safety index				-0.238	0.3756	0.529
Country 2	-0.254	0.2337	0.2813	-2.1060*	1.0625	0.052
Country 3	-1.179***	0.3297	0.0007	-3.0254**	0.0865	0.007
Country 4	-0.141	0.3533	0.6904	-0.102	0.3968	0.7990
Constant	-9.656***	2.0400	0.0000	-10.2448**	3.4823	0.002
N	76			76		
Prob>F	0.0000			0.0000		

* p < 0.05, ** p < 0.01, *** p < 0.001

Since the models exhibited heteroskedasticity and autocorrelation, and since the time periods are few in this panel data set, we use the two-step system GMM to estimate our final models. The final models are specified below, where each coefficient is significant. In both models, we fail to reject the AR(2) test, implying that the serial correlation of order 2 is not present.

$$logWD = -0.12978logGDP + 0.3358logUP + 1.54e^{-10}POP + -0.4518FI$$

$$logWD = -0.2472logGDP + 0.3621logUP + 1.36e^{-10}POP + -0.2668FI$$

The first system GMM model suggests that as GDP per capita increases, water demand decreases by 13%, which is similar to the FE results, but which is inconsistent with our initial hypotheses. However, both urban population and population have a positive effect on water demand, by 33.5% and $1.54e^{8}$% respectively, ceteris paribus. This has implications for cities that have rapid urbanisation and population growth, since they must also take into account how to sustain these growing populations with existing water resources in a sustainable manner, as water consumption rises. Hence, using the first model we can assume that urbanisation and population have a total effect on water demand by 33.5%, and we shall use this result in the Q-model.

Q-model results

The results from the Leontief analysis for 1995 and 2018 across the 4 countries are reported in table 14 and 15. The water inflows have been consolidated into the variable W1, the oil-related energy inflows are consolidated into E1, electricity-related energy inflows are E2, natural gas-related energy inflows are E3, animal-based food inflows are F1 and plant-based food inflows are F2. We consolidated inflows in this manner to make the analysis simpler to interpret. A comparison of the two tables reveals that China's water final consumption (final demand) has increased the most out of the other

sectors' consumptions, from 44 $(10^9)m^3$ to more than 500,000 $(10^9)m^3$ per year, whereas the total water resources available have not increased (3,571 $(10^9)m^3$ per year). This is consistent with the results of Niva et. al (2019) who investigated the sectoral water demand of China and reported that the food and energy security in the country are highly contingent on available water resources, and as a result, the imbalance of sectoral water demand leads to an unsustainable economy (Niva, Cai, Taka, Kummu, & Varis, 2019). This has implications for Chinese policy makers, where new policies to conserve water and to implement efficient water usage practices are of utmost importance for the sustainability of the water sector, and the WEF nexus as a whole.

As for Mexico, we see that both the oil-related energy consumption (E1) and electricity-related energy consumption (E2) have increased over the 2 time periods by more than 10,000 Tera-joules (2800GWh). Scott (2011) explains that this heavy investment into energy is attributable to the increased research and development into the energy sector for purposes of agriculture and rural electrification. Furthermore, Scott (2011) highlights that this has led to over-exploitation of ground water resources, as cheaper innovative technologies are deployed to the general public allowing them to extract groundwater with little constraints (Scott, 2011). This implies that despite the decrease in E1 inputs, the country is still heavily investing into the oil industry, which should imply an increased energy security risk as well as ground-water security risk in the country. This has implications for the policymakers in the country, since the increased oil consumption will be expected to contribute to climate change, and so more adaptive strategies need to be implemented to transition from oil to electricity and other renewable resources.

In South Africa, we see plant-based food inflows increasing significantly from 3,530 tonnes per year in 1995 to over 6million tonnes in 2018. This can be attributed to the increased farming over the years, not only for local consumption but also for exports and for natural gas production, and is evidenced by the small increase in final demand for F2 from 733tonnes to 1,000tones and the substantial increase in E3 from 80,000Tj to 185,000Tj. The increase in plant-based food inflows and energy inflows also has a direct impact on water resources, and this is consistent Conway et. al (2015) who report that the most significant interlinkages in their study were the water for food interdependency, where the food sector in most SSA countries, including South Africa, were dependent on the security of the water sector. This has implications for the

policymakers since the increased food production will be expected to strain existing water resources, where water resources in the country are a closed system (amount of water resources are constant over time). The strain on water resources will continue to present water crises for the cities that are most vulnerable in the region.

Finally, Spain's natural gas sector has also increased in terms of both final demand and inputs, where final demand increased from 6,800Tj to 14,000Tj per year, and inputs increased from 360,000 Tj to 1.3million Tj. The excess natural gas is expected to be consumed mainly by the water sector as seen in the interlinkage section of the table. This implies that Spain's water sector in 2018 uses various sources of energy, including natural gasses. This is consistent with the research done by Matrinez et. al (2018) who report significant interlinkages between the consumption of water resources and irrigated agriculture and food production in the country. The results therefore offer policymakers a challenge to manage the strong relationship between the water sector and the growing natural gas sector, by implementing water conservation and efficient water-usage policies.

Table 12: Results from the input-output Analyses investigating interlinkages between WEF sector resources from final demand and inputs (1995)

CHINA	W1	E1	E2	E3	F1	F2	Final demand (Y)	Input (X)
W1	0	0	3,036	48	0	444	44	3,571
E1	78,065	69,171	19,520	10,140	0	54,244	68,485	299,626
E2	240,631	202,507	111,102	118,836	1,177	205,074	128,641	1,007,969
E3	190,315	175,264	84,512	80,414	4,913	175,929	9,545	720,891
F1	17,994,601	18,002,846	17,872,236	17,875,633	168,074	17,959,920	9,358	89,882,668
F2	46,422	36,706	16,952	8,520	10,411	35,110	23,805	177,925
MEXICO								
W1	0	0	-54	48	0	551	9	553
E1	-4,247	78,157	20,146	10,124	-0	37,220	10,277	151,676
E2	-466,606	-79,883	27,361	30,287	1,245	584,814	55,131	152,348
E3	546,530	431,821	138,515	114,229	2,347	-42,460	12,755	1,203,737
F1	5,681,787	-65,184,143	8,588,507	9,620,643	179,415	41,468,104	1,038	355,352
F2	56,140	43,164	18,508	8,973	21,862	53,225	1,633	203,505
SOUTH AFRICA								
W1	-0	-0	20	46	0	1,360	3	54
E1	-4,254	48,899	7,879	9,735	-0	29,012	12,121	33,115
E2	382,041	-24,987	63,172	32,715	1,303	3,282,060	15,999	185,394
E3	400,205	183,474	-6,500	102,378	2,314	-44,575	0	79,793
F1	5,690,729	-55,926,223	8,588,896	9,641,971	179,425	41,879,262	376	339,690
F2	54,278	29,055	-9,388	8,614	1,428	34,356	733	3,530

SPAIN								
W1	-0	-0	10	42	0	81	5	140
E1	-4,163	34,446	10,989	10,067	-0	29,775	12,116	109,607
E2	390,159	-24,934	-971,710	32,748	1,304	3,396,406	44,646	165,944
E3	569,516	332,852	-5,894	111,514	2,346	-44,182	6,807	359,242
F1	5,645,138	-90,726,204	0,510,504	9,550,188	178,933	22,986,107	976	500,528
F2	63,059	32,754	41,007	8,610	1,426	34,344	586	223,965

Table 13: Results from the input-output Analyses investigating interlinkages between WEF sector resources from final demand and inputs (2018)

CHINA	W1	E1	E2	E3	F1	F2	Final demand (Y)	Input (X)
W1	0	0	2,977	49	0	467	79	3,572
E1	325,564	275,638	25,505	10,736	0	60,064	520,642	1,218,147
E2	2,664,771	2,203,748	447,146	343,297	1,239	436,943	538,459	6,635,604
E3	4,525,656	4,198,134	751,452	464,803	8,033	812,988	153,894	10,914,961
F1	70 million	22,956,495	40 million	24 million	172,003	20 million	20,558	178 mill.
F2	3,769,311	2,341,788	457,474	108,115	195,013	846,742	30,968	7,749,412
MEXICO								
W1	0	0	9	49	0	482	14	554
E1	0	24,597	20,235	10,136	0	37,254	24,369	116,592
E2	0	0	25,165	29,246	868	211,675	73,714	340,668
E3	1,726,334	961,521	189,006	136,900	3,948	0	15,708	3,033,417
F1	1,285,064	0	0	0	149,387	0	2,017	1,436,468
F2	1,997,375	1,191,731	229,916	58,600	2 million	1,797,960	2,285	7,495,601
SOUTH AFRICA								
W1	0	0	29	52	0	33	4	56
E1	0	0	8,067	9,776	0	23,220	17,663	43,498
E2	304,434	2,402	47,314	32,923	730,416	0	27,260	251,392
E3	436,800	162,779	0	103,955	339,286	0	1,918	185,400
F1	168,466	772,304	0	0	0	0	729	305,887
F2	1,790,288	1,870,842	379,243	35,169	1,432,061	5,729,339	1,030	6,225,237
SPAIN								
W1	0	0	36	239	0	167	5	141
E1	0	77,054	17,423	11,013	0	30,910	20,504	119,350
E2	363,658	0	0	32,273	915	2,652,983	43,774	272,956
E3	665,748	999,973	0	123,976	3,729	0	14,735	1,260,198
F1	401,424	0	0	0	133,662	7,170,894	1,136	480,561
F2	143,734	160,918	164,657	11,647	21,868	39,176	693	347,825

The intensities matrix can be seen in table 16, the most significant increase in footprints is the animal-related food sector (F1) water footprint in China, which was 5,039 tonnes/Trillion m^3 in 1995 and increased to 19,740 tonnes/Trillion m^3. This is consistent with results from Lebanon in 2012 reported by Karnib (2017), where the

water for food indicator was 760.95M·m3. Our results imply that over the years, the livestock sector has increased its use of water resources relative to other consumption levels from households, firms and other sectors. This has implications for the policymakers who deal with agriculture sector, because they need to understand that an increase in investment into the livestock industry will result in a strain on water resources.

The other most notable changes in water intensities are of Mexico, where Mexico's plant-based food sector (F2) increased from 101 tonnes/trillion m^3 to 3,607 tonnes/trillion m^3 per year over the 2 decades, while F1 decreased from 10,217 tonnes/trillion m^3 to 2,320 tonnes/trillion m^3 per year, implying that Mexico's economy has focused its water resources into the agricultural sector as opposed to other sectors. Mexico's natural gas sector has also increased its water consumption over the years from 274GWh/10^9m^3 to 867 GWh/10^9m^3 per year. These results are consistent with what was presented in chapter 1, where we highlighted the state of the agricultural and energy sectors. Policymakers must understand that investing into the natural gas sector and into the agricultural sector will impose additional strains on the already low water resources, such as the aquifers. The continued development of maladaptive strategies for these sectors in silo will lead to an unsustainable economic environment.

In Spain, the animal-based agricultural sector (F1) water intensity decreased over the 2 decades implying that the livestock sector has reduced water consumption. Consequently, the plant-based food sector increased from 114 tonnes/10^9m^3 to 260 tonnes/10^9m^3, which is insignificant compared to the reduction of the livestock-water footprint. This implies that Spain's plant-based agricultural sector grows, and in turn, its water footprint. Policymakers must ensure that water resources are sustainably managed such that the agricultural sector avoids unnecessary crises related to water shortages.

Finally, Using the formula presented in equation 4.9, we can evaluate the new amount of output needed from the WEF sectors that would satisfy the increase in demand by 33.5% as derived from the system GMM in section 4.2.1. To evaluate this outcome, we assume that the technology matrices for each country are unchanged, and we only

report the resulting changes in intersectoral amounts (ΔZ) due to the change in demand caused by urbanisation and population growth.

In China, we see an increase in the consumption of all energy sources by the water sector by 10million Tera-joules, which can imply that the water sector will need more energy to be sustained (for example, desalination projects need huge amounts of energy). In Mexico, Spain and South Africa we expect to see the same where the water sector's consumption of energy will increase by approximately 5 million Tj. These results are partially consistent with the results from Karnib (2017), where he reported an increase in food-related and energy-related water consumption for the 2012 Lebanon case study. These results have implications for the policymakers of all countries, where heavy investment in the water sector will be required to sustain the security of the other 2 sectors within the WEF nexus.

Table 14: Results from the input-output Analyses investigating intensities (footprints) of each sector between the WEF sectors.

	Intensity of water use		*Intensity of Energy use*		*Intensity of Food use*	
CHINA	1995	2018	1995	2018	1995	2018
W	0	0	0	0	0	0
E1	22	91	0	0	0	0
E2	67	746	1	2	1	0
E3	53	1,267	1	4	1	0
F1	5,039	19,740	103	27	101	3
F2	13	1,055	0	2	0	0
MEXICO						
W	0	0	0	0	0	0
E1	0	0	1	0	0	0
E2	0	0	0	0	3	0
E3	274	867	4	9	0	0
F1	10,271	2,320	0	0	204	0
F2	101	3,607	0	11	0	2
SOUTH AFRICA						
W	0	0	0	0	0	0
E1	0	0	0	0	0	0
E2	0	550	0	0	16	16
E3	0	789	1	0	0	0
F1	0	304	0	65	214	206
F2	0	3,233	0	0	0	0
SPAIN						
W	0	0	0	0	0	0
E1	0	0	0	1	0	0
E2	705	657	0	0	0	0
E3	1,029	1,202	0	9	0	0
F1	10,204	725	69	0	1	1
F2	114	260	0	2	0	0

CHAPTER 5: CONCLUSION AND POLICY IMPLICATIONS

5.0 Introduction

This chapter summarises and concludes the findings of the study, and offers recommendations to policymakers that could benefit from the results of the paper. The chapter begins with providing a detailed conclusion of the study, and proceeds to provide the policy implications of these results and recommendations.

5.1 Conclusion

This study sought to investigate the impact of urbanization, population and climate change on the WEF Nexus in China, Mexico, South Africa and Spain over a period of 18 years (2000-2018). The study utilised both a panel data approach and Leontief analysis techniques to investigate these relationships. The results from the system GMM model indicate that the climate change variables have an insignificant impact on water consumption over the 2 decades, while urbanisation and population contribute significantly to the water demand over the panels. These results were inconsistent with our initial hypothesis about the impact of climate change on water resources, however, the insignificance of the climate change variables can be attributable to the short time span of the panel. The Q-model results were consistent with most of Karnib's (2017) results, and these results imply that the energy sector and water sector are highly inter-related with each other, and should be taken into consideration by policymakers. The study therefore managed to fulfil our objectives, where we established the relationship between water demand and the 3 key drivers of water consumption using the panel data modelling approach, and where we established the interlinkages between the WEF sectors of the four countries, and the impact of an increase of 33.5% in final demand (due to urbanisation and population) on the interlinkages within the sectors.

5.2 Policy Implications

The study concluded that the positive relationship between urbanisation and population growth rate and water demand will have a significant impact on the WEF nexus, as water requirements from the energy sectors will increase in the countries in order to sustain the existing technology matrix (A). This has severe implications for policy makers, where they must reconsider the heavy investment into the agricultural sector (as in the cases of Spain and South Africa) or the heavy investment into the energy sectors (as is the case of Mexico and China), since these investments will have

adverse effects on the water resources available in the countries, due to the strong interlinkages that exist within the 3 sectors.

As a result, adopting a Water-Energy-Food Nexus approach to policy development will allow these countries to develop adaptive strategies against climate change, and will allow these economies to develop in a sustainable manner with respect to the WEF resources. In the water sector, leaders and policymakers should consider increasing investment into R&D for the water sector (for example, water conservation and quality improvement research, desalination projects R&D). The increased investment into R&D of the water sector could potentially solve the imbalance in the WEF nexus, where water consumption is unsustainable at the moment given current water inputs (aquifers, surface water, etc). This is because, the study provides evidence of the importance of the water sector for the other 2 sectors, where neither can develop sustainably without the support of a strong water sector. Hence, we can expect the WEF Nexus in the countries to fail due to the inevitable depletion of water resources. Policy makers must understand from this study that the key to sustainability of the WEF Nexus is to ensure water security before food or energy security.

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