Time Series Analysis and Statistical Model Development for Food and Water Availability in the Grand River Watershed

by

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ABSTRACT

TIME SERIES ANALYSIS AND STATISTICAL MODEL DEVELOPMENT FOR FOOD AND WATER AVAILABILITY IN THE GRAND RIVER WATERSHED

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Imminent threats of climate change, population growth and associated anthropogenic impacts can have severe implications for food and water resources around the globe. In order to properly manage these resources in the future, it is necessary to understand how they are influenced by stressors. This thesis characterizes recent, historical trends for food and water availability within the Southern Ontario Grand River Watershed (GRW). It then discusses the implications of trends for local food and water security and develops a statistical framework to model crop production in the GRW. The results of this thesis suggest that aspects of water security such as flood control, infrastructure protection and water quality may be threatened by future anthropogenic and environmental changes. Recent fluctuations in climatic patterns and a potential increase in frequency of extreme weather events could also cause periodic issues with crop production and affect the sustainability of current production growth trends.
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CONTRIBUTIONS OF AUTHORS

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# TABLE OF CONTENTS

**ABSTRACT** .................................................................................................................................................. II

**ACKNOWLEDGEMENTS** ................................................................................................................................. III

**CONTRIBUTIONS OF AUTHORS** ................................................................................................................ IV

**LIST OF TABLES** ........................................................................................................................................... VIII

**LIST OF FIGURES** .......................................................................................................................................... IX

**LIST OF APPENDICES** ................................................................................................................................ XI

1 **INTRODUCTION** ........................................................................................................................................ 1

1.1 **Thesis Objectives** ....................................................................................................................................... 2

2 **FOOD AND WATER SECURITY: ANALYSIS OF INTEGRATED MODELLING PLATFORMS** .................. 3

2.1 **INTRODUCTION** ......................................................................................................................................... 3

2.2 **OVERVIEW OF WATER SECURITY** ........................................................................................................... 4

2.2.1 **Water Security Definition** .................................................................................................................... 5

2.2.2 **Review of Global Hydrological Models** ............................................................................................... 5

2.3 **OVERVIEW OF FOOD SECURITY** ........................................................................................................... 7

2.3.1 **Food Security Definition** ...................................................................................................................... 7

2.3.2 **Review of Food Security Models** ......................................................................................................... 8

2.4 **FOOD AND WATER SECURITY MODELS** ............................................................................................. 9

2.4.1 **IMPACT-Water** ....................................................................................................................................... 9

2.4.2 **GLASS** .................................................................................................................................................. 11

2.4.3 **WATERSIM** .......................................................................................................................................... 12

2.4.4 **GEPIC** .................................................................................................................................................. 15

2.4.5 **LPJmL** ................................................................................................................................................... 16

2.4.6 **GCWM** .................................................................................................................................................. 18

2.4.7 **PODIUMSIM** ........................................................................................................................................ 20

2.4.8 **CERES & VIC** ...................................................................................................................................... 21

2.4.9 **CAPRI (Extended Model)** .................................................................................................................... 23

2.4.10 **GFWS** .................................................................................................................................................. 25

2.5 **DISCUSSION** .............................................................................................................................................. 26

2.6 **CONCLUSION** .......................................................................................................................................... 28

3 **TREND ANALYSIS FOR WATER SECURITY IN THE GRAND RIVER WATERSHED** .................. 29

3.1 **INTRODUCTION** ......................................................................................................................................... 29

3.1.1 **Overview of Water Security** ................................................................................................................ 30

3.1.2 **Water Security Analyses** ...................................................................................................................... 31

3.1.2.1 **Water Security Assessment Studies** .................................................................................................. 31

3.1.2.2 **Hydrological Modelling Platforms** ................................................................................................. 33

3.1.3 **The Grand River Watershed (GRW)** ................................................................................................... 34

3.2 **METHODOLOGY** ....................................................................................................................................... 37

3.2.1 **GRW Study Area and Timeline** ........................................................................................................... 37

3.2.2 **Historical Climate Data** ........................................................................................................................ 39

3.2.2.1 **Primary Physical Data Collection** .................................................................................................... 39

3.2.2.2 **Climate Stations** ................................................................................................................................ 39

3.2.2.3 **Compilation of Secondary Data** ...................................................................................................... 42

3.2.3 **Population and Farm Area Statistics** .................................................................................................... 43

3.2.3.1 **Physical Data Collection** .................................................................................................................. 43

3.2.3.2 **Compilation of Secondary Data** ...................................................................................................... 43
3.2.4 Grand River Discharge Data ........................................................................... 43
3.2.4.1 Physical Data Collection ............................................................................ 43
3.2.4.2 Hydrometric Stations ................................................................................. 43
3.2.4.3 Compilation of Secondary Data .................................................................. 45
3.3 RESULTS & ANALYSIS ......................................................................................... 45
3.3.1 Historical Climate Data ................................................................................... 45
3.3.1.1 Temperature ............................................................................................... 46
3.3.1.2 Precipitation .............................................................................................. 48
3.3.2 Population and Farm Area Statistics ................................................................. 53
3.3.3 Grand River Discharge Data ........................................................................... 53
3.3.4 Climatic Variables vs. Surface Water Availability in the GRW ...................... 56
3.3.5 Anthropogenic Variables vs. Surface Water Availability in the GRW .......... 58
3.4 DISCUSSION ......................................................................................................... 59
3.4.1 GRCA Strategic Objectives ............................................................................. 59
3.4.2 Implications for Indigenous Communities ...................................................... 61
3.5 CONCLUSION ....................................................................................................... 61
4 TREND ANALYSIS FOR AGRI-FOOD PRODUCTION IN THE GRAND RIVER WATERSHED ................................................................. 64
4.1 INTRODUCTION ................................................................................................... 64
4.1.1 Overview of Food and Water Security ............................................................ 66
4.1.2 The Grand River Watershed (GRW) ................................................................ 66
4.1.3 Six Nations of the Grand River (SNGR) .......................................................... 68
4.2 METHODOLOGY .................................................................................................. 69
4.2.1 GRW Study Area and Timeline ..................................................................... 70
4.2.2 Historical Climate Data .................................................................................. 71
4.2.2.1 Climate Stations ....................................................................................... 72
4.2.2.2 Compilation of Secondary Data .................................................................. 72
4.2.3 Population and Farm Area Statistics ................................................................ 72
4.2.3.1 Compilation of Secondary Data .................................................................. 73
4.2.4 Grand River Discharge Data ......................................................................... 73
4.2.4.1 Hydrometric Stations ............................................................................... 74
4.2.4.2 Compilation of Secondary Data .................................................................. 74
4.2.5 Agricultural Data ............................................................................................. 74
4.2.5.1 Compilation of Secondary Data .................................................................. 75
4.3 RESULTS & ANALYSIS ....................................................................................... 76
4.3.1 Historical Climate Data .................................................................................. 76
4.3.1.1 Temperature ............................................................................................. 76
4.3.1.2 Precipitation ............................................................................................. 77
4.3.2 Population and Farm Area Statistics ............................................................... 78
4.3.3 Grand River Discharge Data ......................................................................... 78
4.3.4 Agricultural Data ............................................................................................. 80
4.3.4.1 Field Crop Production .............................................................................. 80
4.3.4.2 Implications of Field Crop Production Trends for Food and Water Security ........................................................................... 83
4.3.4.3 Horticultural Crop Production ................................................................. 85
4.3.4.4 Implications of Horticultural Crop Production Trends for Food and Water Security ................................................................. 88
4.3.5 Visual Comparison between Agricultural, Environmental and Anthropogenic Trends ................................................................. 90
4.3.5.1 Climatic Variables vs. Agricultural Production ....................................... 91
4.3.5.2 Hydrometric Variables vs. Agricultural Production ................................ 93
4.3.5.3 Anthropogenic Variables vs. Agricultural Production ......................... 93
4.4 DISCUSSION ....................................................................................................... 95
4.5 CONCLUSION ..................................................................................................... 96
5 MODELLING CROP PRODUCTION IN THE GRAND RIVER WATERSHED: A STATISTICAL REGRESSION ANALYSIS 98
5.1 INTRODUCTION ................................................................................................ 98
5.2 METHODOLOGY

5.2.1 Data Collection

5.2.1.1 Study Area and Timeline

5.2.1.2 Historical Climate Data

5.2.1.3 Population and Farm Area Statistics

5.2.1.4 Grand River Discharge Data

5.2.1.5 Agricultural Data

5.2.2 Exploratory Analysis

5.2.3 Model Development

5.3 RESULTS & ANALYSIS

5.3.1 Exploratory Analysis

5.3.1.1 Preliminary Analysis with Annual Data Values

5.3.1.2 Secondary Analysis with Monthly Data Values

5.3.2 Model Development

5.4 CONCLUSION

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 FOOD AND WATER SECURITY: ANALYSIS OF INTEGRATED MODELLING PLATFORMS

6.2 FOOD AND WATER SECURITY IN THE GRAND RIVER WATERSHED

6.2.1 Trend Analysis for Water Security in the Grand River Watershed

6.2.2 Trend Analysis for Agri-Food Production in the Grand River Watershed

6.2.3 Modelling Crop Production in the Grand River Watershed: a Statistical Regression Analysis

6.3 RECOMMENDATIONS

REFERENCES

APPENDIX
LIST OF TABLES

TABLE 5.1: DEPENDENT AND PREDICTOR VARIABLES IN THIS ANALYSIS ..............................................................105
TABLE 5.2: MOST SIGNIFICANT ANNUAL VARIABLES BASED ON R² VALUES IN INDEPENDENT, UNIVARIATE QUADRATIC REGRESSION ANALYSES. .........................................................108
TABLE 5.3: MOST SIGNIFICANT MONTHLY AND ANNUAL VARIABLES BASED ON R² VALUES IN INDEPENDENT, UNIVARIATE QUADRATIC REGRESSION ANALYSES. ..........................................................110
TABLE 5.4: STATISTICAL MODELLING PARAMETERS AND VALUES OF MODEL CONSTANTS ............................................113
LIST OF FIGURES

FIGURE 3.1: THREE-DIMENSIONAL CONCEPTUAL FRAMEWORK FOR FOOD AND WATER SECURITY .......................................................... 32
FIGURE 3.2: THE GRAND RIVER WATERSHED (GRW) AND SURROUNDING REGION ................................................................. 35
FIGURE 3.3: THE GRW AND COUNTIES INCLUDED IN THE STUDY ...................................................................................................... 38
FIGURE 3.4: CLIMATE STATIONS AND HYDROMETRIC STATIONS INCLUDED IN THIS STUDY .......................................................... 40
FIGURE 3.5: (a) (b) (c) MEAN, MAXIMUM AND MINIMUM ANNUAL TEMPERATURE AT Fergus Shand Dam, respectively; (d) (e) (f)
MEAN, MAXIMUM AND MINIMUM ANNUAL TEMPERATURE AT ROSEVILLE, RESPECTIVELY; (g) (h) (i) MEAN, MAXIMUM AND
MINIMUM ANNUAL TEMPERATURE AT HAMILTON A, RESPECTIVELY; (j) (k) (l) MEAN, MAXIMUM AND MINIMUM ANNUAL
TEMPERATURE AT PORT COLBORNE, RESPECTIVELY ................................................................................................................. 47
FIGURE 3.6: SPATIAL VARIATION IN OVERALL MEAN TEMPERATURE BETWEEN 2000 AND 2015 ....................................................... 49
FIGURE 3.7: (a) (b) (c) TOTAL ANNUAL PRECIPITATION, RAINFALL AND SNOWFALL AT Fergus SHAND DAM, RESPECTIVELY; (d) (e) (f)
TOTAL ANNUAL PRECIPITATION, RAINFALL AND SNOWFALL AT ROSEVILLE, RESPECTIVELY; (g) (h) (i) TOTAL ANNUAL PRECIPITATION,
RAINFALL AND SNOWFALL AT HAMILTON A, RESPECTIVELY; (j) (k) (l) TOTAL ANNUAL PRECIPITATION, RAINFALL AND SNOWFALL AT
PORT COLBORNE, RESPECTIVELY ........................................................................................................................................... 50
FIGURE 3.8: SPATIAL VARIATION IN MEAN ANNUAL PRECIPITATION BETWEEN 2000 AND 2015 ......................................................... 52
FIGURE 3.9: TOTAL POPULATION VS. TOTAL FARM AREA WITHIN THE GRW STUDY AREA BETWEEN 2001 AND 2016 ......................... 54
FIGURE 3.10: ANNUAL FLOW RATIO FOR THE SIX GRAND RIVER FLOW GAUGES BETWEEN 2000 AND 2015 ................................. 54
FIGURE 3.11: MEAN ANNUAL RIVER DISCHARGE FOR THE SIX GRAND RIVER FLOW GAUGES BETWEEN 2000 AND 2015 ............. 56
FIGURE 3.12: (a) MEAN ANNUAL RIVER DISCHARGE AT BRANTFORD VS. MEAN ANNUAL TEMPERATURE AT HAMILTON A; (b) MEAN
ANNUAL RIVER DISCHARGE AT MARSVILLE VS. MEAN ANNUAL TEMPERATURE AT ORANGEVILLE MOE ........................................... 57
FIGURE 3.13: (a) MEAN ANNUAL RIVER DISCHARGE AT BRANTFORD VS. TOTAL ANNUAL PRECIPITATION AT HAMILTON A; (b) MEAN
ANNUAL RIVER DISCHARGE AT MARSVILLE VS. TOTAL ANNUAL PRECIPITATION AT ORANGEVILLE MOE ........................................... 57
FIGURE 3.14: (a) MEAN ANNUAL RIVER DISCHARGE AT BRANTFORD VS. TOTAL POPULATION AND TOTAL FARM AREA; (b) MEAN ANNUAL
RIVER DISCHARGE AT MARSVILLE VS. TOTAL POPULATION AND TOTAL FARM AREA ................................................................. 59

FIGURE 4.1: THREE-DIMENSIONAL CONCEPTUAL FRAMEWORK FOR FOOD AND WATER SECURITY .......................................................... 67
FIGURE 4.2: THE GRAND RIVER WATERSHED (GRW) AND SURROUNDING REGION ................................................................. 68
FIGURE 4.3: THE GRW AND COUNTIES INCLUDED IN THE STUDY ...................................................................................................... 71
FIGURE 4.4: CLIMATE STATIONS AND HYDROMETRIC STATIONS INCLUDED IN THIS STUDY .......................................................... 73
FIGURE 4.5: (a) TOTAL GRAIN CORN PRODUCTION IN THE SEVEN GRW COUNTIES; (b) TOTAL SOYBEAN PRODUCTION IN THE SEVEN GRW
COUNTIES; (c) TOTAL WINTER WHEAT PRODUCTION IN THE SEVEN GRW COUNTIES; (d) TOTAL FIELD CROP PRODUCTION (GRAIN
CORN, SOYBEAN AND WINTER WHEAT) IN THE SEVEN GRW COUNTIES ............................................................................................. 81
FIGURE 4.6: MEAN ANNUAL CROP PRODUCTION FOR THE GRW STUDY AREA BETWEEN 2000 AND 2015 ................................. 84
FIGURE 4.7: (a) TOTAL GRAPE PRODUCTION IN THE HAMILTON, HALDIMAND AND NORFOLK COUNTIES; (b) TOTAL APPLE PRODUCTION IN
THE WELLINGTON, WATERLOO, BRANT, HAMILTON, HALDIMAND AND NORFOLK COUNTIES; (c) TOTAL SWEET CORN PRODUCTION
IN THE WELLINGTON, WATERLOO, BRANT, HAMILTON, HALDIMAND AND NORFOLK COUNTIES; (d) TOTAL FIELD TOMATO
PRODUCTION IN THE HAMILTON, HALDIMAND, NORFOLK AND BRANT COUNTIES .......................................................................... 86
FIGURE 4.8: (a) MEAN ANNUAL APPLE PRODUCTION FOR THE GRW STUDY AREA BETWEEN 2000 AND 2015; (b) MEAN ANNUAL SWEET
CORN PRODUCTION FOR THE GRW STUDY AREA BETWEEN 2000 AND 2015 ......................................................................... 89
FIGURE 4.9: (a) TOTAL FIELD CROP PRODUCTION IN WELLINGTON COUNTY VS. TOTAL ANNUAL PRECIPITATION AT Fergus Shand Dam
CLIMATE STATION; (b) TOTAL APPLE PRODUCTION IN HALDIMAND/NORFOLK COUNTIES VS. TOTAL ANNUAL PRECIPITATION AT PORT
COLBORNE CLIMATE STATION ................................................................................................................................................. 92
FIGURE 4.10: (a) TOTAL FIELD CROP PRODUCTION IN WELLINGTON COUNTY VS. MEAN ANNUAL TEMPERATURE AT Fergus Shand Dam
CLIMATE STATION; (b) TOTAL APPLE PRODUCTION IN HALDIMAND/NORFOLK COUNTIES VS. MEAN ANNUAL TEMPERATURE AT PORT
COLBORNE CLIMATE STATION ................................................................................................................................................. 92
FIGURE 4.11: (a) TOTAL FIELD CROP PRODUCTION IN WELLINGTON COUNTY VS. TOTAL GRW POPULATION AND TOTAL GRW FARM AREA;
(b) TOTAL APPLE PRODUCTION IN HALDIMAND/NORFOLK COUNTIES VS. TOTAL GRW POPULATION AND TOTAL GRW FARM AREA. 94
FIGURE 4.12: (a) TOTAL FIELD CROP PRODUCTION IN WELLINGTON COUNTY VS. MEAN ANNUAL RIVER DISCHARGE AT SHAND DAM
HYDROMETRIC STATION; (b) TOTAL APPLE PRODUCTION IN HALDIMAND/NORFOLK COUNTIES VS. MEAN ANNUAL RIVER DISCHARGE
AT BRANTFORD HYDROMETRIC STATION ...................................................................................................................................... 94
Figure 5.1: The GRW and counties included in the study. ................................................................. 101
Figure 5.2: Climate stations and hydrometric stations located within the GRW study area. .................. 102
Figure 5.3: Actual production vs. predicted production based on statistical regression modelling for individual crops within the GRW study area from 2000 to 2015 (Total production in Wellington county for soybean, winter wheat, grain corn and total field crop, total production in Haldimand/Norfolk county for grape, apple, sweet corn and tomato). ......................................................................................................................... 114
LIST OF APPENDICES

TABLE A1: AVAILABILITY OF SUFFICIENT TEMPERATURE DATA FOR CLIMATE STATIONS IN THIS STUDY BETWEEN 2000 AND 2015........140
TABLE A2: AVAILABILITY OF SUFFICIENT PRECIPITATION DATA FOR CLIMATE STATIONS IN THE STUDY BETWEEN 2000 AND 2015 ........140
TABLE A3: AVAILABILITY OF SUFFICIENT RIVER DISCHARGE DATA FOR RIVER STATIONS IN THIS STUDY BETWEEN 2000 AND 2015........140
TABLE A4: REVIEW OF FOOD AND WATER SECURITY MODELLING PLATFORMS........................................................................141
TABLE A5: PRIMARY DRIVERS OF JOINT FOOD AND WATER SECURITY MODELLING PLATFORMS........................................142
TABLE A6: PRIMARY LIMITATIONS OF JOINT FOOD AND WATER SECURITY MODELLING PLATFORMS...............................144
1 Introduction

Water is, and always has been crucial for human survival. It remains our most valuable resource, providing fresh drinking water and directly impacting almost every aspect of daily life including health and sanitation, disease transmission and prevention, food production and transportation. As a result of their influence over our daily lives, water resources have the ability to dictate food security, economic, political and social security, human health, prosperity, happiness and ultimately, survival. According to Vörösmarty et al., 2000, close to 30% of the global population lived under severe water stress in the early 21st century and many more could be at risk. Especially considering the growing threat of global climate change and rapidly increasing global population, it is more important now than ever before to gain a deeper understanding of our water resources systems and the challenges they may face in the coming decades.

One of the most significant factors pertaining to the security of water resources is food production. It is estimated that agricultural production currently accounts for about 70% of global freshwater use (United Nations Department of Economic and Social Affairs 2014). Agriculture also contributes substantially to the deterioration of water quality as fertilizers, pesticides and livestock waste products can easily be transported to surface water bodies after heavy rainfall. Conversely, fresh water availability is also mandatory to ensure crop growth and livestock survival in the agri-food industry. Food and water resources each play a vital role in the other’s overall security, reinforcing the need to consider food and water security from an interdisciplinary perspective to achieve global health and security.

The primary aim of this research is to evaluate recent trends related to food and water security within the Grand River Watershed (GRW) in Southern Ontario, Canada, and develop a framework to empirically model these trends. The GRW is the largest watershed in Southern Ontario, influencing agricultural production, food and water security for a considerable number of people in the region. It is therefore an appropriate and relevant selection as a case study for this analysis. Recent trends are important because they can help to understand localized patterns and predict future, short-term availability for food and water resources.

Before the aims of this research can be accomplished a comprehensive understanding of food and water security, as well as current integrated modelling platforms is required. The independent
manuscript presented in Chapter 2 of this thesis contains an extensive literature review concerning these topics, which was published in *Agricultural Water Management*. The remaining portion of this thesis comprises a multi-phase study beginning with a time series analysis examining climate variability, anthropogenic changes, water availability and crop production in the GRW.

Rather than using various process or simulation-based modelling techniques, this analysis is more direct, using real, historical data to develop a better understanding of more recent trends in food and water security. These types of analyses can be useful to examine regions where data availability is limited and may also have the ability to capture the effects of more localized or poorly understood processes. This section spans Chapters 3 and 4 of this thesis and contains two additional, independent manuscripts. These chapters are followed by a final independent manuscript (Chapter 5), which models the data presented in Chapters 3 and 4 through statistical regression analyses. The final chapter of this thesis (Chapter 6) summarizes research findings and discusses the overall conclusions that are formed at the end of this research.

### 1.1 Thesis Objectives

The aims of this research influenced the development of four specific thesis objectives, which are as follows:

1) Review and discuss current integrated food and water security modelling platforms (*Chapter 2*);
2) Examine recent, localized trends in water availability within the GRW and discuss the implications for food and water security (*Chapter 3*);
3) Examine recent trends in agri-food production within the GRW and discuss the implications for food and water security (*Chapter 4*); and
4) Develop a statistical model for crop production in the GRW (*Chapter 5*).
2 Food and Water Security: Analysis of Integrated Modelling Platforms

2.1 Introduction

Globally, both food and water resources are under significant pressure to meet the needs of a growing population. Millions of people worldwide face considerable threats to their food and water security, and the impacts of these issues will only be intensified with future effects of global climate change and changes to land-use. It has thus become apparent in recent years that the connections between food and water supply must be explored in order to work toward a state of global food and water security.

Water supply and availability directly affect food production through agricultural practices. Sufficient water supply is vital to ensure crop growth and livestock survival, and agriculture accounts for approximately 70% of global freshwater use (United Nations Department of Economic and Social Affairs 2014). Conversely, improper management practices in the agricultural sector can result in runoff and contamination by excess nutrients or chemicals entering the water supply. As a consequence, neither food or water security can realistically be achieved on a global scale without the other. It is therefore important to consider food and water security from an interdisciplinary perspective in the pursuit of global security. In order to work toward global food and water security, it is first necessary to understand how global food and water systems operate, how they are affected by various drivers, and how they will be expected to change in the future. Modelling platforms allow researchers to simulate and understand current systems, identify key drivers and their potential impacts, and make specific parameter alterations to predict future scenarios. They also provide the basis for critical thought necessary to design and simulate solutions for system improvement.

Previous research has led to the development of a number of modelling platforms to jointly analyze food and water security (Alcamo et al. 2001; Blanco, Van Doorslaer, and Britz 2012; Bondeau et al. 2007; de Fraiture 2007; Grafton, Williams, and Jiang 2015; Liu et al. 2007; Amarasinghe 2005; Mark W Rosegrant et al. 2008; Siebert and Döll 2008; Wei et al. 2009). These models have been developed for a variety of circumstances and conditions and have vast differences in their operation and overall purpose. This review and analysis is intended to provide a basis for research studies
concerned with the application or adaptation of interdisciplinary food and water security models. A fundamental understanding of the depth of potential modelling platforms, and their various capabilities and uses, is required prior to selecting the appropriate tool for a particular application. This manuscript attempts to identify key drivers of food and water security models and offers a basis for comparison of several of the models according to these key drivers, input requirements, model limitations and advantages.

This manuscript initially discusses the fundamental concepts of food and water security to provide the broader context and requisite background on these topics. In doing so, the manuscript summarizes current hydrological and food production and consumption modelling structures that have been applied independently for either water or food security analyses. This information serves as a foundation for research and provides insight into more detailed and complex interdisciplinary models. The paper then focuses on ten food and water security models to critically review and analyze their application, processes, input data and information, advantages and limitations. Results from this analysis will provide guidance for model selection and development to improve understanding of the interdisciplinary nature of food and water security.

2.2 Overview of Water Security

Globally, fresh water may be our most precious resource; however, threats to global water security continue to impact the health of our fresh water resources. The global water cycle is being significantly altered by land development and the resulting effects on runoff, evapotranspiration and groundwater recharge processes. In urban and other developing areas, population growth decreases the availability of fresh water while urbanization decreases recharge to groundwater and increases stormwater runoff. Urbanization also impacts water quality, as the high volume of stormwater runoff transports contaminants from urban areas to groundwater and surface water bodies. The conversion of natural vegetation to agricultural land results in the over-extraction of water to support crop production (Siebert and Döll 2010), thereby decreasing fresh water availability. Additionally, chemical agricultural controls including fertilizers and pesticides have been used indiscriminately to promote food growth, resulting in violations of water quality standards (Poincelot 1986).
Climate change is another significant threat to global water security. Changes in the frequency, pattern and volume of precipitation events will affect water quality and availability, as well as the ability of current infrastructure to respond to extreme weather hazards. Rising temperatures also threaten seasonal availability and quality of fresh water resources. Successfully addressing the challenge of global water security will require a holistic and interdisciplinary approach that incorporates all factors influencing the availability, accessibility, and sustainability of water resources.

2.2.1 Water Security Definition

The concept of water security is dynamic and multi-dimensional. According to Jansky, Pachova, and Nakayama 2008, the term “water security” should consider “all aspects of human security pertaining to the use and management of water”. This view is somewhat anthropocentric, however, in that it overlooks the importance of environmental considerations in its definition of water security (Cook and Bakker 2012). The definition of water security has since evolved, and the provision of water resources to sustain and enhance ecosystem functions has become a priority (Cook and Bakker 2012). The definition of water security now encompasses “sustainable access… to adequate quantities of water of acceptable quality to ensure human and ecosystem health” (Norman et al., 2010, p. ii).

By this definition, all aspects of water security can be summarized in three dimensions: availability, accessibility and sustainability. In this manuscript, the assessment of water security has been generalized and incorporates the availability aspect of the definition of water security. Water availability is given by the total supply of both renewable and nonrenewable water sources leftover after water demands are satisfied. Supply must outweigh demand in order to avoid water stress and insecurity. Increasing pressures on fresh water resources have prompted the development of several global assessment models which attempt to evaluate the overall water balance.

2.2.2 Review of Global Hydrological Models

In an attempt to manage and protect global fresh water resources, a number of global hydrological models (GHMs) have been developed that incorporate precipitation patterns, temperature, runoff, and other climate variables into their framework (Giuntoli et al. 2015). These models use scenario
analysis to assess the performance of water resource systems under circumstances of global climate change and rapidly varying water demand (McKinney et al. 1999).

According to Wood et al., 2011, current hydrological models lack the capabilities to address societal requirements for information about the global water system. Although water quality is a significant aspect of water security and it is necessary to understand the processes that control water quality in surface water and groundwater bodies, current models lack this ability to simulate movement of water at and near the ground surface (Wood et al. 2011). Further development of GHMs should incorporate water quantity and quality, as well as environmental sustainability in the assessment of water security (McKinney et al. 1999). These models should be able to simulate how adverse effects of population growth and climate change will impact water availability and food security in time and space, as well as potential hydrological impacts to biodiversity (Wood et al. 2011). High-resolution hydrological and land surface models will allow for the detailed simulation of storage, movement and quality of water at and near the ground surface – and will lead to higher-resolution flood and drought forecasting (Wood et al. 2011).

In the framework of both the European Union Integrated Project Water and Global Change (EU-WATCH) and the Water Model Inter-comparison Project (WaterMIP), it was noted that precipitation and runoff are significant sources of uncertainty in many GHMs (Schewe et al., 2014). These uncertainties stem from the climate models that have been integrated into many GHM platforms, which do not accurately reproduce current precipitation patterns and changes in climate variability (Schewe et al. 2014). Additionally, runoff generation processes are often conceptualized without significant consideration to local geology, hydro-climatology, or snow and permafrost dynamics (Bierkens 2015).

A vital component of the majority of GHMs is considering the allocation of water for agricultural purposes as a fundamental component of water use. Due to the relationship between food and water security, there is vast potential for the use of GHMs in combination with agricultural modelling frameworks. Some hydrological models have now been adapted to perform analyses of water availability on food production (Bierkens 2015) which will be discussed in Section 4 of this manuscript following an introduction to food security.
2.3 Overview of Food Security

Food insecurity represents one of the most significant challenges for the global population. Each year, more people die from malnutrition than from AIDS, tuberculosis and malaria combined (World Food Programme 2016). Food insecurity can also lead to civil unrest and violence, justifying the need for government assistance and investment in agriculture in order to reduce conflict and build social capital (Notaras 2011). Population growth, urbanization, and climate change are just a few of the current socioeconomic and environmental challenges to global food security (Steinmann and Del Col 2008). The growing global population consumes and requires more food every day, putting pressure on agricultural and food production industries around the world. With growing populations, cities are also expanding and using more land for urban development. Climate change poses a significant threat to global food security, as it can affect precipitation and temperature patterns, and result in more extreme weather events. These factors have the potential to limit land available for food production, shift consumption patterns, and affect overall agricultural productivity (Msangi and Rosegrant 2011). Addressing the concern of global food security will require effective preservation and redirection of surplus food in an attempt to eliminate malnutrition through adequate food distribution (Stephens and Cowin 2015). To do so it is necessary to investigate and understand the many variables that influence food security and impact agriculture, food production and consumption patterns.

2.3.1 Food Security Definition

According to the World Food Summit, food security exists when “all people at all times have… access to sufficient, safe, and nutritious food to meet dietary needs and food preferences for an active and healthy life” (United Nations Department of Economic and Social Affairs 2014). Food security comprises “availability (i.e. sufficient quantities of food), access (i.e. adequate resources to obtain food), utilization (i.e. nutritious and safe diets, and clean water) and stability (i.e. the temporal dimension of the other three dimensions)” (Van Dijk and Meijerink 2014).

In this manuscript, food security is assessed through comparison of food supply and demand. Sources of food include crop and livestock production, forage for wild edibles, hunting and fishing practices and production with the use of additive manufacturing. Food demand, feed consumption and food waste all represent sectors of demand for food resources. Additional demand is derived
2.3.2 Review of Food Security Models

Van Dijk and Meijerink, 2014 assessed twelve studies that focus on investigating and modelling various food security issues and scenarios. Seven core models are used in these studies to estimate various food security indicators and assess a total of 43 different scenarios. Predictions of food supply are given by these models and combined with projections for additional factors derived from secondary sources to assess food security based on one or all of the following indicators: food prices, undernourishment, calorie availability and child malnutrition. Many of the studies incorporate climate change, the increasing use of biofuels and biomaterials, and shifts in diets and consumption patterns in some form; however, the direct impacts of these factors on food and water availability are not fully analyzed (Van Dijk and Meijerink 2014).

Most of these studies and modelling approaches report food availability using estimates of calorie availability. Access is partially addressed in some studies with projections for food prices. It is also presented using variables including poverty and household income, household composition, education, waste and consumption behaviour. Many of the modelling approaches discussed do not adequately address utilization or nutrition security, as estimates of food utilization, child malnutrition and undernourishment neglect household and demand-level factors (Van Dijk and Meijerink 2014). The fourth dimension of food security, stability, is not generally reflected in these modelling efforts as they are primarily focused on the analysis of long-term trends.

Apart from the conventional drivers of food security, other factors that have substantial impacts on food supply and availability include post-harvest losses, food supply chain waste, alternative food sources, farm adaptations, and water availability (Van Dijk and Meijerink 2014). Few models examine the effect of these factors on food security; however, efforts are underway to incorporate these elements into future modelling platforms and include micro-level indicators of food and nutrition security in future modelling and scenario analysis efforts (Van Dijk and Meijerink 2014).
2.4 Food and Water Security Models

The interdependence between water and food security emphasizes the importance of studying these variables in an inter-connected manner. Recently, there have been substantial advances in the creation of modelling frameworks that address food and water collectively. A comprehensive review of the literature reveals ten existing models that jointly analyze food and water security, in order to characterize and evaluate the interactions between the two concepts. A brief review of the primary focus of each of these models is given in Table A4, along with the suitable spatial scale for simulations in each model. This table also mentions the regions where each of the models have been applied. The ten models are critically reviewed in the following sections to assess input data, processes, model assets and limitations.

2.4.1 IMPACT-Water

The integration of a water simulation software with the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was one of the first global and regional scale assessments of the effects of water availability and climate variability on food production (de Fraiture, 2007). IMPACT was first developed due to a lack of understanding in terms of the measures needed to be taken to achieve global food security and reduce poverty. It was originally designed to analyze the impact of population, investment, and trade on food security (Rosegrant et al., 2008). Despite many successful modelling efforts with IMPACT, the model was not able to incorporate climate variability in its estimations of food production and trade (Rosegrant et al., 2008).

This realization led to the establishment of the IMPACT-Water model, which considers water availability and demand through the use of a water simulation module (WSM). In addition to the WSM, the current IMPACT-Water model incorporates Earth System Models (ESMs), value chain models, as well as consideration for crop simulations, land-use, nutrition, and health and welfare analysis (Robinson et al., 2015). Details pertaining to the function and characteristics of the IMPACT-Water model are given according to Rosegrant et al., 2008. Spatial resolution was improved in the IMPACT-Water model. The world is divided into 320 “food-producing units”, as compared to the initial IMPACT model, which used only 36 regions (Robinson et al., 2015). The
current model utilizes 62 commodities in total, including 39 crop, 6 livestock and 17 processed varieties (Robinson et al., 2015).

The WSM evaluates basin-level hydrology to address the potential impacts of significant climate and hydrological variations at larger scales (McKinney, 1999). Water demand is divided between irrigation, livestock, industrial and domestic needs and committed flows for environmental, ecological, navigational and off-stream water requirements. Price is also factored into water demand predictions. In the estimation of total available water supply, precipitation, evapotranspiration, runoff, and anthropogenic factors (including flow diversion, groundwater pumping, water pollution and water allocation policies) are considered. In order to analyze water availability for crop production, effective rainfall is estimated based on total rainfall, soil moisture content, soil characteristics and evapotranspiration.

The analysis is optimized by assuming that minimal water shortages occur within a river basin; however, this approach does not allow for full assessment of future water supply uncertainties. In order to allow for consideration to environmental impacts, the concept of “maximum allowable water withdrawal” was introduced, to constrain water withdrawal and account for in-stream environmental water requirements (M. W. Rosegrant, Cai, and Cline 2006). Other environmental impacts are explored through analysis of salt leaching requirements, soil salinity control, and alternative rates of groundwater withdrawal (Rosegrant and Cai, 2002).

The food portion of the IMPACT-Water model comprises a system of equations to analyze various scenarios for food demand, supply, trade, income and population. Projections of food supply are divided between crop and livestock production, while estimations of food demand consider food, feed, production of biofuels and other uses. Crop production and harvested area projections are functions of prices, water availability, and other exogenous factors such as population pressure, soil degradation and land conversion. Crop yield estimates incorporate the impacts of agricultural technology improvements including crop management research, conventional plant breeding, hybridization breeding and transgenic breeding, on productivity development. Ongoing research has improved the range of crop commodities available in the model to include aquaculture, groundnuts, cotton, fodder crops, and major dry-land grains and pulses. Livestock production is a function of price, consideration to competing products, feed and growth in livestock slaughtered.
In this model, food prices are considered as a function of world prices. Additionally, food supply, demand and prices for each sub-model are linked through trade. In its analysis of food security, the IMPACT-Water model platform focuses on undernutrition statistics of children under the age of five in Sub-Saharan Africa. This region was selected due to the prevalence of undernourishment. People in this region experience undernourishment more than anywhere else in the world (World Food Programme, 2016). According to Rosegrant et al., 2008, “any child whose weight-for-age is more than two standard deviations below the weight-for-age standard set by the World Health Organization is considered malnourished”. This term was later updated to the more precise term, “undernourished” (Robinson et al. 2015). The IMPACT-Water model predicts the number of undernourished children under the age of five for various scenarios in order to provide a basis for comparison of the level of food security in different situations.

The process followed within the combined food and water model begins with the assumption that there is no shortage of water. Harvested crop area and crop yield are then estimated with consideration to inputs including price, labour, fertilizer, and technological advancements. Water availability for crop production is estimated, thereby influencing new calculations of crop area and yield. Food and global trade are projected, and crop prices are adjusted iteratively until the global trade balance equals zero. The newest version of the IMPACT-Water model (IMPACT 3) provides a more user-friendly interface as it streamlines computational requirements (Robinson et al. 2015). The IMPACT model has been applied in regions in Sub-Saharan Africa by Rosegrant et al., 2005, in various countries in the Arab region by Sulser et al., 2011, as well as in other global applications.

2.4.2 GLASS

Alcamo et al., 2001 identified the need to quantify the impact of changes in the environment on human health and security. With the development of the Global Assessment of Security (GLASS) model, Alcamo et al., 2001 attempted to assess the risk to society associated with extreme environmental events including droughts, floods and air pollution. The preliminary version of the GLASS model was designed to assess the impact of changing climate on food and water security. Various characteristics of the GLASS model are outlined below, with details given primarily in Alcamo et al., 2001.
To simulate changes in land cover, the model uses the Land Cover model of IMAGE 2 (Zuidema et al. 1994; Alcamo et al. 1998). For long-term changes in climate, the climate model of IMAGE 2 (de Haan et al. 1994; Alcamo et al. 1998) or other general circulation models are used, while short-term variations in climate are estimated using a gridded historical database (New, Hulme, and Jones 2000). Changes in crop productivity are computed within the GLASS model using the FAO Crop Suitability model (FAO 1978), which uses climate data to estimate the yield of various crops on a global scale. Crop yield estimates consider local temperature, moisture conditions and specific soil conditions. Hydrological variations are modelled using the WaterGAP model, which provides estimations of water use and availability over 1,162 watersheds, spanning 150 countries (Alcamo et al. 1997; P Döll et al. 1999). This model accounts for domestic, industrial and agricultural water uses, as well as river runoff and groundwater recharge. Major drivers of global environmental change include the global population, economic changes and advances in technology. Other drivers not considered in the GLASS model include political-economic institutions and cultural and habitual practices (Stern, Young, and Druckman 1991).

A vital component of this model is the “Crisis model”, which attempts to estimate the probability of crises arising in countries across the world. It determines environmental stresses in a region by computing the deviations of water availability or crop productivity from their normal, or expected conditions. To represent “normal” conditions, the GLASS model used climatic, land-use, hydrological and agricultural data from 1961 to 1990, and measured deviations from these average values for any particular year. A significant aspect of the “Crisis model” within GLASS is the concept of “security diagrams”. Security diagrams link levels of environmental stress and state susceptibility (the ability to resist or recover from crises) for various countries at any point in time. According to this model, countries that experienced higher levels of environmental stress would be expected to experience more frequent crises. The GLASS model has been applied in a study assessing the potential impacts of climate change on food and water availability in Russia by Alcamo et al., 2007.

2.4.3 WATERSIM

The Water, Agriculture, Technology, Environment and Resources Simulation Model (WATERSIM) assesses the impact of food and water policies on water availability, food security and the environment (de Fraiture 2007). Both the IMPACT-Water and PODIUM models are
utilized as the foundation for the WATERSIM framework (de Fraiture 2007). The initial PODIUM model considers one crop category (cereals) to assess food and water security at a national level. Limitations of the PODIUM model include that it fails to consider individual crops within the cereal category, capture spatial variations in the water balance, or model at a sub-national level (Amarasinghe 2005).

WATERSIM gives a global context for national and basin level analyses by considering the relationship between global economy, basin or country-level water use and availability, and agricultural production (de Fraiture 2007). It is quite flexible, allowing for the simulation of a variety of scenarios, although the wide spatial scale also limits the level of detail in model simulations (de Fraiture 2007). A major advantage of the WATERSIM model over other food and water security models is the use of feedback mechanisms between food and water analyses (de Fraiture 2007). An example of one of these feedback mechanisms would be the impact of a water shortage, and the resulting deficiency in food and increase in food prices on food production in the following year (de Fraiture 2007).

According to de Fraiture (2007), the WATERSIM model divides the world into 125 river basins in its analysis of hydrological processes. The food module uses 115 economic regions which, combined with the river basin grid, produce 282 sub-basins, or “Food Producing Units (FPU’s). FPU’s are used to model hydrological or economic processes over a specific river basin or economic region. WATERSIM models economic processes, food supply and demand using an annual time step, while specific crop related parameters are determined either on a monthly or seasonal basis. Climate and hydrological processes are modelled at a monthly time-step, along with water supply and demand. WATERSIM projects food and water security scenarios for the year 2025; however, there is some flexibility which allows for shorter or longer-term projections.

The food portion of the model projects food supply, demand, prices and trade. It considers income growth in agricultural and non-agricultural sectors in its projections. Supply is a function of crop and livestock yield and incorporates 32 agricultural commodities. Crop production depends on price, competition, growth trends, water availability, labour and capital, and is considered separately for irrigated and rain-fed areas. WATERSIM defines irrigated and rain-fed areas through modification of the Global Map of Irrigation Areas (Siebert, Hoogeveen, and Frenken...
The trend factor considers improvements in agricultural technology including crop management, conventional plant breeding, hybridization breeding and transgenic breeding, on increased productivity. Livestock production is a function of price, competition, feed and growth in terms of livestock slaughtered. Demand calculations estimate requirements for food, feed, and other uses through consideration to prices, competition, income, population, and livestock production. Domestic prices are a function of world prices, and trade links various regions on a global scale. The model also captures changes in harvested area resulting from population pressures, soil degradation or conversion of land to non-agricultural uses. The food module assumes that there is an overall balance in the world market and that agricultural production equals demand plus any change in stocks.

The water portion of the model is based on a water balance, and projects water demand as a function of agricultural, industrial and domestic requirements. An advantage of WATERSIM is its differentiation between depletion and total diversions, where depletion renders water unavailable for future use. To compute agricultural water requirements, WATERSIM considers irrigated area, cropping patterns, crop water requirements, effective rainfall and effective efficiency (i.e. a factor that determines efficiency of the use of depleted water). Industrial water requirements consider manufacturing, energy and agro-industry, while domestic water demand considers requirements of both urban and rural areas based primarily on income and population. Water supply is derived from such sources as runoff, groundwater recharge, and inflow from inter-basin transfer. The storage capacity of a particular basin is simulated using the Basin Equivalent Storage (BES), and supply is then optimized using a reservoir operation model, as per Rosegrant and Cai, 2002. WATERSIM also considers in-stream environmental requirements; however, it assumes that the percentage of total river flow dedicated to in-stream environmental requirements remains equal on a monthly basis. Environmental policies concerning ecological water requirements may be entered into the system as either hard or soft constraints, allowing for flexibility in the simulation.

The water and food modules are linked primarily through agricultural area and crop price. The model iterates between these two modules to reach a final market equilibrium and water balance. The overall modelling approach for WATERSIM requires considerable data derived from a variety of sources, resulting in a computationally-intensive calibration process. The water module is calibrated using data from Aquastat and other national databases, while the food module uses data
from the FAOstat database for calibration. Due to the global scale of this model, limits on data availability and computing power result in a limited level of detail as compared to smaller scale models. Simulations occur in General Algebraic Modeling System (GAMS), and output is in a spreadsheet file format. Model output for one scenario may be produced within about 10 hours on a high-end PC. The WATERSIM model has been applied in China and India by De Fraiture et al., 2008 and in regions in Sub-Saharan Africa by de Fraiture, 2005.

2.4.4 GEPIC

The GIS-based Environmental Policy Integrated Climate (GEPIC) model attempts to address the global challenge of producing more food with less water through its analysis of crop water productivity (CWP). A description of this model and its various advantages and limitations is given primarily by Liu et al., 2007. The combination of a crop growth model with GIS software was developed due to the need to address applicability and spatial variability in crop growth models. The foundation of GEPIC is the EPIC model, which projects yields for more than 100 different crops and has been successfully implemented around the world to simulate output for varying climates, soil properties, crops and management scenarios. Williams et al., 1989 found that the EPIC model simulations for wheat, corn, rice, soybean, corn soybean and sunflower in locations in the U.S., Asia, France and South America were consistently within 7% of measured yields. EPIC is also a public domain software, and requires minimal data input.

The primary objectives of the EPIC model are to simulate crop yield, evapotranspiration (ET) and CWP. It uses a daily time step to simulate weather, hydrology, nutrient cycling, tillage, plant environmental controls and agronomics. Crop yield depends on the interception of solar radiation, crop parameters, leaf area index, and harvest index. Potential growth may also be affected by deficiencies in water, nitrogen or phosphorus, extreme temperatures or poor soil aeration. The estimated aboveground biomass is multiplied by an index that considers water stress, which is measured by the ratio of water withdrawal to water availability (Liu et al. 2013). ET may be estimated using one of five available methods in EPIC: Hargreaves (Hargreaves and Samani 1985), Penman (Penman 1948), Priestley–Taylor (Priestley and Taylor 1972), Penman–Monteith (Monteith 1965), and Baier–Robertson (Baier and Robertson 1965). Evaporation and transpiration are computed separately similarly to Ritchie, 1972. Crop water productivity is defined here as the
ratio of crop yield to ET. This relationship compares the total yield of a certain crop with the amount of water used that is no longer available for other uses.

The GEPIC model combines EPIC with GIS software using an approach to transfer data between the two. ArcGIS is used to edit input data and program and display simulated output. Types of input data required for the GEPIC model include location, slope, climate, soil, land-use, plant and management information. GIS raster datasets are used to input data into GEPIC. The “UTIL” program is used to generate “EPIC input files”, and GEPIC runs the EPIC model for each simulated grid. Output files are generated for three primary output variables: crop yield, ET and CWP.

The GEPIC model is advantageous for users who wish to model crop yield, ET and CWP at varying spatial scales, ranging between field and global levels. The relatively straight-forward graphical user interface (GUI) also makes the GEPIC model user-friendly. GEPIC-simulated output was compared with FAO statistical yields for 102 countries over 10 years, and it was concluded that the model performed well. Due in part to its collaboration with the GIS software, the accuracy of GEPIC model output is strongly correlated to the quality and level of detail of input data. Simulations with the GEPIC model could be improved with more detailed knowledge of the spatial distribution of crops and crop planting patterns. GEPIC is limited in that it is not yet capable of accurately addressing the issue of pest infestation on a global scale, although EPIC does have a generic component to address this problem. For use in large countries, GEPIC should be calibrated and validated on a smaller-than-national scale. The GEPIC model has been applied in a variety of studies at the global scale, including those by Liu, 2009 and Rosenzweig et al., 2013. The GIS-based EPIC model has also been applied at a national scale, such as in an application of the model in China by Peng et al., 2007.

2.4.5 LPJmL

The Lund-Potsdam-Jena managed Land (LPJmL) model was developed in response to a need to evaluate agriculture on the basis of global climate and vegetation, as identified by Bondeau et al., 2007. LPJmL is a global vegetation and water balance model. It analyzes the conversion of vegetative areas to agricultural land under global climate change scenarios and investigates the non-linear biophysical and biogeochemical features associated with this conversion. It also attempts to assess the impact of factors such as climate, CO2 levels, land management and land-
use change on future provisions of ecosystem services including food, fibre and energy crops, climate regulation and water purification.

The concept of crop functional types (CFTs) was developed to group crops or grasses according to similarities in function. Thirteen CFTs in total were added, covering both arable crops and grasslands. The use of CFTs in the LPJmL model allows for an acceptable variety of plant types to be used in simulation, while increasing the applicability of the model overall by neglecting to mimic any specific cultivar of crop. Various crop characteristics (summer vs. winter cultivars for example) reflect an optimal variety of plant types. Additionally, in order to simulate the impacts of environmental and management factors on crop yield and development, a daily carbon allocation scheme is used.

Overall crop growth and yield for each CFT are simulated according to sowing date, phenology, leaf area and growth, carbon allocation, irrigation, harvest, residue management, intercropping and managed grass/grazing. Crops modelled within LPJmL have annual life cycles (due to climate or human actions). Processes with both daily and annual time-steps are used to model crop growth, including photo-synthesis, respiration, evapotranspiration and the allocation of photosynthates to plant organs. Crop growth modelling in both the SWAT (Arnold et al. 1994) and SWIM (Krysanova and Wechsung 2000; Krysanova, Hattermann, and Wechsung 2005) models is considered in the implementation of LPJmL. Other input data required include climate, atmospheric CO₂ and land-use information extending from the year 1901 to 2000. Climate input is accepted on a monthly temporal scale for temperature, precipitation, total number of wet days and sunshine hours at a 0.5° resolution. Water storage derived from fossil groundwater resources or reservoirs is not computed due to a lack of appropriate data. Soil and atmospheric CO₂ information are used as in Sitch et al., 2003. Uncertainties arise due to significant variations in global estimates of soil carbon. Bondeau et al., 2007 have concluded that total soil carbon results from LPJmL are reasonable, if uncertain. Additionally, the model does not currently simulate fluxes associated with greenhouse gases other than CO₂, although methane and N₂O emissions will be implemented into the same structure.

The LPJmL model is relatively simple as it requires few input parameters compared to other crop and water balance models. The model is widely applicable because it uses local climate data to
simulate various factors associated with crop phenology. The underlying concepts of the model have also been validated through analysis of simulated data against selected benchmarking data from various sources. Biophysical and biogeographical observations such as leaf phenology, CO$_2$ fluxes and crop yields align well with model predictions, as do hydrological simulations including soil moisture, runoff and evapotranspiration (Rost et al. 2008). The LPJmL model has been used to test the influences of land-use or management practices on food/feed production. According to Bondeau et al., 2007 it is expected that LPJmL would perform well under a variety of unknown future conditions including climate change scenarios and increased atmospheric CO$_2$ levels. LPJmL has been applied in a variety of global applications, including those by Rosenzweig et al., 2013 and Gerten et al., 2011.

2.4.6 GCWM

While there have been many statistical studies on global blue water resource consumption, the concept of green water consumption and its temporal variability has, despite its importance, not been the focus of global water resources assessments (Rost et al. 2008). Blue crop water use refers to the evapotranspiration of irrigation water that originates from surface or subsurface water bodies, while green crop water use refers to evapotranspiration due to precipitation on cropland (Siebert and Döll 2010). The Global Crop Water Model (GCWM) was developed to establish a clear distinction between blue and green crop water use, allowing for an improved analysis of human impacts on global freshwater sources (Siebert and Döll 2010). GCWM is a crop water model that simulates both the blue and green water requirements of three primary crop groups (23 major crops in total) and is described fully in Siebert and Döll, 2008. Simulations are run on a daily time step at a spatial resolution of 5ft by 5ft.

GCWM builds on the Water GAP model with improvements including input requirements for cropping patterns and cropping calendar, increased range of crop commodities from two to 23 and increased spatial resolution from 30 to 5 arc minutes. Portmann et al., 2008 determined cropping patterns at a 5ft by 5ft spatial resolution and growing seasons for 402 spatial units. Climate input parameters include monthly values for precipitation, number of wet days, mean temperature, diurnal temperature range and cloudiness at a spatial resolution of 30ft by 30ft. Long-term averages for precipitation, number of wet days, diurnal temperature range, sun shine percentage, wind speed
and relative humidity are also required at a spatial resolution of 10’ by 10’. At this resolution, daily values are interpolated from monthly values by applying cubic splines as in Press et al., 1992.

Reference evapotranspiration in GCWM is simulated using either the Priestley-Taylor method (Priestley and Taylor 1972) or the FAO Penman-Monteith approach (Allen et al. 1998). Maximum daily crop evapotranspiration is also computed based on the evapotranspiration expected from healthy and well-watered crops. According to Allen et al., 1998 this parameter is a function of a crop coefficient and the reference evapotranspiration. Actual evapotranspiration is also computed following Allen et al., 1998, as a function of soil water content, soil water capacity, the fraction of total soil water capacity that can be extracted by a crop from the root zone without water stress, and the maximum daily crop evapotranspiration. Soil water balances are computed for each sub-crop of an overall crop class in each of the 5ft by 5ft grid cells.

For rain-fed crops, green water consumption is equal to actual evapotranspiration. For irrigated crops, soil water balances are performed separately for two cases: first for the assumption that the soil does not receive irrigation water, and second for the assumption that the soil does receive irrigation water. Green water consumption for irrigated crops is computed as actual evapotranspiration, while blue water consumption for irrigated crops is equal to the difference between computed and actual evapotranspiration. In GCWM, evapotranspiration may also be computed separately for conditions with snow or frozen soil.

Sources of uncertainty identified by Siebert and Döll, 2008 include crop growing areas, cropping calendars, parameters used to compute daily crop coefficients, the methodology used to compute reference evapotranspiration and spatial and temporal resolution of climate data. Other uncertainties are introduced due to soil properties, limited availability of input data (resulting in grouping of several crops), sensitivities in paddy rice cultivation and assumptions for water use in irrigated agriculture (Siebert and Döll 2010). While it is difficult to validate the model’s simulations with data for rainfed crop production, simulations of irrigated crop production are relatively consistent with external statistical information in Europe, the U.S.A. and other developing countries. Suggested improvements for future use of the GCWM model include attempting to use actual soil depth to restrict effective rooting depth for crops, improving the spatial resolution of climate input data, acquiring more extensive data on irrigated and rain-fed agriculture.
for countries other than the U.S.A., and comparing and validating GCWM against other global models (Siebert and Döll 2010). GCWM has been applied in a variety of global studies, including that of Siebert and Döll, 2008.

2.4.7 PODIUMSIM

The PODIUMSIM model, described in full detail by Amarasinghe, 2005, is a tool designed to assess water balance and food security under various future scenarios. The PODIUMSIM model was developed on the same foundation as the PODIUM model, which considers four main categories for analysis: 1) food consumption, 2) food production, 3) water demand, and 4) water supply. The PODIUMSIM model does vastly improve the spatial and temporal scales of analysis from the PODIUM model. Food consumption simulations remain on national and annual scales; however, while remaining on a seasonal temporal scale, food production migrates from a national to a river basin scale. Water demand and supply estimations are also performed at river basin and annual scales in PODIUMSIM, with the exception of irrigation water requirement calculations, which use a monthly temporal scale.

The water balance depends on water supply and water demand and considers water requirements for irrigation, domestic, industrial and environmental uses. Irrigation water requirements for agriculture are estimated based on 75% exceedance probability rainfall, potential evapotranspiration, crop calendars, length of crop growth periods, crop coefficients, crop areas, groundwater irrigated area, percolation requirements for paddy and project efficiency (both in terms of surface irrigation and in terms of groundwater irrigation). Domestic and industrial water requirements differentiate between human and livestock water allocations, and are a function of urban and rural populations, daily withdrawals per capita for urban and rural populations, percent urban and rural populations with pipe water supply, number of animals, daily per animal water requirement and total industrial water requirement. Consideration to environmental flow requirements is new to the PODIUMSIM model. Drivers of this component of water demand include annual river flow requirement, monthly renewable surface water resources, potentially usable water resources, and percentage of minimum flow needed to be met from potentially usable water resources. The estimation of usable water resources reflects water availability for agricultural, domestic and industrial sectors. This factor is now estimated at the river basin level, and considers surface water, groundwater, water transfers to other river basins, and the
environmental water requirement. For water used in the agricultural, domestic and industrial sectors, the PODIUMSIM model also estimates evapotranspiration or consumptive use, balance flows, return flows, groundwater recharge, non-process evaporation, and non-usable or usable flows to sea.

Food consumption and production simulations are based on consumption and production patterns for eleven crop categories. Consumption considers population, daily calorie supply, percentage of calorie supply to various food sectors, per capita food consumption, feed conversion factors and other uses. Crop production is a function of gross and net irrigated area, irrigated and rain-fed crop areas, and irrigated and rain-fed crop yield. Applications of PODIUMSIM include previous studies in Uzbekistan by (Yakubov and Manthrithilake, 2009), China (Li et al., 2007) and India (Yee et al., 2009).

2.4.8 CERES & VIC

The amalgamation of the Crop Environment REsource Synthesis (CERES) model and the Variable Infiltration Capacity (VIC) hydrological model allows for an assessment of future climate change scenarios on cereal production in China. The joint application of these two models was introduced in Wei et al., 2009. As explained in Jones et al., 2004 and Xu et al., 2007, high-resolution climate scenarios (at a scale of 50km by 50km) are produced using the ‘Providing Regional Climates for Impacts Studies’ (PRECIS) atmospheric regional model. Changes in future CO$_2$ emissions are used to produce simulated changes in daily temperature, radiation and precipitation. One limitation in this procedure is that a simple carbon cycle model is used, and thus the effects of feedback in the climate-carbon cycle are not considered in the estimations of CO$_2$ concentrations. Future socio-economic scenarios are also produced at the provincial level using methodology outlined in Nakicenovic and Sward, 2000 and Gaffin et al., 2004.

Agricultural, industrial, domestic and municipal water requirements represent water demand projected for these scenarios. Agricultural/irrigation water requirements are projected based on the assumption that technological advancements, management and policies will continue to improve irrigation water use efficiency. Economic and technological advancements are also considered for industrial and domestic water demands. Future conversions in arable land are projected at a 50km by 50km grid scale using provincial level relationships between GDP and change in arable land
area. Three primary adaptations are considered in the agricultural sector: changes to water allocation policies, changes to arable land policies, and improvements in agricultural technology. For water allocation policies, highest priority is given to the domestic sector, followed by the agricultural sector. In terms of arable land policies, future conversion of arable land is assumed to decline to half the current conversion rate. Future crop yields are assumed to increase due to general improvements in agricultural technology.

Three CERES models are used to project crop yield and potential irrigation demand for rice, maize and wheat in future scenarios at a 50km by 50km resolution. Both rain-fed and irrigated crop areas are considered and modelled according to crop pattern distributions from China in 2000 (Wei et al. 2009). Crop responses to CO$_2$ levels in climate change scenarios are simulated based on FACE experiments Kimball et al., 2002. Total cereal production is estimated based on projected arable land conversion rates, crop-planting patterns and crop mix, irrigated or rain-fed crop areas and crop yield per land area unit.

Runoff, surface flow, groundwater flow, lateral flow and evapotranspiration are all considered in hydrological estimations using the VIC model. For each grid cell, daily water yield is calculated and transformed into annual total water yield for ten river basins across China. Water available for irrigation purposes is calculated and compared to crop irrigation water demand. Available water is then allocated to paddy rice (due to the prevalence of paddy rice across China) and then to maize and wheat.

This modelling framework produces estimations of total and per capita cereal production from 2011 to 2050 using the following combinations of scenarios:

- Climate change;
- Climate change and CO$_2$ fertilization effects;
- Climate change and water availability;
- Climate change, CO$_2$ fertilization effects and water availability;
- Climate change, water availability and arable land loss;
- Climate change, CO$_2$ fertilization effects, water availability and arable land loss.
The results of these simulations are compared with current production simulations (climate data from 1961-1990 and agricultural technology and area information for the year 2000). It should be noted that the PRECIS model gives wetter conditions than the average model output. There is also significant uncertainty in the ability of the climate model to fully capture spatial and temporal variations for extreme events. Important events such as temperature peaks and soil moisture deficits may also increase uncertainty when simulated in crop models during critical stages in growth cycles. Rates of change and areal estimates associated with agricultural land-use have large uncertainty due primarily to issues with measured data and the role of policy interventions in arable land conversion. The crop growth model does not consider influences due to changes in distribution, pests, disease, changes in management practice, or the multiple cropping index, and optimum crop inputs are assumed. The hydrological model assumes that current management practices and water-use efficiency will continue in the future, and that the initial planting and irrigation areas may be used to make any future predictions. Computations of water demand do not consider requirements for non-grain crops or for livestock and it is assumed that water available for irrigated agriculture is always available at the appropriate times.

The overall model is likely to underestimate the negative effects of extreme scenarios on crop growth and water availability. Variables not considered in the overall modelling approach include changes in groundwater levels due to irrigation and urban water use, declining soil fertility, crop prices, international trade and changes in food consumption patterns. Spatial scale limits the ability of the modelling framework to identify significant variations in results at the provincial level. It is also limited in its ability to differentiate between simulated results for a variety of crops and identify the effects of more extreme high temperatures on crop yield. The amalgamation of the CERES and VIC models was applied by Wei et al., 2009 in a study of future cereal production in China.

2.4.9 CAPRI (Extended Model)

Due to the need to improve sustainable water use in agricultural practices, the following model, proposed by Blanco et al., 2012, built on the CAPRI agricultural modelling framework (Leip et al. 2011). It includes a new component to assess irrigated agriculture in its analysis of water use and agricultural production in the European Union (EU).
The CAPRI model comprises a supply module, which estimates agricultural production over approximately 280 regions with up to ten farm types per region, and a market module, which simulates the market for approximately 60 agricultural commodities in 77 countries and 40 trade blocks. Input data for the model are derived from well-documented sources including the Food and Agriculture Organization of the United Nations (FAOSTAT), the Organization for Economic Co-operation and Development (OECD), and a source for European statistics (EUROSTAT). The supply module comprises individual models that each estimate agricultural activities over different regions. These models incorporate an approach based on Leontief technology, which is associated with production variables including land, feed and crop nutrient requirements. They also include a non-linear cost function which incorporates labour and capital in terms of agricultural practice. Land supply and demand, agricultural policy, nitrogen, phosphorus and potassium mass flows and greenhouse gas emissions are considered in the supply models; however, prices are separate, and are considered in the market module.

The CAPRI model has several advantageous characteristics as compared to other agricultural models. Incorporation of crop-water relationships and changes in land constraints are relatively simple. Irrigation water may be input as a quasi-fixed production factor, which is desirable in the EU because the availability of irrigation water may limit agricultural production in some regions. Environmental indicators including irrigation intensity, water use intensity and water stress may also be computed at a regional level.

The proposed extended CAPRI model incorporates water use for irrigation/agricultural practices in the supply module. Crop production is divided into irrigable and non-irrigable categories, and irrigable activities are further divided by irrigated and rain-fed areas. Irrigation water use for specific crops is estimated based on theoretical crop water requirements, rain-fed and irrigated crop shares and crop yield. CAPRI uses an econometric method for the allocation of costs in farming practices. In addition to agricultural water demand, municipal, industrial and livestock requirements are also considered in the extended model. Several key considerations for these sectors include population, industrial production and herd sizes. A distinction is made between total water use, consumptive water use and water withdrawal. Water use efficiency is given by the ratio of consumptive water use to water withdrawal. This modelling approach was tested in a pilot case study in Andalusia (Blanco, Van Doorslaer, and Britz 2012); however, it has not yet been
further developed and tested in other regions. A limitation of the extended CAPRI model is the lack of relevant homogenous data available across the EU. The model should also be altered so as to accurately consider competition between agricultural and non-agricultural water uses. The developed model is intended to assess potential impacts of climate change and water availability on agricultural production. The extended CAPRI model (with water analysis included) has not yet been implemented, but has been proposed for study within the European Union by Blanco et al., 2012.

2.4.10 GFWS

The Global Food and Water System (GFWS) platform examines food and water security for various scenarios affecting population growth, changes in food consumption patterns, fertilizer use, water use, crop improvement, land-use and irrigation rates (Grafton, Williams, and Jiang 2015). It does so by simulating gaps between food production and demand, and water supply and agricultural water demand. Details associated with the function, operation, advantages and limitations of the GFWS model are all based on work by Grafton et al., 2015. Nineteen countries that have significant food production contributions are included in the analysis, along with seven major crop types: wheat, rice, maize, sorghum, barley, oats, and soybean. The platform allows user alterations for crop improvements and changes to arable land area.

Several key parameters for the food demand sector include population growth and food requirement growth. Food supply is a function of crop yield and area, as well as irrigation and fertilizer rates. A linear annual increase in productivity is used to simulate genetic improvements. Water demand for agricultural purposes is a function of land-use, crops and area under irrigation. In this case, the area under irrigation is determined according to FAO statistics. Climate data is derived from the SWAT database, and crop calendars for irrigated crops are given by the FAO database.

In the GFWS platform, weather, crop, soil and management input data are used to simulate crop yield using the Agricultural Production Systems Model (APSIM) according to McCown et al., 1995, McCown et al., 1996 and Keating et al., 2003. Water availability and nitrogen use are modified between simulations, and a crop yield database for a variety of conditions is established. Separately, various scenarios for population growth, calorie demand, dietary change, international
trade and irrigation techniques are formed using the OECD, UN or FAO. Scenarios are designed in a spreadsheet format where they are blended with information from the crop yield database to analyze future gaps in the water and food balance.

Scenarios of population growth are formed using population projections by World Bank up to the year 2050. Food requirements are altered using information from the FAO forecast, as are changes in meat consumption patterns, which in turn affect feed requirements. Data required to simulate food export for various countries is also given by the FAO database. Arable land area may be increased by up to 50% by the user to simulate land-use change scenarios, with arable land data derived from the World Bank database.

The GFWS model platform does not account for increases in water demand for industrial, domestic or environmental purposes, which results in over-estimation of available water. Model output indicates that increased food production will require input intensification, implying that increases in agricultural land, water use or fertilizer use will be necessary. This will present a challenge due to ever-increasing competition for these resources from other sectors. The GFWS model was applied in a global context by Grafton et al., 2015.

2.5 Discussion

The ten food and water security models reviewed in the past section were all created under different circumstances in order to serve a variety of purposes. While some of the platforms are suitable for global analyses of food and water security, others require more detailed input data and have been validated at regional or river basin scaled analyses (see Table A4). Several models place more focus on either food or water security indicators in terms of their model output.

Before using one of these modelling platforms, it is essential that any user identify and understand the primary goal of their study. With this goal in mind, an appropriate food and water security model can be selected or adapted to fit the needs of the study based on its primary purpose, area of application, spatial and temporal scale of analysis, level of complexity and input parameters.

Other factors to consider when choosing an appropriate modelling platform include type of output or information provided, and previous regions of application or validation for the model. Several key drivers have been identified to contrast and compare the ten food and waters security models
described in this manuscript. These drivers are derived from six principle categories: water demand, water supply, food demand, food supply, climate-related input and economic factors. A preliminary analysis to fit several of these key drivers to the scope and overall purpose of a modeler’s study will supply the foundation upon which to begin model selection and input data collection. Table A5 presents a comparison of these factors for the ten food and water security models reviewed in the preceding sections.

Key concepts that differentiate most of these models include depth of scenario analysis for climate change impacts, consideration to environmental water requirements, estimation of water requirements outside of the irrigation sector, consideration to green water requirements in addition to blue water, range of crop commodities utilized, and the impact of international trade. Many existing models focus on climate change impacts, and fail to consider variability, frequency, and intensity of extreme climate events (Y. Kang, Khan, and Ma 2009). Some of the models optimize growing conditions and water availability, which results in over-estimation of available water resources (de Fraiture, 2007). Environmental flow requirements are neglected in several of the modelling approaches (Alcamo et al., 2001; Bondeau et al., 2007; Grafton et al., 2015; Liu et al., 2007; Siebert and Döll, 2008; Wei et al., 2009); if ignored, this could potentially result in resource degradation due to mismanagement and overuse. The relationship between land-use and green water is frequently ignored, as water policy refers almost exclusively to blue water consumption (Lundqvist and Steen 1999). Considering both green and blue crop water use in analysis is important as the majority of the world’s food production comes from rain-fed agriculture, which is related to green water consumption (Lundqvist and Steen 1999). Table A6 presents several limitations of each of the food and water security modelling approaches reviewed in this manuscript.

In order to move forward with the application of any of these food and water security modelling platforms, several points for potential improvement should be considered. Variations in crop consumption patterns affect the overall water balance through evapotranspiration and irrigation water requirements, while variations in meat and poultry consumption patterns affect the overall food balance due to changes in feed requirements. Appropriate modelling platforms should be flexible to allow for adaptations to consumption patterns and diets, soil parameters, climate, economic factors and other geographic variables.
Future modelling efforts should also consider the influences of agricultural, domestic, industrial, livestock and environmental requirements on water use and availability. Due to the prevalence of green water consumption in agricultural production, this concept should also be considered in an effective model. Spatial and temporal resolution should continue to be improved to increase the level of detail and accuracy in model output. Greenhouse gases other than CO$_2$ should be considered when modelling future climate change scenarios. Models should be able to be calibrated and run on a sub-national level, especially for larger countries. Lastly, less data-intensive models would be appropriate for assessment in regions with limited data availability.

2.6 Conclusion

As challenges to global food and water security persist and intensify, the study of their connection and relationship to one another is becoming increasingly imperative. There remains considerable uncertainty with regard to the ability of predictive tools to assess the state of future global food and water situations. Modelling platforms to jointly analyze food and water systems exist; however, further developments and adaptations are still required in order to improve modelling capabilities and provide opportunity for a more complete analysis and understanding of future food and water security. Models must be able to assess a wide variety of potential future scenarios in geographically diverse locations. To accomplish this, appropriate spatial and temporal scales and correct input parameters for the diverse locations are required. Without water security, food security will be unattainable. Research into the fundamental connections between food production and water availability are an essential step toward achieving global food and water security while ensuring environmental sustainability.
3  Trend Analysis for Water Security in the Grand River Watershed

3.1  Introduction

Water security is an indicator for overall health, prosperity and happiness within communities, and insecurities currently pose a significant threat to the global population. According to Vörösmarty et al., 2000, approximately 1.8 billion people (30% of the global population at the time) were living under severe water stress. A more recent study assessing water security and threats to biodiversity on a global scale concluded that nearly 80% of the global population’s water security is at risk (Vörösmarty et al. 2010). Countries in Africa, South Asia and the Middle East are most at risk to experience water scarcity, although areas in the United States, Australia and Southern Europe experience relatively high water scarcity as well (Gain, Giupponi, and Wada 2016).

Many physical, economic and social factors influence water security in a region. Some of these stressors include environmental factors such as climate, topography, geology and geography, as well as anthropogenic variables such as population growth, urbanization and industrial or commercial development. In the coming decades, water resources systems will be under a considerable amount of pressure as the total global population continues to grow and global weather patterns shift in response to climate change. Due to the inevitability of these factors, developing an understanding of our water resources systems is as important now as it has ever been, in order to adopt appropriate measures for water governance and land-use management.

While Canada is often thought to be highly “water secure” due to the abundance of fresh water available for consumption, various sectors of the population do still face significant threats to water security. In the prairie region of central Canada, water availability is ever-decreasing and a growing concern, while water quality and availability remain a significant concern for many Indigenous communities across the country (Cook and Bakker 2012). In Ontario, the province with the highest population density in all of Canada, the total population is expected to increase by at least 30% over the next 25 years (Ontario Ministry of Finance 2017), exacerbating the pressures on local water resources systems. In Southern Ontario this growth is magnified, with the total population of the Greater Toronto Area expected to increase by over 40% during this time (Ontario Ministry of Finance 2017).
The goal of this study is to analyze trends in water security for a particular region in this highly populated area of Southern Ontario: the Grand River Watershed (GRW). Located west of the Greater Toronto Area, the GRW is the largest watershed in Southern Ontario, thereby influencing water security for a large proportion of the total population in the region. Although previous studies have used various modelling techniques and assessment tools to analyze water security in the watershed (Southam et al. 1999; Sanderson 1993), there is a need for more direct analyses, using real historical data to develop a better understanding of more recent localized trends. The primary objectives of this study include the following: (1) identify environmental and anthropogenic stressors affecting water security in the GRW, (2) characterize recent, historical trends in the temporal and spatial distribution of these variables, (3) analyze the potential impacts of these stressors on water availability and (4) assess the general state of water security in the GRW.

3.1.1 Overview of Water Security

Water security is a multidimensional concept that has been defined and redefined over decades. Previous definitions focused primarily on human aspects of water quantity and availability, including water governance and the management of fresh water resources for human consumption. These definitions encompass the need for fresh drinking water as well as water requirements for agricultural use, health and sanitation and industrial and commercial processes. Definitions of water security have since been revised to incorporate environmental water requirements, recognizing the importance of maintaining ecosystem functions for biodiversity (Cook and Bakker 2012).

This study utilizes a three-dimensional conceptual framework to assess water security. This framework incorporates three key elements: availability, accessibility and sustainability. Availability is the total supply of water resources available to satisfy all human and environmental water requirements. Accessibility is defined as the physical and economic access to water resources of adequate quality to sustain human and ecosystem health. Sustainability encompasses water governance and management to maintain availability and accessibility in the long-term and protect against water-related hazards including flooding and drought. These definitions are summarized in Figure 3.1.
3.1.2 Water Security Analyses

Many studies have used a variety of different methods to quantify and assess water security across the globe. These methods include indicators and assessment tools that measure water stress, availability and scarcity, concisely presenting scientific data to stakeholders from a variety of different academic backgrounds. Other methods include various conceptual, empirical, analytical and simulation-based modelling frameworks that indirectly evaluate the impact of changing variables and scenarios on water security. The spatial scales of these tools vary, from the community or sub-basin level to a global scale.

3.1.2.1 Water Security Assessment Studies

Norman et al., 2013 developed a method for assessing water security status at a watershed, or sub-watershed, scale. Identifying the need for a connection between scientific assessment or measurement of fresh-water related security issues and changes in governance and policy, this study developed an original approach to improve upon these and other drawbacks of existing indicators. The Water Security Status Indicators (WSSI) method adapts to incorporate governance, participation and overall scale on a community-level. The findings of this study by Norman et al., 2013 determined that one of the key barriers to assessing water security issues is data – availability, accessibility, quality, consistency and dissemination being the primary data-related issues barring successful water security analyses. Other important considerations that were identified for future assessments included identification of specific groundwater/surface water-related issues and attention to water quality and quantity.

Plummer et al., 2013 developed a process to assess water vulnerability in First Nations communities in Southern Ontario, identifying the need for approaches that consider socioeconomic, as well as physical barriers to water security. Their approach recognizes the ‘holistic’ and culture-based perspective of Indigenous peoples in relation to water and other natural resources (Plummer et al. 2013). The research process involved developing a conceptual framework with specific indicators for various sub-dimensions of water vulnerability, community questionnaires, interviews and analysis of secondary data (Plummer et al. 2013). The results produced a water vulnerability score for each First Nations community involved in the case study,
highlighting specific vulnerabilities for each community and gaps in knowledge for further assessments.

Both studies by Norman et al. 2013 and Plummer et al. 2013 identified key issues that may be overlooked or underestimated in current water security assessments. These include data availability, which is a major constraint for many studies of this nature and limits the temporal and spatial resolution of analyses and findings. As it is widely accepted that the ideal spatial scale for analyzing and regulating water-related issues is within a watershed, a high level of detail is required in terms of climatic, hydrological, topographical and geological data. Data consistency and availability is therefore an area with vast potential for improvement, especially for smaller, less-studied watersheds across the globe. Another key observation was the need for holistic approaches that incorporate socioeconomic considerations throughout the analysis of water security and other related issues. In terms of water security specifically, socioeconomic factors such as income level, rates of chronic and mental illness and cultural ties to the environment are deeply impactful. This observation highlights the importance of recognizing the unique and specific needs of various communities and sub-groups with respect to water use, management and research. Water security assessments and analyses should therefore aim to tailor their research and methodologies to consider the direct and indirect implications of results for vulnerable sectors of the population or local sub-groups with significant socioeconomic disparities.
3.1.2.2 Hydrological Modelling Platforms

Southam et al. 1999 examined the potential impact of climate variability and future climate change on water supply and demand in the Grand River Watershed in Ontario, Canada. Using the Water Use Analysis Model (WUAM) and 21 scenarios incorporating future population, water use/regulations and surface water supply, the study assessed the capability of the local hydrologic system to maintain target streamflow levels at specific locations throughout the watershed.

Adamowski and Bocci, 2001 analyzed monthly and annual trends in historical river discharge data using observations from 248 river stations in the Environment Canada ‘Reference Hydrometric Basin Network’ (RHBN). Grouping these stations into ten, non-overlapping, homogenous regions across Canada, each with strongly correlated data between river stations, the study developed a spatiotemporal model to estimate regional temporal trends in river discharge.

Döll et al., 2003 used the WaterGAP Global Hydrology Model (WGHM) to quantify and derive water availability indicators. The WGHM uses 0.5° grid cells as well as the highest-quality available data sets to compute monthly runoff and river discharge (Petra Döll, Kaspar, and Lehner 2003). Long-term average river discharge is computed at more than 700 gauging stations globally, within 1% of observed values (Petra Döll, Kaspar, and Lehner 2003). Döll et al. 2003 assert that the WGHM can produce reliable results for river basins larger than 20,000km². All of these factors make the WGHM a suitable framework for global analysis of water security.

These studies used different tools to assess changes in water supply and availability for varying spatial scales. Some used unique and holistic methods to assess water stress and vulnerability for local regions and communities based on a variety of site-specific indicators. Others indirectly evaluated the potential impact of climate change projections and other scenarios on future water security. For regional analyses, historical observations may be able to provide a clearer picture of localized trends at a watershed, or sub-watershed scale, and could provide more accurate estimates of the potential effects of changing anthropogenic and environmental variables on water security in the immediate future. These direct analyses, utilizing real data, could be extremely important when it comes to managing local water resources and developing related policies and regulations in the near future.
3.1.3 The Grand River Watershed (GRW)

The Grand River Watershed (GRW) is the largest watershed in Southern Ontario, spanning a 6,800 km\(^2\) area north of Lake Erie between Toronto and London (Grand River Conservation Authority 2018b). Figure 3.2 shows the GRW and surrounding cities and surface water bodies. The watershed is currently home to approximately one million people, and this number is steadily growing. Although close to 70% of the GRW is made up of agricultural land, the recent population growth trend has resulted in land development surrounding larger cities such as Guelph, Waterloo, Kitchener and Brantford.

The GRW includes regions with both moderate and cool-temperate general climate patterns. There are four primary seasons, with relatively cold winters seeing precipitation in the form of snow, and hot and humid summers (Lake Erie Source Protection Region Technical Team 2008). Although relatively evenly distributed throughout the year, precipitation patterns are usually inconsistent from month to month. The GRW comprises four climate regions: the Dundalk Uplands, Huron Slopes, South Slopes and Lake Erie Counties. Sitting at the highest elevation within the watershed, the climate in the Dundalk Uplands is slightly cooler, with average annual temperatures of about five to six degrees Celsius and 950 to 1,000 mm of precipitation annually. The Huron Slopes and South Slopes, both located in the centre of the GRW, are impacted by winds from the Northwest over Lake Huron. The result is a “snowbelt” with higher rain and snowfall accumulation (Lake Erie Source Protection Region Technical Team 2008). The average annual temperature in these regions is between six and seven degrees Celsius, with total annual precipitation between 850 to 950 mm. The Lake Erie Counties region experiences milder temperatures due to winds over Lake Erie, with average annual temperatures between seven to seven and a half degrees Celsius, and total annual precipitation between 850 and 900 mm. The GRW experiences extreme and unpredictable weather events including tornadoes, extreme snowfall, droughts and the remnants of major hurricane events (Lake Erie Source Protection Region Technical Team 2008).

Hydrologic conditions vary significantly throughout the GRW. The topography is quite flat in the northern region of the watershed and is primarily till plain, resulting in higher surface runoff and low infiltration to groundwater. The centre of the watershed is primarily moraine and sand/gravel deposits, resulting in very high infiltration rates and low surface runoff. The southernmost area of the GRW is located in the Haldimand Clay Plain region, again with very high surface runoff and
low infiltration (Lake Erie Source Protection Region Technical Team 2008). About 82% of the total population within the GRW relies on groundwater for water supply, with the remaining percentage relying primarily on the river system (Lake Erie Source Protection Region Technical Team 2008).

The Grand River Conservation Authority (GRCA) is the oldest water management agency in Canada, overseeing planning and management for water and other natural resources throughout the GRW (Grand River Conservation Authority 2018a). In 2012, the GRCA Board approved the new GRCA Strategic Plan, with the following five key Strategic Objectives to promote environmental health and sustainability within the GRW:

- Protect life and minimize property damage from flooding and erosion;

Figure 3.2: The Grand River Watershed (GRW) and surrounding region.
▪ Improve watershed health;
▪ Connect people with the environment through outdoor experiences;
▪ Maintain an organization with a focus on teamwork, development, engagement and positive change; and
▪ Deliver value and innovation to watershed stakeholders.

These objectives aim to maintain or improve water availability and quality, reduce flood damages, protect biodiversity and provide environmental education (Grand River Conservation Authority 2018a). Results from the present research may have significant implications in terms of the achievement of the Strategic Objectives outlined by the GRCA.

The GRW is also home to the largest First Nations reserve in Canada, Six Nations of the Grand River (SNGR), with members from the Mohawk, Cayuga, Onondaga, Oneida, Seneca and Tuscarora nations. Located approximately 25 km southwest of Hamilton, the SNGR territory spans close to 18,000 hectares, with a total population of about 12,000 to 13,000 people (Six Nations Elected Council 2018). Although SNGR resides close to some of the largest urban cities in Canada, it remains one of the most vulnerable communities in the region in terms of food, water and socioeconomic security. This is due in part to the history of abuse, neglect and forced cultural assimilation that has impacted Indigenous peoples across Canada since the arrival of European settlers in the 16th century (Préfontaine 2018). This has resulted in newer generations being disconnected from spiritual and cultural traditions, history and ways of life, experiencing mental and chronic illnesses at higher rates than the general population (Chiefs of Ontario and Cancer Care Ontario 2016).

Studies assessing water security in a region or watershed should pay special consideration to vulnerable sectors of the population. Many of these communities already face dire situations in terms of water health and may be more heavily impacted by anthropogenic and environmental changes. SNGR is a significant consideration for water health and security within the GRW, and this research will discuss potential impacts of the results of this study on vulnerable sectors of the population in the watershed.
3.2 Methodology

Environmental and anthropogenic factors affecting water security in the GRW were identified based on a review of ongoing and historical changes in the GRW region. The primary stressors in this region include population expansion and urbanization, due to exponential population growth in Southern Ontario, and global climate change. Several key variables that represent these stressors were selected for analysis based on the availability and accessibility of associated data and include: precipitation, temperature, population and farming area. Precipitation and temperature are both climatic variables representing the impacts of global climate change on localized weather patterns. Population represents the overall population growth in the area, while total farming area is a general representation of changes in land use and development occurring in the GRW region.

To characterize spatial and temporal changes in these factors and water availability throughout the GRW, data on each of these variables were collected. River discharge data were retrieved from a Government of Canada (GOC) source for hydrometric tools and data (Government of Canada 2018b). Precipitation and temperature data were retrieved from GOC archives of historical climate data (Government of Canada 2018a). Population and farming area data are both available on a county-level basis and were retrieved from Statistics Canada census profiles for population (Statistics Canada 2001; Statistics Canada 2006; Statistics Canada 2011; Statistics Canada 2016) and agriculture (Ontario Ministry of Agriculture Food and Rural Affairs 2018a). Due to the spatial resolution of these data by county, the total study area for this research was expanded beyond the boundaries of the watershed to include counties either completely, or partially contained within the GRW.

3.2.1 GRW Study Area and Timeline

The main interest of this research was to evaluate recent trends in the GRW, to better understand and be able to estimate future trends in the short-term. Based on this objective and the temporal availability of data for each of the variables involved in this analysis (discussed below), the most suitable timeline for this study was 2000-2015. Figure 3.3 shows the GRW and the counties and First Nations territory that were included in this study. The Wellington, Waterloo and Brant counties are all located almost entirely within the GRW. Dufferin county was included as it spans the northernmost region in the GRW. Hamilton county was included, as a sizeable portion of the
county lies within the GRW. It also encompasses a relatively densely populated area in close proximity to the Greater Toronto Area, with significant potential to impact present and future changes within the GRW. Haldimand county was included as it covers the entire lower portion of the watershed, including the watershed outlet. Finally, although most of Norfolk county is not located within the GRW, it was incorporated in this study because statistics for the Norfolk and Haldimand counties are jointly published. Additionally, the First Nations territory located within the watershed encompasses both the Six Nations of the Grand River (SNGR) and Mississaugas of the New Credit (MNC) First Nations. Together, these counties, territories and the GRW comprise the total study area for this research.
3.2.2 Historical Climate Data

3.2.2.1 Primary Physical Data Collection

Environment and Climate Change Canada retains archives of historical data as observed, recorded and reported by the Meteorological Service of Canada. These archives provide daily, hourly or monthly recordings of climatic variables such as temperature, total precipitation, depth of snow on the ground and wind speed, reported at over 8,700 climate stations throughout the country. The procedures followed to record and report these measurements have been developed in accordance with methodology established by the World Meteorological Organization (Government of Canada 2016).

Several different types of climate stations display data in these archives. Many are staffed volunteer stations, observing climate data twice daily and using these observations and a ‘climate day definition’ to report daily measurements. Other stations are automated, reporting daily measurements based on six-hour summary reports. Measurements of total precipitation at these climate stations include rainfall, drizzle, freezing rain, freezing drizzle, snowfall, snow pellets, snow grains, ice pellets, dew, frost, rime and glaze. To the nearest 0.2mm, measurements are given by the vertical depth of water (or equivalent) that reaches the ground in a particular area and are taken using a variety of suitable gauges and calibrated graduates. Temperature measurements indicate mean, maximum and minimum temperature over a specific interval using a combination of thermometers and other equipment.

3.2.2.2 Climate Stations

The various types of historical climate data discussed above were available for multiple climate stations throughout the study area, over varying periods of time. Initially, precipitation and temperature data were collected for nine climate stations spanning the region with available and accessible data. After further analysis, the Brantford MOE climate station was eliminated because a vast number of data points were missing, and the results were not usable. The remaining eight climate stations used in this study are shown in Figure 3.4.

Although the Port Colborne climate station is located outside of the GRW study area, it most accurately represents climate in the southernmost region of the GRW region. The other seven climate stations (Orangeville MOE, Fergus Shand Dam, Glen Allan, Roseville, Hamilton, Scotland
and Delhi) best represent climate conditions over the rest of the watershed study area. Together, these eight stations give a reasonable indication of varying climate patterns across the region. The historical timeline for data collection, method of operation and frequency of observations for each climate station are summarized below.

**Orangeville MOE Station**

At the Orangeville MOE Station, daily and monthly climate data are available from 1961 to 2015. This station is a manned volunteer station reporting temperature and precipitation measurements once daily, in the morning, until service was permanently discontinued in 2015. The Mono Centre Station (located about 14km away) is now the station closest in proximity to Orangeville MOE that continues to report climate data.

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Figure 3.4: Climate stations and hydrometric stations included in this study.

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Fergus Shand Dam Station

At the Fergus Shand Dam Station, daily and monthly climate data are available from 1939 to present. This station reports temperature and precipitation measurements twice daily, in the morning and afternoon.

Glen Allan Station

At the Glen Allan Station, daily and monthly climate data are available from 1955 to 2013. This station reports temperature and precipitation measurements twice daily, in the morning and afternoon. The most recent data observed at this station is not publicly available but has been recorded on paper charts.

Roseville Station

At the Roseville Station, daily and monthly climate data are available from 1972 to present. This station reports temperature and precipitation data twice daily, in the morning and evening.

Scotland Station

At the Scotland Station, daily and monthly climate data are available from 1971 to 2014. This station reports temperature and precipitation measurements twice daily, in the morning and evening. The most recent data observed at this station is not publicly available but has been recorded on paper charts.

Delhi Station

At the Delhi Station, hourly, daily and monthly climate data are available from 1997 to present. This station is automated, reporting daily data based on six-hour summary reports.

Hamilton A Station

At the Hamilton A Station, hourly, daily and monthly climate data are available from 1970 to present. This station is owned and operated by NAV CANADA (a privately-run company that owns and operates civil air navigation service within Canada (Nav Canada 2018)).
Port Colborne Station

At the Port Colborne Station, daily and monthly climate data are available from 1964 to present. This station reports temperature and precipitation measurements twice daily, in the morning and afternoon or evening.

3.2.2.3 Compilation of Secondary Data

Daily precipitation and temperature data were collected at each of these climate stations and converted to represent annual values. Missing data was an issue for many of these climate stations. This could be attributed to measurements being missed for certain days, either due to human error or equipment malfunction. Additionally, for climate stations that depend on two observations to report daily measurements, if only one of these observations is received, the daily data is not derived and therefore not reported. Several methods do exist to handle or estimate missing data values including listwise deletion, which omits cases with missing data, mean substitution, which utilizes the mean value of a variable in place of all missing data values, and the last observation carried forward (LOCF) method, which replaces missing data values with the observation that immediately precedes it (Kang 2013). These methods all have drawbacks that must be considered before they are utilized. The listwise deletion method, which is most commonly used, may introduce bias by simply ignoring data that is missing or incomplete (Kang 2013). The mean substitution method may also introduce bias, especially when missing data values are not necessarily random (Kang 2013). The LOCF method relies on the assumption that the variable outcome is unaffected by the missing data, and therefore also introduces bias (Kang 2013). In this study, a protocol was developed to deal with missing data in such a way that most of the available data could be used, while attempting to maintain the reliability of the reported observations and reduce bias for stations with large amounts of missing data.

Before converting the collected daily data to annual values, the number of days missing data per year at each climate station was calculated. Any years missing more than 60 days of data (in total) were automatically eliminated. For years missing between 0 and 60 days of data, only those missing more than 15 consecutive days of data were eliminated. This allowed for preservation of reliable data for the analysis, while ensuring that years missing entire months of data or more...
would not skew the final results. Tables A1 and A2 summarize the years for which temperature and precipitation data were incorporated into this study for each climate station.

3.2.3 Population and Farm Area Statistics

3.2.3.1 Physical Data Collection

Statistics Canada utilizes the Census Program to provide national, provincial and municipal statistics every five years (Statistics Canada 2018). The program records economic, social and cultural statistics relating to household and family characteristics, as well as economic agricultural statistics. Data types include age, occupation and income level, languages spoken and mobility status (Statistics Canada 2018).

3.2.3.2 Compilation of Secondary Data

The Census Program is run every five years, giving population and agricultural statistics in 1996, 2001, 2006, etc. For this study, population and farm area statistics within the GRW study area were retrieved for the years 2001, 2006, 2011 and 2016. Although the timeline for this study was 2000-2015, these are the years for which the Census profiles align most closely with the given timeline. Population estimates could not be found for the SNGR community for 2001 and 2006. The total population in the GRW study area is therefore underestimated by the uncertainty in the SNGR population estimate for those periods, which is approximately 12,000 (representing an error of less than 1%).

3.2.4 Grand River Discharge Data

3.2.4.1 Physical Data Collection

Environment and Climate Change Canada retains historical collections of hydrometric data, recorded at over 7,700 hydrometric stations across Canada. Current hydrometric observations are monitored at over 1,900 hydrometric stations across the country. These archives give daily or monthly measurements of river discharge and primary water level.

3.2.4.2 Hydrometric Stations

Historical hydrometric data were available for multiple river gauge stations throughout the GRW study area. Since the Grand River is the primary tributary conveying water through the watershed
to the basin outlet at Lake Erie, it was the main focus for assessing water availability in the GRW study area. Hydrometric data were retrieved for the six stations along the Grand River located within the study area (Grand River at Brantford, Grand River at Galt, Grand River near Doon, Grand River at West Montrose, Grand River below Shand Dam and Grand River near Marsville). All these stations operate and record hydrometric observations on a continuous basis. The historical timeline for data collection and gross drainage area for each river station are summarized below.

Grand River at Brantford
At this river station, hydrometric data are available from 1913 to present. The gross drainage area for the Grand River at this location is approximately 5,200 km$^2$.

Grand River at Galt
At this river station hydrometric data are available from 1913 to present. The gross drainage area for the Grand River at this location is approximately 3,520 km$^2$.

Grand River near Doon
At this river station hydrometric data are available from 2006 to present. The gross drainage area for the Grand River at this location is approximately 2,490 km$^2$.

Grand River at West Montrose
At this river station hydrometric data are available from 1967 to present. The gross drainage area for the Grand River at this location is approximately 1,170 km$^2$.

Grand River below Shand Dam
At this river station hydrometric data are available from 1950 to present. The gross drainage area for the Grand River at this location is approximately 785 km$^2$.

Grand River near Marsville
At this river station hydrometric data are available from 1947 to present. The gross drainage area for the Grand River at this location is approximately 663 km$^2$. 

44
3.2.4.3 Compilation of Secondary Data

Monthly mean river discharge and mean water level data were collected at each of these river stations and converted to represent annual values. Missing data was also a critical issue for many of these river stations, likely due to human error or equipment malfunction. To deal with the missing data while ensuring that most of the available data could be used, a similar protocol to the one applied with the climate data was used for the hydrometric data.

Before converting the collected monthly data to annual values, the number of months missing data per year at each river station was determined. Since the number of consecutive days per month missing data could not be determined, any years missing an entire month of data or more were eliminated. Through this analysis it was also determined that an adequate supply of water level data was not available, and only river discharge data would be considered. Table A3 summarizes the years for which river discharge data was incorporated into this study at each river station.

To compare and analyze river discharge at each of the river stations along the Grand River, a flow ratio was used (given by Equation 3.1). The flow ratio is a measure of mean annual river discharge (m$^3$/s) at a specific river station versus total drainage area (km$^2$) for that river station.

$$\text{Flow ratio} = \frac{\text{Mean river discharge}}{\text{Drainage area}}$$ (3.1)

3.3 Results & Analysis

The compilation of these data at various points and regions across the GRW study area led to a more comprehensive understanding of both temporal and spatial changes in the GRW since the year 2000. Annual variations in each variable were examined over the 16-year study period to understand overall temporal trends. Spatial variations were analyzed using GIS software to estimate and interpolate values over the entire study area.

3.3.1 Historical Climate Data

To illustrate temporal climatic variations across the GRW study area, and simplify the presentation of these data, results are shown below for four of the eight climate stations identified earlier: Fergus Shand Dam, Roseville, Hamilton A and Port Colborne. These four climate stations were chosen
for two reasons: altogether they have the fewest gaps in data availability during the study period, and effectively capture temporal variations across the entire study area.

3.3.1.1 Temperature

Figure 3.5 shows plots of mean, maximum and minimum annual temperature at the Fergus Shand Dam, Roseville, Hamilton A and Port Colborne climate stations for the years 2000-2015. The black data points indicate years missing sufficient data to be included in this study. For these points, the curves simply interpolate values for those years. Figures 3.5 (a), (d), (g) and (j) illustrate that the mean annual temperatures at each of these climate stations followed similar patterns over time. These trends are periodic in nature, with peaks occurring approximately every four to six years. A slight downward overall trend in mean annual temperature for the GRW region between 2000 and 2015 is observed in most of these plots. A more apparent visual trend appears for extreme values of the mean annual temperature curves at each climate station. Each plot shows a clear upward trend for the peak values on the curve, and a downward trend for the low values. This suggests that although the mean annual temperature at each climate station did not appear to trend upward or downward significantly over the 16-year study period, the overall mean temperatures are tending toward values of higher magnitude each cycle. A variety of factors could be contributing to these more erratic weather patterns. Local changes in population, land-use and a variety of other anthropogenic factors could be impacting local climate. This could also be a small indication that local weather patterns are being affected by global climate change, as this phenomenon is predicted to increase the occurrence of extreme weather events.

Figures 3.5 (b), (e), (h) and (k) show the maximum annual temperatures at the four climate stations between 2000 and 2015, while Figures 3.5 (c), (f), (i) and (l) show the minimum annual temperatures during this time. These data show similar periodic fluctuations to the mean annual temperature data, although there is an increased frequency in variations. This is to be expected, since maximum and minimum annual values are measures of temperature on one single day of the year, while mean annual temperature considers data points over the course of the year. The mean, maximum and minimum temperature plots do reach peak values and low values on roughly the same timeline. This indicates that most years that had higher overall mean temperatures also experienced the highest maximum temperature values, while years that had lower overall mean temperatures also experienced the lowest minimum temperature values. The highest overall mean
Figure 3.5: (a) (b) (c) Mean, maximum and minimum annual temperature at Fergus Shand Dam, respectively; (d) (e) (f) Mean, maximum and minimum annual temperature at Roseville, respectively; (g) (h) (i) Mean, maximum and minimum annual temperature at Hamilton A, respectively; (j) (k) (l) Mean, maximum and minimum annual temperature at Port Colborne, respectively.
temperatures were observed in 2001, 2006 and 2012, while the lowest overall mean temperatures were seen in 2003, 2009 and 2014.

Figure 3.6 illustrates the spatial variation in overall mean temperature throughout the study area between 2000 and 2015. This map was developed using GIS software and the ‘spline’ method to interpolate a smooth surface using data points at each of the eight climate stations in this study. This interpolation method depends on two primary criteria: the interpolated surface passes directly through the input points and must have minimum curvature (Esri 2018). The map in Figure 3.6 shows a clear pattern for overall mean temperatures throughout the study area, with the lowest temperatures occurring in the northernmost region of the watershed, and the highest temperatures occurring in the southernmost region. Notably, the highest temperatures also occurred closest to the Great Lakes, while the lowest temperatures occurred farther in-land.

In certain regions the Great Lakes can impact temperatures by creating somewhat milder climates, especially near the Niagara Peninsula, where the Niagara Escarpment drastically affects temperatures within tens of kilometres. The Port Colborne climate station and southernmost portion of the GRW are located on the border of Lake Erie and close to the Niagara Peninsula, while the northernmost portion of the GRW is located roughly 100km in-land from any of the Great Lakes. It is therefore expected that temperatures in the South, near the Great Lakes, would be warmer on average than temperatures in the northern GRW.

### 3.3.1.2 Precipitation

Figure 3.7 shows plots of total precipitation, total rainfall and total snowfall at the Fergus Shand Dam, Roseville, Hamilton A and Port Colborne climate stations for the years 2000-2015. The black data points indicate years missing too many daily observations to be acceptable for this study. Figures 3.7 (a), (d), (g), and (j) illustrate that the total annual precipitation at each of these climate stations fluctuated periodically from year to year, similarly to the patterns exhibited with the temperature data. Figures 3.7 (b), (e), (h) and (k) show total annual rainfall at the four climate stations between 2000 and 2015, while Figures 3.7 (c), (f), (i) and (l) give total annual snowfall during this time.

Precipitation patterns were different at each climate station, with the Fergus Shand Dam station showing a clear upward trend in total annual precipitation and rainfall, and the other stations
showing downward trends, especially at the Port Colborne station. These two stations also exhibited the largest and most consistent fluctuation patterns from year to year, while at the Hamilton A and Roseville climate stations precipitation levels fluctuated less consistently. Of the four climate stations, the Fergus Shand Dam station experienced the most snowfall, on average, while the Port Colborne station received much less snowfall during this time period. Conversely, average rainfall was slightly higher at Port Colborne than at Fergus Shand Dam. The increase in rainfall and decrease in snowfall at Port Colborne could be a result of the milder temperatures observed at this climate station (see previous section). The highest precipitation values were observed at most of these climate stations in 2006, 2008 and 2011. In 2008 several stations also experienced more snowfall in comparison to other years. The lowest precipitation values were
Figure 3.7: (a) (b) (c) Total annual precipitation, rainfall and snowfall at Fergus Shand Dam, respectively; (d) (e) (f) Total annual precipitation, rainfall and snowfall at Roseville, respectively; (g) (h) (i) Total annual precipitation, rainfall and snowfall at Hamilton A, respectively; (j) (k) (l) Total annual precipitation, rainfall and snowfall at Port Colborne, respectively.
generally observed in 2007, 2012 and 2015. 2012 was also the year with the lowest recorded snowfall for many of these climate stations.

Figure 3.8 illustrates the spatial variation in mean annual precipitation throughout the GRW study area between 2000 and 2015. This figure shows that although a spatial pattern in precipitation across the watershed is not as easily identifiable as the spatial variation in mean temperature, less precipitation is generally observed toward the centre of the region, as compared to the watershed border.

In terms of the overall climate, average temperatures within the GRW fluctuated relatively consistently from 2000 to 2015, with the most extreme temperatures having been observed close to the end of the study period. Spatially, average temperatures varied consistently throughout the GRW, likely due in part to geographical features in the area including the Great Lakes and the Niagara Peninsula. If climate trends from the past 15-20 years are a possible indication of local weather patterns in the GRW in the short-term future, it may be expected that every four to six years warmer-than-average temperatures will be experienced in the region, followed by much colder average temperatures several years later. Precipitation patterns were less consistent than temperature patterns over time and at different climate stations, although at most of the stations precipitation did fluctuate periodically from year to year.

Extremely warm or cold years within the GRW study area do not appear to correlate strongly with total precipitation or rainfall; however, there could be a relationship between mean annual temperature and total annual snowfall. The years with the highest mean annual temperatures (2001, 2006, and 2012) also had minimal snowfall as compared to other years in this study. This is expected, as with higher temperatures more precipitation would tend to fall as rain or sleet, than as snow.

These climatic trends could have significant implications for planning, policy and resource management within the GRW and associated counties over the next 15-20 years. Two key areas that could be affected are agricultural production and water resources management. Even seemingly minute changes in mean annual temperature can adversely affect agricultural production, both directly and indirectly. This is evidenced by findings from Peng et al., 2004, which found that a 1°C increase in mean annual minimum temperature correlated with a 10%
decline in grain yield in a study analyzing historical climate and agricultural data in the Philippines between 1979 and 2003. Precipitation and extreme weather events may intensify in certain regions, according to current climate change scenario projections (Rosenzweig et al. 2002). Increased precipitation and resulting floods can negatively impact agricultural production, damaging crops and reducing yield for food production. Rosenzweig et al. 2002 used a dynamic crop model to simulate the effect of increased precipitation on crop growth and determined that corn production losses in the United States may double between 2002 and 2032 (Rosenzweig et al. 2002). The recent temperature and precipitation patterns observed within the GRW could have similar adverse impacts on crop production that should be investigated in the next few years.

Figure 3.8: Spatial variation in mean annual precipitation between 2000 and 2015.
In terms of water resources management, the observed changes in temperature within the GRW could have a significant impact on hydrologic cycles in the area. Warmer periods could increase summer evapotranspiration, decreasing groundwater recharge and surface runoff rates and elevating the risk of drought. These periods could also decrease total annual snowfall and increase the frequency of melt events during winter months. Cooler periods could be accompanied by increased precipitation and surface runoff, along with higher flood risk. A potential increase in either flooding or drought periods could have adverse effects on stormwater management, flood risk management and water quality.

3.3.2 Population and Farm Area Statistics

Figure 3.9 illustrates the variation in total population and total farm area within the study area between 2001 and 2016. The total population in the region increased steadily, by close to 15%, since 2001. Southern Ontario and the Greater Toronto Area are the most populated regions in all of Canada, attracting migrants from across Canada and the world. The population in the GRW and surrounding regions will therefore likely continue to increase over the next 15-20 years. In contrast, total farm area increased slightly in 2006, and decreased afterward as compared to 2001 census data. The considerable decrease in total farm area over this time could be an indication of urbanization and commercial or residential land development in the area, coinciding with the increase in population.

These changes have potential implications for agricultural and water management as well. Population growth increases stress on existing food and water resources, as demand for food and water also increases. Urbanization not only minimizes land use for agricultural production, it can also have a significant impact on hydrologic cycles, increasing surface runoff and adversely affecting water quality.

3.3.3 Grand River Discharge Data

Figure 3.10 shows the annual flow ratios for each of the six Grand River stations between 2000 and 2015. These data all exhibit a very similar overall pattern, ranging from minimum values of 0.0075\(\text{m}^3/\text{s}/\text{km}^2\) to maximum values of 0.0207\(\text{m}^3/\text{s}/\text{km}^2\). The Marsville and West Montrose river stations generally had the highest flow ratios, while the Brantford and Doon stations had the lowest flow ratios. This could partially be attributed to the fact that the Marsville and West Montrose...
Figure 3.9: Total population vs. total farm area within the GRW study area between 2001 and 2016.

Figure 3.10: Annual flow ratio for the six Grand River flow gauges between 2000 and 2015.
stations are both farther north, in less populated and less developed regions of the GRW. With less land development in these areas, surface runoff to the Grand River and its tributaries would likely be lower; however, there would also be far less consumption of river water, as there are few towns or cities located upstream of these stations. At each of the flow gauges, data exhibit periodic fluctuations similarly to the climate data discussed above. Figure 3.10 also shows a substantial increase in the magnitude of these fluctuations midway through the study period in 2006, indicating that at this time the mean river discharge began to reach more extreme maximum and minimum values. The increased fluctuations in river discharge could be associated with the observed decrease in total farm area, which is a potential indicator for increased land development and higher surface runoff. It could also be an indication that annual consumptive water use has not been consistent in this region.

Figure 3.10 also illustrates a clear upward trend in the annual flow ratios at all river stations. The upward trend is most likely indicative of changes to the local hydrologic cycle, and this could be attributed to a multitude of factors. Climatic variations affecting precipitation levels in the region are a likely cause, as precipitation directly impacts the volume and distribution of surface water. These effects could be intensified in the Grand River, because it is the primary conduit conveying water throughout the GRW. Therefore, changes in precipitation throughout the watershed could indirectly impact the Grand River through any of its tributaries. Other possible factors are increasing land development in the region, which would reduce soil permeability and increase surface runoff, and the effects of wastewater effluent on river discharge.

Figure 3.11 shows the mean annual river discharge for each of the Grand River stations between 2000 and 2015. Mean annual river discharge was highest at the southernmost river station along the Grand River (Brantford), closest to the watershed outlet, and lowest at the northernmost river station (Marsville).

Water management and availability have significant implications for many aspects of resource protection and control. First, the demonstrated increase in total flow along the Grand River could have severe environmental and safety implications. Higher-than-average flows could be detrimental for local ecosystems and species and could decrease water quality by introducing larger amounts of sediment to river discharge. Environmental and water quality issues in the Grand
River and its tributaries affect water security not only within the watershed, but also below the watershed outlet (in this case, Lake Erie). Increased flow could also affect safety and security in terms of flood risk and its potential impact on physical property, financial security and preservation of human life. The increased intensity of yearly fluctuations in river discharge could contribute to safety concerns by increasing the frequency of more extreme flow levels. These fluctuations also make future water availability less consistent and less predictable, affecting communities that depend on the Grand River for fresh water supply.

3.3.4 Climatic Variables vs. Surface Water Availability in the GRW

Figures 3.12 and 3.13 show mean annual river discharge alongside mean annual temperature and total annual precipitation, to provide a basis for analyzing the potential relationships between river discharge and these climatic variables. Grand River flow gauges at Brantford and Marsville were chosen for this analysis because they had the most available data and are also the southernmost and northernmost river stations along the Grand River, respectively. Hamilton A and Orangeville MOE climate stations were selected because they are located closest to the Brantford and Marsville river stations, respectively, and are the best estimates of climatic variations at these locations.
Mean annual temperature and mean annual river discharge show a positive correlation between 2000 and 2007 for both locations (Figure 3.12). During this time, increases in overall temperatures generally correlated with increases in mean river discharge, while average temperature decreases correlated with decreases in mean river discharge. After 2007, this trend changes, with peaks in temperature corresponding to large drops in mean river discharge, and vice versa. The timing of this change in pattern aligns with the increase in intensity of yearly river discharge fluctuations (mentioned above), which could be a contributing factor. Additionally, over the 16-year study period the fluctuations of both variables intensified simultaneously (i.e. the amplitudes of the curves have increased with time). These plots suggest that a relationship could exist between mean
annual temperature and mean annual discharge in the Grand River. Without further statistical analysis the relationship is difficult to precisely define; however, if temperatures continue to intensify over the next 15-20 years (as described by the trends in Section 3.1.1), it is possible that fluctuations in mean river discharge will also continue to intensify, as was observed over the study period.

Figure 3.13 shows mean annual river discharge along with total annual precipitation. These plots illustrate a correlation between these variables, as expected due to the direct impact of precipitation on river discharge. The trends are not perfectly correlated however, suggesting that precipitation is not the only variable influencing discharge conditions along the Grand River. Additionally, although mean annual discharge along the Grand River trended upward over this period, total annual precipitation trended slightly downward over the same time.

These plots show that there is a relationship between total annual precipitation and mean annual discharge along the Grand River. Although localized precipitation certainly does not seem to be the primary factor influencing the large increase in river discharge in the latter half of the study period, this could be attributed to the fact that precipitation patterns across the GRW indirectly affect flow in the Grand River through each of its tributaries. Future precipitation trends across the entire watershed would impact flow rates in the Grand River. If current precipitation trends intensify, as may be expected as a result of global climate change (Meehl et al. 2000), fluctuations in river discharge throughout the Grand River would likely intensify as well. These changes would have significant implications for the environment, infrastructure, and safety throughout the watershed, primarily in relation to flood control. There could also be implications for irrigation and agricultural practices in the region, with infiltration and soil saturation being affected by a changing hydrological cycle.

### 3.3.5 Anthropogenic Variables vs. Surface Water Availability in the GRW

Figure 3.14 displays the mean annual river discharge together with total population and total farm area between 2000 and 2016 (according to available data). With the increase in population observed over this time, and the associated increase in demand for water resources, river discharge would not necessarily be expected to increase during this period, as it is shown to. As mentioned previously in this study, less than 20% of the total population within the GRW relies on the river
network for water supply, with just over 80% relying on groundwater instead. Still, with a higher population and increased demand for fresh water, it could be expected that river discharge would fluctuate accordingly. Possible explanations for the overall upward trend in river discharge include changes in water use efficiency/management or an increase in land development. The latter is supported by the downward trend in total farm area shown in these figures, which could indicate that farm area in the region is being developed, thereby increasing total surface runoff into the Grand River and its tributaries.

Based on these observations, total population within the GRW study area has not necessarily had a direct impact on flow in the Grand River since 2000. In contrast, changes in total farm area may have impacted Grand River discharge during this period. Since population growth, urbanization and land development are likely to continue within the GRW over the next 15-20 years, it can be expected that these trends will continue, if not intensify. Continued land development within the watershed would have considerable implications for surface water protection and hydrologic cycles in the region.

3.4 Discussion

3.4.1 GRCA Strategic Objectives

The results of this study have implications for the achievement of the five Strategic Objectives laid out in the 2012 GRCA Strategic Plan. The first objective, concerned with preserving infrastructure
and human life from flooding and erosion, could be impacted by the erratic and fluctuating nature of climatic and hydrological observations since the year 2000. Observed mean annual temperatures tended toward values of higher magnitude, while total annual precipitation fluctuated inconsistently and somewhat unpredictably during the study period. If these trends continue and extreme weather events become more common, as may be anticipated with the effects of global climate change (Meehl et al. 2000), it will become more difficult to manage flooding within the GRW and protect against potential damages. Additionally, with a general upward trend in mean annual river discharge, it may become more difficult to adapt and protect current infrastructure during seasons with high water levels. Working toward this objective over the next 15-20 years will require improvements to new and existing infrastructure, as well as management plans developed to handle the potentially erratic nature of future weather patterns in the region.

The second objective, focused on improving overall watershed health, could certainly also be impacted by the trends shown with these climatic and hydrological observations. If the observed increase in magnitude of mean annual temperatures continues, this could affect hydrological system parameters such as evaporation, infiltration and surface runoff, impacting groundwater and surface water levels within the watershed. The increasing rates of population growth and land development within the GRW are also a concern for overall watershed health. The trends seen in this study could negatively impact water quality, decreasing more pervious land area and increasing surface runoff through urban areas. These changes could also affect groundwater recharge in the area – a significant concern since so much of the population depends entirely on groundwater for water supply. If more communities instead turn to the river network for water supply in the future, environmental water requirements will be a concern, and it will become more difficult to maintain both aquatic and terrestrial ecosystem health. Over time, even minor changes in mean annual river discharge, mean annual temperature or total annual precipitation could have a significant effect on factors such as agricultural production, plant life and biodiversity. Maintenance and improvement of overall watershed health will require continued observation of these trends in the future, and the use of measures that reduce the impact of pervious land development, where possible.

The final GRCA Strategic Objective focuses on the partnerships between the GRCA and various stakeholders within the region, including municipalities, provincial authorities, community groups
and First Nations communities. One challenge for this analysis and other similar studies is the contrast between the GRW boundary and municipal borderlines, making it more difficult to obtain fully accurate estimates of population or other census statistics within the watershed. In the future, these types of partnerships could be utilized to reduce these challenges and facilitate simpler, more comprehensive analyses at the watershed level.

### 3.4.2 Implications for Indigenous Communities

The changes being observed within the GRW and surrounding counties could have significant implications for the SNGR and MNC First Nations communities. A potential increase in more extreme weather patterns due to global climate change (Meehl et al. 2000) would certainly impact life in these communities, especially since the historical, cultural and spiritual roots of many Indigenous peoples are in the environment and the land. Although most dwellings in SNGR rely on groundwater for freshwater supply, a newly-built water treatment plant supplies water from the Grand River to approximately 500 homes and businesses, while another 315 homes are left without direct access to fresh water (McNeil 2014). It is clear that water access is still very much a concern for many members of this community, and the barriers to access could potentially increase along with the current environmental and anthropogenic factors affecting the GRW. This would be especially true if the magnitude of fluctuations in mean annual river discharge continue to increase.

SNGR is located in the south GRW, close to the outlet, where flow along the Grand River is much higher. The increasing trend in river discharge observed since 2000 therefore increases the risk of flooding and environmental damage near SNGR, as the effects would be compounded by any upstream tributaries throughout the watershed. Potential impacts to water quality due to increased river discharge would also impact SNGR and the surrounding area as these effects would also be compounded moving south through the watershed.

### 3.5 Conclusion

This study presented a methodology for directly analyzing historical data and the potential impacts of changing variables within the GRW on water security. The findings show that changes in local climate may have a substantial impact on surface water availability and river discharge throughout the watershed. As these climatic variables tend toward more extreme values, as is expected with global climate change and evidenced by some of the results in this paper, the local hydrologic
cycle and overall water security in the watershed will be affected. As it is the largest watershed in Southern Ontario, the GRW could also be an indicator for changes throughout the entire region.

The objectives of this research were achieved despite several constraints including the limited timeline and temporal scale for secondary data collection and analysis. Several other limitations that may affect future studies should be considered, and include the following:

- Limited availability of acceptable data (both spatially and temporally) for several key variables including precipitation, temperature and river discharge;
- Limited ability to capture detailed, localized changes in precipitation due to spatial data availability; and
- Lack of reliable ‘water level’ data for most hydrometric stations in this study.

For future studies in the GRW region to be successful, as many operable climate stations as possible are required, along with more consistent monitoring. This would vastly improve the ability to extend the timeline of analyses such as the one presented in this paper. It would also improve the spatial resolution of results. Recommendations for future studies addressing trends in water security in other watersheds include the following:

- Address inconsistencies with monitoring, recording and publicizing climatic and hydrological data (some stations continue to be monitored, but frequently experience data handling errors that render data unusable for monthly or annual analyses);
- Increase the number of climate stations and/or flow gauges included in future studies, if possible;
- Expand future analyses to consider multiple surface water bodies within the river network;
- Increase the overall timeline of future analyses to 25 or more years, if possible;
- Examine monthly data as well as annual data, to better understand seasonal variations; and
- Investigate groundwater and ways that historical data from monitoring wells across the region could be incorporated into the analysis.

Many studies have analyzed the potential impacts of climate change and other factors on water security using indicators, assessment tools and various modelling frameworks. It is also important, however, to examine trends in real historical data, as these observations could show key
relationships between different variables, help to predict short-term water availability and develop water management measures to preserve this resource.
4 Trend Analysis for Agri-food Production in the Grand River Watershed

4.1 Introduction
Globally, new challenges to food and water security continue to be presented by climate change and population growth. Food and water resources worldwide are under considerable pressure to meet resource demands, with undernourishment affecting an estimated 815 million people in 2016 (Food and Agriculture Organization of the United Nations 2017), and close to 2.1 billion people lacking access to safe drinking water (United Nations 2017). Recently, food insecurity in parts of Sub-Saharan Africa, South Eastern and Western Asia has worsened, especially in regions experiencing conflict or water-related hazards such as drought (Food and Agriculture Organization of the United Nations 2017). Countries in Africa, South Asia and the Middle East are also most heavily impacted by water scarcity (Gain, Giupponi, and Wada 2016).

Although Canada is usually considered “secure” in terms of both food and water resources, food and water security are still a concern for some of the population now and will continue to be a challenge in the future. Canada has an abundance of fresh water resources, yet many Indigenous communities across the country do not have access to safe drinking water and sanitation services. Additionally, the sustainability of food and water resources in Canada remains uncertain due in part to climate change, population growth and land development. Proper management of resources now and in the future is required to maintain and ensure overall food, water, social and economic security for future generations. In order to aid with resource management and decision-making, a number of studies have created or utilized various assessment tools, indicators or modelling frameworks to evaluate food or water security on different scales.

Lipper et al. 2014 introduced a unique approach for agricultural management under new scenarios of climate change. This climate-smart agriculture (CSA) approach aims to support future food security by integrating climate change into planning and management of agri-food systems (Lipper et al. 2014). CSA is intended to sustainably increase agricultural productivity, build resilience to the impacts of climate change on sub-regional and national scales and seek opportunities to reduce greenhouse gas emissions from agriculture (Lipper et al. 2014). This report represents a more conceptual, policy-centred approach to food security and resource management.
Kang et al. 2009 conducted a review of global climate and crop growth models, evaluating potential impacts of climate change on crop production and soil water balance. This study reviewed a number of process-based crop models, including Crop Environment Resource Synthesis (CERES) models for maize and wheat, the soil-water-atmosphere-plant (SWAP) model and the InFoCrop model (Y. Kang, Khan, and Ma 2009). These modelling frameworks suggest that with climate change impacts, crop yield will increase in some areas, primarily in cooler regions with more precipitation or irrigation, and yield will decrease in other areas (Y. Kang, Khan, and Ma 2009). Crop growing seasons may also increase along with CO₂ levels in certain areas, although incidences of pest and disease losses may also increase as well (Y. Kang, Khan, and Ma 2009).

Other process-based crop models include the Model to capture the Crop-Weather relationship over a Large Area (MCWLA), utilizing a daily time-step and various physiological processes to simulate crop growth and development (Tao, Yokozawa, and Zhang 2009), and the AquaCrop model, which simulates rainfed and irrigated crop yields based on plant transpiration, computed biomass and harvest index (Steduto et al. 2009). Other types of modelling frameworks that may be used to assess trends in crop production and future food security include empirical models, which rely on past observations to make predictions and meta-analyses, which combine data from multiple studies to identify overall patterns and assess the consistency of findings.

Located just west of the Greater Toronto Area, the Grand River Watershed (GRW) is a highly populated, agriculturally dominated region in Southern Ontario. This study aims to present and analyze recent, localized trends in food security in the GRW and, in conjunction with the previous analysis in Chapter 3 of this thesis, develop a better understanding of the potential impacts of various anthropogenic and environmental stressors on future food and water security. While previous studies have used a variety of water vulnerability indicators, assessment tools and conceptual, analytical or simulation-based modelling frameworks to indirectly assess water security within the GRW, to the authors’ knowledge, no study has attempted to jointly analyze food and water security-related trends in the GRW.

The trend analyses and discussion in this study will be important for future studies seeking to apply other statistical, analytical or simulation-based modelling frameworks in the GRW, or other similar locations. The visual analysis allows researchers to first use knowledge and experience to evaluate
possible food and water-related trends and their implications within the GRW before using further methods to study the data.

The primary objectives of this study include the following: (1) analyze and discuss recent spatial and temporal variations in climatic, hydrometric and anthropogenic variables within the GRW (as identified in earlier study by McNeill et al.); (2) characterize recent, historical trends in field crop and horticultural crop production throughout the GRW; (3) analyze the potential impacts of climatic, hydrometric and anthropogenic stressors on agri-food availability and food and water security within the GRW; and (4) assess the potential implications of recent trends for Indigenous communities located within the GRW.

4.1.1 Overview of Food and Water Security

The definitions of the terms ‘food security’ and ‘water security’ have been refined over the past several decades, yet they continue to vary considerably across different disciplines and fields of study. This study utilizes a three-dimensional conceptual framework to define food and water security, integrating three core elements: availability, accessibility and sustainability. Availability is defined as the total supply of food or water resources available for human use or consumption as well as, in the case of water availability, total supply available to satisfy environmental water requirements. Accessibility is defined as physical, social and economic access to food and water resources of adequate quality to sustain human and ecosystem health and support community health and security through spiritual, cultural and traditional ties to food and water. Sustainability incorporates governance and management strategies that are able to maintain long-term availability and accessibility and protect and against food and water-related crises. These definitions are summarized in Figure 4.1.

4.1.2 The Grand River Watershed (GRW)

Spanning a total area of 6,800 km², the GRW (shown in Figure 4.2) is located north of Lake Erie between Toronto and London and is the largest watershed in Southern Ontario (Grand River Conservation Authority 2018b). The watershed has a total population of close to one million people, and this number is steadily increasing. Approximately 70% of the land in the GRW is dedicated to agri-food production, although land surrounding larger cities such as Guelph, Brantford, Kitchener or Waterloo is steadily undergoing development.
There are four primary seasons in the GRW, with cold, snow-filled winters and hot, humid summers (Lake Erie Source Protection Region Technical Team 2008). Since it spans such a vast area, the GRW has various sub-climates with both moderate and cool-temperate climatic patterns. The four climate regions located within the GRW include the following: the Dundalk Uplands, Huron Slopes, South Slopes and Lake Erie Counties. Average annual temperatures in the northern Dundalk Uplands are generally between five and six degrees Celsius, with 950 to 1,000 mm of precipitation annually. In the centre of the GRW, climate in the Huron Slopes and South Slopes is influenced by winds from the Northwest over Lake Huron, resulting in higher rain and snowfall accumulation (Lake Erie Source Protection Region Technical Team 2008). Average annual temperatures in these regions are generally between six and seven degrees Celsius, with total annual precipitation ranging from 850 to 950 mm. The southernmost region, Lake Erie Counties, experiences average annual temperatures between seven and seven and a half degrees Celsius, with total annual precipitation between 850 and 900 mm. The GRW is located in a region that can also experience extreme weather events including tornadoes, extreme snowfall, droughts and remnants of hurricane events (Lake Erie Source Protection Region Technical Team 2008).

In the northern region of the GRW the topography is relatively flat. The primary soil type in this region is till plain, which contributes to higher surface runoff and low infiltration. In the central region of the watershed, moraine and sand/gravel deposits lead to very high infiltration and low

Figure 4.1: Three-dimensional conceptual framework for food and water security.
surface runoff. The southern portion of the watershed is located in the Haldimand Clay Plain region, which contributes to the very high surface runoff and low infiltration (Lake Erie Source Protection Region Technical Team 2008). Approximately 82% of the GRW population relies on groundwater for fresh water supply, while the remaining percentage primarily use the river supply network (Lake Erie Source Protection Region Technical Team 2008).

4.1.3 Six Nations of the Grand River (SNGR)

Located approximately 25 km southwest of Hamilton and within the GRW boundaries, Six Nations of the Grand River (SNGR) is the largest First Nations reserve in Canada. The SNGR territory spans close to 18,000 hectares and the total on-reserve population is between 12,000 and 13,000 (Six Nations Elected Council 2018). The SNGR community comprises the Mohawk, Cayuga,
Onondaga, Oneida, Seneca and Tuscarora nations. In terms of food, water and socioeconomic security the SNGR community remains vulnerable due to the many hundreds of years of abuse and forced cultural assimilation Indigenous peoples living on these territories have faced, which has resulted in the severance of many spiritual and cultural traditions and practices.

Due to these factors the accessibility aspect of food and water security, particularly in relation to the sustenance of community health through spiritual, cultural and traditional ties to food and water, remains a key concern for SNGR and many other Indigenous communities across Canada. Today, cultural knowledge surrounding the procurement, preparation and nutritional value of traditional foods is no longer the primary source for obtaining food for the SNGR community (Lickers 2014). Due to a lack of access to food options, food is primarily being procured off the reserve territory (Lickers 2014). One community initiative (“Our Sustenance”) aims to combat this reliance on externally-sourced food products. This initiative runs several programs including a Six Nations Community Garden, Six Nations Farmers Market, Good Food Box Program, Greenhouse operation and other food security-related workshops (Our Sustenance 2018). For fresh water supply, the majority of the SNGR community relies on groundwater, although a newly-built water treatment plant services close to 500 dwellings from the Grand River. Approximately 315 homes in the community do not have direct access to fresh water (McNeil 2014).

Due to the barriers and specific challenges that are faced by Indigenous communities in Canada in relation to sustainability and food and water accessibility, studies relating to food and water security should pay special consideration the needs and ideas of these communities and other vulnerable sectors of the population. These communities may be more heavily impacted by changes caused by anthropogenic or environmental disturbances. This study will discuss potential implications of results for SNGR food and water security.

4.2 Methodology

The methods and resources used for data collection and analysis in this study align closely with the methodology used in Chapter 3 of this thesis, which analyzed water security trends in the GRW and provides a foundation for the following research.
Stressors affecting food security and sustainability within the GRW were identified based on a review of recent changes in the region. The primary anthropogenic and environmental stressors that could influence food security include population growth, urbanization, water availability and security and localized impacts of global climate change. In order to quantify these stressors, characteristic variables were identified and selected for this analysis based on data availability and accessibility. These variables include the following: precipitation and temperature, which characterize localized weather patterns and climate change; total population; total farming area, which could be a representation of changes in land use and development in the region; and river discharge, which illustrates changes in water availability and overall water security in the region.

Data for each of these variables were collected from a variety of sources, and initially presented in the Chapter 3 of this thesis. Precipitation and temperature data were retrieved from GOC archives of historical climate data (Government of Canada 2018a). Total population and total farming area are both available on a county-level basis and were retrieved from Statistics Canada census profiles for population (Statistics Canada 2001; Statistics Canada 2006; Statistics Canada 2011; Statistics Canada 2016) and agriculture (Ontario Ministry of Agriculture Food and Rural Affairs 2018a). River discharge data were collected from a Government of Canada (GOC) source for hydrometric tools and data (Government of Canada 2018b). Data relating to agricultural production were retrieved from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) (Ontario Ministry of Agriculture Food and Rural Affairs 2018b). Due to the nature and availability of some of these data by county, the total study area for this analysis includes the GRW and several overlapping counties.

4.2.1 GRW Study Area and Timeline

The study timeline was limited to encapsulate recent food security trends in the early 21st century. The most suitable timeline, based on this aim and on the availability and accessibility of data, was 2000-2015. The total study area for this research (shown in Figure 4.3) comprises the GRW, seven overlapping counties and Indigenous territories. The Dufferin, Wellington, Waterloo, Brant and Haldimand counties all have a sizeable area located within the GRW. Hamilton County is primarily outside of the watershed boundary; however, a high population density means this region may still have a significant impact on changes within the GRW. Finally, although most of Norfolk County is not located within the GRW, this county was included in the study area because data from the
Haldimand and Norfolk counties are published together. Indigenous territories located within the watershed and this study area include Six Nations of the Grand River (SNGR) and Mississaugas of the New Credit (MNC) First Nations territory.

### 4.2.2 Historical Climate Data

Environment and Climate Change Canada retains archives of historical data, reporting climatic data observed and recorded at over 8,700 climate stations throughout the country by the Meteorological Service of Canada. Details pertaining to the use, operation and maintenance of these climate stations, specifically for those used in this study, can be found in Chapter 3 of this thesis.
4.2.2.1 Climate Stations

Eight climate stations (shown in Figure 4.4) located near the study area had suitable data for this analysis. Seven of these stations (Orangeville MOE, Fergus Shand Dam, Glen Allan, Roseville, Hamilton A, Scotland and Delhi) are located within the GRW study area. Although the Port Colborne climate station is located outside of the study area, it is the most accurate representation of climate in the southernmost region of the GRW study area. The timeline of historical data collection, method of operation and frequency of reported observations differ for each climate station and are summarized in Chapter 3 of this thesis.

4.2.2.2 Compilation of Secondary Data

Although annual precipitation and temperature values were used in this study, daily climatic data were initially collected from historical archives. Many of these climate stations displayed missing data for several days, weeks or even months within a given year. For these stations, missing data records could likely be attributed to human error or equipment malfunction while recording observations. Some of these stations rely on two measurements per day to derive daily data, so if only one of these observations is received, the data is not reported. To ensure that the data used in this study is reliable and reduce bias for stations with significant data shortages, a procedure was developed to either accept or reject annual values based on data availability for that year.

The number of days missing data per year, at each climate station, was calculated before converting the daily data to annual values. Years missing more than 60 days of data, in total, were eliminated. For years missing fewer than 60 days of data, only those missing more than 15 consecutive days at a time were eliminated from the analysis. This helped to ensure that years missing entire months of data or more would not skew results. Tables A1 and A2 summarize years for which climatic data were accepted for this study, for each climate station.

4.2.3 Population and Farm Area Statistics

The Census Program, operated by Statistics Canada, provides national, provincial and municipal estimates of household, family and agricultural statistics every five years (Statistics Canada 2018). Types of data recorded include age, occupation, income level, language spoken and mobility status (Statistics Canada 2018).
4.2.3.1 Compilation of Secondary Data

The Census Program provides economic, social, cultural and agricultural statistics for the years 1996, 2001, 2006, etc. For this study, county-level population and farm area statistics were collected for 2001, 2006, 2011 and 2016 as these were the years that fit best with the study timeline. Population estimates could not be found for the SNGR community for 2001 and 2006, so the total population for the study area in these years is underestimated by the estimated SNGR population for those periods, which is approximately 12,000 (close to 1% of the total population).

4.2.4 Grand River Discharge Data

Hydrometric data, including river discharge and water level data, are currently observed and recorded at over 1,900 hydrometric stations across Canada, and reported by Environment and
Climate Change Canada. Historical hydrometric archives are retained for over 7,700 hydrometric stations across the country.

4.2.4.1 Hydrometric Stations

The Grand River is the main tributary that conveys water through the GRW to the basin outlet at Lake Erie. For this analysis, river discharge along the Grand River was the primary variable used to assess trends in water availability within the study area. Data were retrieved for all six Grand River hydrometric stations located within the study area (Grand River at Brantford, Grand River at Galt, Grand River near Doon, Grand River at West Montrose, Grand River below Shand Dam and Grand River near Marsville). The historical timeline for data collection and gross drainage area for each hydrometric station are summarized in Chapter 3 of this thesis.

4.2.4.2 Compilation of Secondary Data

Monthly hydrometric data were collected and converted to annual values, in a similar process to the one used for the climatic data. Missing data, associated with human error or equipment malfunction, was an issue for these data as well. A similar protocol to the one used to evaluate the reliability of the climatic data was applied to the hydrometric data. The number of months missing data per year was calculated for each hydrometric station and any years missing an entire month of data or more were eliminated. Table A3 summarizes the years for which mean river discharge values were accepted for this study at each hydrometric station.

4.2.5 Agricultural Data

The OMAFRA compiles economic and agricultural data for the province of Ontario, in conjunction with the Agriculture Division of Statistics Canada (Ontario Ministry of Agriculture Food and Rural Affairs 2017). The OMAFRA provides yearly statistics related to the production of horticultural and field crops, dairy products, poultry and livestock. It also compiles information related to farming operations such as farming area, land-use type and overall provincial farming income, as well as economic statistics including manufacturing industry statistics for food, beverage and tobacco, sales statistics for the foodservice industry, and international trade data.

These data are acquired from three primary sources: surveys, the Census of Agriculture, and ‘administrative data’. Telephone, mail-in and enumerative surveys of farmers provide most
agriculture production statistics and are supported by supplementary information from government field officers, agribusiness personnel, and farm marketing boards (Ontario Ministry of Agriculture Food and Rural Affairs 2017). The Census of Agriculture is conducted every five years by Statistics Canada, and provides benchmark estimates for livestock inventory, crop area, land use and farm types, among others. ‘Administrative data’ refers to complete or nearly complete counts of certain statistics including imports and exports, and marketings of inspected or controlled commodities (Ontario Ministry of Agriculture Food and Rural Affairs 2017).

4.2.5.1 Compilation of Secondary Data

Several field and horticultural crops were chosen for this analysis. For the sake of simplicity, the scope of this study did not include analysis of dairy, livestock or poultry production, although these could certainly be key considerations for future studies. It should also be noted that various crops may be produced and utilized for purposes other than direct human consumption (for example, the use of corn in the production of ethanol), and these uses were not generally discussed within the scope of this study. Field and horticultural crops were chosen based on the total area dedicated to growing each crop in Ontario, as well as data availability. Historically, the four major field crops in Ontario are hay, soybean, grain corn and winter wheat. These four crops also exhibit the highest production values of all field crops in Ontario. Although hay production can have a significant impact on food production as it is used for animal feed, hay was not considered for this analysis because it is not directly consumed by humans. Annual data were therefore compiled for the three other major field crops during the study period. Total field crop production was also analyzed in this study. Grain corn, soybean and winter wheat accounted for between 55-70% of the total land area grown to field crops in Ontario from 2001 to 2016, or about 78-87% of the total land area grown to field crops excluding hay (Mailvaganam 2017). Given that grain corn, soybean and winter wheat account for such a high percentage of the field crop production in Ontario, it was assumed that together, these crops could provide a relatively accurate estimate of trends in overall field crop production.

In terms of horticultural crop production, the two most-grown fruits and two most-grown vegetables in Ontario (by area) were chosen for this analysis. The two major fruits for production in Ontario are grapes and apples. These two fruits exhibit the highest production values by far of all fruits grown in Ontario (Ontario Ministry of Agriculture Food and Rural Affairs 2018b). For
vegetables, data availability and production limitations in the study area meant that the first and fourth most-grown ‘vegetables’ in Ontario were chosen: sweet corn and field tomatoes (Mailvaganam 2017). In terms of total production, field tomatoes and sweet corn are the first and third most-grown ‘vegetables’, respectively (Mailvaganam 2017). Annual data were compiled for these four major horticultural crops during the study period.

4.3 Results & Analysis

Climatic, hydrometric, demographic and agricultural data were compiled across the GRW study area in order to better understand the temporal and spatial changes throughout the watershed over the period 2000-2015. Temporal variations were analyzed by evaluating annual data over the 16-year study period, while spatial variations were analyzed using GIS software to interpolate surfaces over the study area.

4.3.1 Historical Climate Data

To simplify the analysis, climatic variations are presented for four of the eight climate stations identified in this study: Fergus Shand Dam, Roseville, Hamilton A and Port Colborne. These stations have the most available data during the study timeline and are also spread throughout the study area so that they effectively capture spatial variations throughout the watershed. The results of this analysis are presented in Chapter 3 of this thesis.

4.3.1.1 Temperature

Chapter 3 showed plots of mean, maximum and minimum annual temperatures over time, at each of the four climate stations mentioned above between 2000 and 2015. According to the data presented in Chapter 3, mean annual temperatures within the GRW fluctuated periodically during the study period, with peaks occurring approximately every four to six years. Although a significant upward or downward trend in mean annual temperature could not be determined visually for any of these climate stations, most stations exhibited a very slight downward overall trend for this variable. All stations also exhibited a visible upward trend for the peak values of mean annual temperature, and a downward trend for the low values. This is an indication that mean annual temperature within the GRW is tending toward more extreme values over time. This phenomenon could be attributed to the effects of global climate change, as it has been predicted to cause more extreme weather patterns and events in the future.
The results from this study also indicated that most years that experienced the highest overall temperatures were also years that had the highest maximum temperature values, while years that experienced the lowest overall temperatures also had the lowest minimum temperature values. Notably, the highest overall mean temperatures occurred in 2001, 2006 and 2012, while the lowest overall mean temperatures occurred in 2003, 2009 and 2014.

Spatially, overall mean temperatures showed a clear pattern throughout the GRW. The lowest annual temperatures occurred in the northernmost regions, while the highest annual temperatures occurred in the southernmost regions, closest to the Great Lakes. These milder temperatures are likely significantly influenced by the effects of both the Great Lakes and the Niagara Peninsula.

4.3.1.2 Precipitation

Chapter 3 of this thesis also showed plots of total precipitation, total rainfall and total snowfall for the four climate stations between 2000 and 2015. According to these data, total annual precipitation also fluctuated periodically during the study period. The largest and most consistent fluctuations occurred at the Fergus Shand Dam (northernmost) and Port Colborne (southernmost) climate stations. Overall trends in total annual precipitation and rainfall were not consistent between climate stations, trending upward at the Fergus Shand Dam station and downward at the other three stations. The Fergus Shand Dam station experienced the highest snowfall during the study period, while the Port Colborne station recorded much less snowfall. Conversely, total rainfall was slightly higher, on average, at the Port Colborne station than at the Fergus Shand Dam station. These trends could both be attributed to the locations of these two stations with respect to one another, in that the Port Colborne station is located farther south and impacted more significantly by the Great Lakes. Overall, the highest precipitation levels were generally recorded in 2006, 2008 and 2011, while the lowest precipitation levels were seen in 2007, 2012 and 2015. The highest recorded snowfall occurred in 2008, while the lowest occurred in 2012. Spatially, a pattern for total annual precipitation is not easily identifiable, although there does appear to be slightly less precipitation toward the centre of the watershed, compared to near the boundaries.

These climatic trends could indicate that fluctuations in mean annual temperature may increase in magnitude over the next 10 to 15 years. There does not appear to be a strong relationship between the extremities in temperature fluctuations and total precipitation or rainfall; however, there could
be a relationship between mean annual temperature and snowfall. The highest annual temperatures overall (occurring in 2001, 2006 and 2012) correlated with minimal snowfall over the study period. These trends could have implications for resource management in the short and long-term future. More extreme temperatures and weather events could have adverse impacts on agricultural production, natural hydrologic cycles, stormwater management and water quality.

4.3.2 Population and Farm Area Statistics

Chapter 3 of this thesis also reported considerable changes in overall population and total farming area during the 16-year study period (adjusted to align with Census Program statistics). Between 2001 and 2016, the total population within the GRW study area increased by close to 15%. Due to the influence of attractive migratory destinations including Toronto and its surrounding cities, this level of population growth is expected, and will likely continue to increase significantly in the next 10-15 years. Conversely, total farming area showed a slight increase in 2006 as compared to 2001, and then decreased significantly by 2016. These changes in land-use could be a strong indicator for urbanization and land development in the area, coinciding with the increase in population. These changes also have implications for resource management within the GRW. Both agriculture and water management are severely impacted by anthropogenic changes that accompany population growth, as well as land-use changes that accompany urbanization. These changes could therefore increase stress on existing food and water resources within the watershed.

4.3.3 Grand River Discharge Data

Chapter 3 of this thesis compared annual flow ratios as well as mean annual discharge at each of the six Grand River hydrometric stations used in this study. The flow ratios for these stations aligned closely with one another, with the Marsville and West Montrose stations exhibiting the highest flow ratios on average, and the Brantford and Doon stations exhibiting the lowest flow ratios. Both the Marsville and West Montrose stations are located in the northern, less populated region of the watershed, and so this could be partially attributed to the lack of upstream water consumption in these areas. The overall trend for the flow ratio at all six river stations is upward, indicating possible changes to the hydrologic cycle associated with changing precipitation levels, and/or increasing land development in the region, which tends to increase surface runoff to surface water bodies.
Mean annual river discharge increased steadily from the northernmost hydrometric station to the southernmost station. This is to be expected as the GRW drains at its southernmost point, and the Grand River flows south, accumulating flow from each of its tributaries along the way. At each of these hydrometric stations, mean annual river discharge fluctuated periodically, with a substantial increase in the magnitude of these fluctuations in 2006. This abrupt increase in river discharge could be associated with the land-use changes and overall decrease in pervious land-cover associated with the observed population growth. It could also be associated with inconsistencies in water usage and management.

Chapter 3 also assessed the relationships between river discharge and climatic trends, overall population and total farm area. These analyses showed that, in the earlier half of the study period, mean annual temperature and mean annual river discharge correlated positively. After 2007, the trend reversed, with peaks in temperature corresponding to large decreases in river discharge. Both variables saw an increase in the magnitude of fluctuations over the study period, which could indicate that if mean temperature fluctuations continue to intensify over the coming years, fluctuations in river discharge could do the same. Total annual precipitation showed a positive correlation with river discharge over the study duration. These trends are not perfectly aligned however, indicating that variables other than precipitation also have a significant impact on river discharge.

The overall increase in river discharge over this study period aligns with substantial population growth and decreased farming area. Since less than 20% of the GRW population relies on surface water for consumptive uses, the changes in land use likely have more influence on river discharge trends than consumption. It therefore makes sense that decreasing farm area, indicating potential development of the more pervious farmland, aligns with increasing flow volume to the river network.

The changes observed for these anthropogenic and environmental factors, and the resulting trends in river discharge, could severely impact water security in the GRW in the coming years. The increase in river discharge could have negative implications for the environment, as higher flow rates could decrease water quality and be detrimental for both aquatic and terrestrial species. Increased flow along the Grand River could also impact planning and management in terms of
safety and security. With a higher risk of flooding, physical property, financial security and human life could face increasing threats. The annual fluctuations in river discharge could also make water supply less predictable for those communities that depend on this resource. With population growth, land development and the predicted increase in more extreme weather patterns and events with global climate change (some of which may already be being observed with these results in the GRW), environmental and safety implications to water security could become more severe as well. More recent research efforts are recognizing the significance of water security as it relates to food security and overall socioeconomic status as well. It is therefore vital to appreciate the importance of assessing these types of variables using an interdisciplinary approach, to fully comprehend the implications of the results presented in Chapter 3. The results presented above could have serious implications for agricultural production and food security within the GRW, as these factors are so closely linked to water health and security.

4.3.4 Agricultural Data

To illustrate trends in agricultural production throughout the GRW, both field and horticultural crop production data were compiled for the seven counties in this study. Some of the fruit and vegetable crops chosen for this analysis are not cultivated in every county. This is likely due to varying climatic, or possibly hydrological and geological conditions throughout the watershed. Some of these horticultural crops also exhibit data gaps in certain regions of the GRW. The results for horticultural crop production are therefore limited to specific counties based on available data for each crop.

4.3.4.1 Field Crop Production

Figure 4.5 shows total production in all seven counties for grain corn, soybean, winter wheat and total field crop (total sum of grain corn, soybean and winter wheat production) between 2000 and 2015. Total production for all of these variables increased significantly over the study period. For grain corn, total production nearly doubled, increasing from approximately 600,000 tonnes in 2001 to about 1,200,000 tonnes in 2015. The increase in production for this crop was relatively steady, with only a few large dips or peaks in production throughout the 16-year period. In Southern Ontario, corn is usually planted in late April or early May, with production peaking during longer and warmer growing seasons (Ministry of Agriculture Food and Rural Affairs 2017). This
Sensitivity to length of growing season could help to explain the observed production decreases in 2004 and 2014, and increased production in 2010.

For soybean, total production increased substantially, from about 200,000 tonnes in 2001 to nearly 500,000 tonnes in 2015. Production for this field crop was slightly more erratic, with more significant deviations from the average production. Similarly to grain corn farming, the highest soybean yields are generally seen when the crops are planted in late April or early May (Ministry of Agriculture Food and Rural Affairs 2017). While hard spring frost can kill soybean crops that have been planted early, these crops can still withstand slightly lower short-term temperatures than

Figure 4.5: (a) Total grain corn production in the seven GRW counties; (b) Total soybean production in the seven GRW counties; (c) Total winter wheat production in the seven GRW counties; (d) Total field crop production (grain corn, soybean and winter wheat) in the seven GRW counties.
corn plants. In general, soybeans are a warm-season crop that may be more susceptible to sustained colder temperatures (Ministry of Agriculture Food and Rural Affairs 2017).

In terms of winter wheat, total production over the study period increased from about 180,000 tonnes in 2000 to about 300,000 tonnes in 2015. Production for this crop varied significantly, as compared to grain corn and soybean, with significant fluctuations occurring almost annually. Winter wheat is generally planted sometime in early autumn with planting dates in the GRW varying between September 15 farther north, to October 5 in the South (Ministry of Agriculture Food and Rural Affairs 2017). Like many other cereal crops, winter wheat is more responsive to planting date than corn and can be planted too early (Ministry of Agriculture Food and Rural Affairs 2017). The winter growing season for winter wheat crops could contribute to the more erratic fluctuations in production shown in these results. Winter cereals can be severely affected by frost heaving, ice, low temperatures and snow mould (Ministry of Agriculture Food and Rural Affairs 2017). In Ontario, early spring freeze/thaw cycles are a primary reason for winterkill in crops like winter wheat (Ministry of Agriculture Food and Rural Affairs 2017). Additionally, while winter wheat and other similar crops are able to survive extremely cold temperatures relatively well (they can survive temperatures down to -24°C), cold injury can still affect final yield (Ministry of Agriculture Food and Rural Affairs 2017). These additional and somewhat unique challenges to winter crop growth could help to explain some of the more significant variations in winter wheat production observed during the study period.

Total field crop production showed a clear upward trend over the study area as well, increasing from about 1,000,000 tonnes in 2001 to almost 2,000,000 tonnes in 2015. Production fluctuated periodically over this time, peaking approximately every two to three years. There are multiple factors that could contribute to these observed trends. With substantial population growth in the region, the food industry must continue to meet the needs of an ever-increasing population. Demand for agri-food products outside of Ontario and Canada is also continuously increasing, meaning that companies and organizations relying on exports must produce more food to meet those needs. The periodic nature of fluctuations in production could be associated with the many vulnerabilities of plants to environmental, anthropogenic and management-related issues.
Figure 4.6 illustrates the spatial variation in mean overall field crop production throughout the GRW study area between 2000 and 2015. This map shows that the density of field crop production (measured in tonnes/km²) is generally highest in the centre of the watershed, in the Waterloo and Brant counties. These counties also contain the most populated cities in the watershed, including Brantford, Waterloo and Kitchener. The Wellington, Haldimand and Norfolk counties had the second highest production densities per square kilometre. These three counties all produce a significant amount of agri-food products, and together their mean total field crop production over the study period was more than double that of the Waterloo and Brant counties. The Wellington, Haldimand and Norfolk counties also span a vast area as compared to the other counties in this study, and the density of field crop production does not necessarily illustrate this. The Hamilton and Dufferin counties showed the lowest field crop production levels in the study area.

4.3.4.2 Implications of Field Crop Production Trends for Food and Water Security

These results indicate potential challenges for resource management now and in the future. In terms of food availability, the GRW study area has an abundant supply of field crops, increasing from just over 600 kilograms per capita in 2001 to almost 1,200 kilograms per capita in 2015. Availability of agri-food resources in Southern Ontario is also impacted by extensive trade practices in the food industry in Ontario. In 2015, the province of Ontario exported close to $14.1 billion worth of agri-food products and imported about $26 billion worth. From 2002, total exports increased by close to 70%, while total imports increased by almost 110%. These statistics indicate that international trade is a principle component of food availability in Ontario; however, it is unclear whether the current growth trends in production and trade will be sustainable in the long-term future. Although the availability of field crops within the GRW appears to be very high, there could still be other challenges with respect to other dimensions of food security and water security in the region as well.

In terms of food accessibility, not all communities in the GRW have equal access to the abundance of food and agri-food resources in the region. The SNGR and MNC First Nations communities, in particular, have been stripped of the access to traditional territories and natural resources that are required to maintain traditional diets that relied on hunting, fishing and growing of traditional plants such as corn, beans and squash (Kruse-Peeples 2016). As a result of the assimilative practices and colonization that have taken place and affected Indigenous peoples over the past
several centuries, the ‘quality’ aspect of access to food resources in these communities has also been affected. Generations of Indigenous peoples have been disconnected due to these practices, resulting in a loss of traditional knowledge and practices. This has forced many Indigenous peoples to rely on external food sources and the less expensive, processed food options are often the most accessible resources for these communities. For those members of the community that seek externally produced agri-food resource options, there is also a lack of sufficient access to nearby grocery stores and markets in SNGR and MNC.

These results also showed that the GRW counties with the highest densities of field crop production have the highest population densities as well, due to larger cities including Brantford, Kitchener, Waterloo and Cambridge. In terms of water resources management, these could both negatively affect natural hydrological cycles in these areas. Population growth tends to coincide

Figure 4.6: Mean annual field crop production for the GRW study area between 2000 and 2015.
with decreased perviousness of the ground surface and increased surface runoff, and agricultural production utilizes and/or diverts available fresh water from its natural pathways. The availability of freshwater resources for human consumption could be affected by these factors, especially if both agricultural production and total population continue to grow. Both of these variables could impact water quality in the region as well. Without significant intervention in terms of management and mitigation, population growth results in decreased water quality as stormwater runoff picks up more contaminants in impervious urbanized areas and lacks natural filtering and treatment. Agricultural production also severely impacts the quality of runoff due to the use of fertilizers. This is also a concern in the southernmost region of the watershed, where field crop production in the Haldimand and Norfolk counties is very high. Since Haldimand County is the only direct pathway to the GRW drainage outlet, agricultural production in this county could severely affect water quality in the watershed and in Lake Erie.

In terms of sustainability, the current upward trends in field crop production within the GRW may not be sustainable over the next 15-20 years, or longer. If current population growth trends continue, agricultural land area will likely continue to decrease and at some point, technological advancements in agriculture will not be able to continue to increase productivity and efficiency. This could affect international trade in this region, which would have unknown implications for food availability (if agri-food imports are affected). Additionally, as agricultural production continues to increase in the GRW, challenges to water availability, accessibility and quality, and mitigation of water-related hazards will continue to grow also. Future management policies should consider whether current agricultural practices will be able to support communities within the GRW in the next 15-20 years, or whether considerable policy changes should be made to preserve and protect food and water security in the watershed in the future. It is also important to consider that although agricultural statistics are reported on a county-level, agricultural management practices should also operate on a watershed-level to effectively preserve overall watershed health and security.

4.3.4.3 Horticultural Crop Production

Figure 4.7 shows total production in all seven counties for grapes, apples, sweet corn and field tomatoes between 2000 and 2015. Grape production data were only available for the Hamilton, Haldimand and Norfolk counties, likely because grapes aren’t grown in any areas farther north in
the watershed. Data for apple and sweet corn production were available for all counties except Dufferin County, which had significant data gaps for all horticultural crop data. For field tomatoes, sufficient data were only available for the Hamilton, Haldimand, Norfolk and Brant counties. Figure 4.7 shows that for grapes and apples, average production decreased considerably over the study period, while average production for sweet corn and tomatoes increased.

For grapes, total production was reduced from just under 6,500,000 lb in 2000 to just over 4,000,000 lb in 2015. Grapes are especially susceptible to extremely cold temperatures and damage due to frost. It is widely recognized that growing grapes, tender fruits and some other fruit crops
requires milder climatic conditions which, in Canada, are typically only found on the West Coast in British Columbia, and in Southern Ontario. Large-scale and commercial production of these crops in Canada is therefore limited to these areas. The Niagara Peninsula, located in Southern Ontario, experiences a moderated climate influenced by both Lake Ontario and the Niagara escarpment, making it an ideal location to grow grapes and tender fruits. This region produces approximately 90% of Ontario’s grapes, peaches, nectarines and apricots. The southern Haldimand and Norfolk counties, however, are located closer to Lake Erie, which is a relatively shallow lake as compared to the other Great Lakes. If parts of this lake freeze over in the winter (which does tend to happen on occasion), the moderating effects are lost, posing a serious threat to the growth of tender fruit and grapes in this area. This could help to partially explain some of the substantial dips in grape production over the 16-year duration of this study.

Total apple production also decreased substantially over the study period, from about 95,000,000 lb in 2000 to just under 50,000,000 lb in 2015. Production for this crop followed a relatively consistent downward trend, except for two years with significant drops in production: 2002 and 2012. This suggests that there could be a specific factor, such as mean temperature, total precipitation or snowfall, to which apples are especially vulnerable. The Great Lakes are important for apple production in Southern Ontario, as they cause the air temperature around them to change more slowly between seasons, resulting in extended growing seasons for apple trees. Modern technology has also allowed production in apple orchards in Ontario to become more efficient over the past years. Similarly to grape production, apple trees’ sensitivity to rapid changes in climate could also help to explain some of the substantial dips in apple production in several years, as extremely cold years would have a significant effect on the Great Lakes, and therefore fruit production. The downward trend in fruit production (seen here with both grape and apple production) could be attributed to a number of causes. First, it is possible that land area originally dedicated to either grape or apple production is being converted to growing area for other fruits as consumer preferences or tastes change. It is also possible that agricultural land originally dedicated to these two crops is being developed and converted to residential or commercial areas to service the growing population. Since it is known that production efficiency is improving overall, it is most likely that some type of land-use change is causing these downward trends in fruit production. Long-term climatic changes could also negatively these crops, resulting in lower yields or increased spoilage even with the increased production efficiency. Finally, there could be changes
occurring with international trade, resulting in higher import levels for these fruits and lower
demand for production within the province.

Total sweet corn production also followed a relatively consistent trend, increasing from around
25,000,000 lb in 2000 to just over 60,000,000 lb in 2015. There are two significant outliers with
these data. The years 2003 and 2006 both saw significant increases in sweet corn production. Total
production of field tomatoes followed a less predictable trend over the study period. Production
was very low (below 10,000,000 lb per year) from 2000 to 2002, and then increased substantially
in 2003 to around 90,000,000 lb. From this point on, tomato production levelled for several years,
before beginning an overall decrease in 2009. The significant difference in production between
2002 and 2003 could be explained by changes in consumer taste/preference, changes to land-use
or possibly a significant change in how the data was reported that year. Similarly to the trends in
fruit production, the overall upward trend in the production of these vegetables could be attributed
to changes in land-use due to conditions, consumer demands, or development, overall climatic
changes affecting yield and production, or again, differences in international trade agreements.

Figure 4.8 illustrates the spatial variation for mean overall apple production and mean overall
sweet corn production in the GRW study area between 2000 and 2015. These maps show that, for
both of these variables, density of crop production (measured in ‘000 lb/km²) occurred primarily
in the southernmost regions of the GRW. The Haldimand and Norfolk counties illustrated the
highest production densities for these fruit and vegetable crops. This is expected since this region
experiences the mildest temperatures, moderated by the effects of the Great Lakes and the Niagara
Escarpmment. Production was far lower in the northernmost counties (Dufferin and Wellington).

4.3.4.4 Implications of Horticultural Crop Production Trends for Food and Water Security

These results could also influence resource management now and in the future. With respect the
availability of horticultural food products, grape availability decreased from just under 6 kg per
capita in 2000 to about 2.3 kg per capita in 2015, while apple availability decreased from close to
38 kg per capita in 2000 to just over 10 kg per capita in 2015. Fruit availability (in terms of these
variables) has certainly decreased substantially, and these results indicate demand for fruit
products is likely being met through sources outside of the GRW, or the country. If agri-food trade
agreements were to be impacted in the near future, availability of fruits such as grapes and apples
would almost certainly be under pressure. In the GRW, availability of sweet corn increased from about 2.7 kg per capita in 2000, to over 15 kg per capita in 2015, while availability of field tomatoes increased from around 6 kg per capita in 2000 to just under 40 kg per capita in 2015. Availability of these types of vegetables increased substantially over this time period, although other factors could impact access to these foods, or the long-term sustainability of production.

In terms of food accessibility, similar issues exist within the GRW as with field crops. Communities such as the SNGR and MNC First Nations face a lack of access to resources (primarily hunting, fishing and agricultural territory) necessary to maintain traditional diets, as well as limited access to high-quality, externally-sourced agri-food products, including fruits and vegetables.

Figure 4.8: (a) Mean annual apple production for the GRW study area between 2000 and 2015; (b) Mean annual sweet corn production for the GRW study area between 2000 and 2015.
These results also indicated that production of these fruits and vegetables is highest in the southernmost counties: Haldimand and Norfolk. This could certainly have implications for water management, as a portion of Haldimand county drains directly into Lake Erie. The smallest of the Great Lakes (by volume), Lake Erie has been severely affected by water quality issues in recent years, with elevated levels of nutrients leading to excessive eutrophication and algal blooms. Agricultural production is a known source of such contaminants, including phosphorus and nitrate, and horticultural production in this area could pose a serious risk to the health of the Great Lakes. With respect to sustainability, it is unclear whether current horticultural production trends will be sustainable over the next 15-20 years. Total land area dedicated to agricultural production is decreasing steadily, meaning that future production of fruits such as apples and grapes could be under stress, while the upward-trending production of sweet corn and field tomatoes could eventually be halted. Additionally, these trends in horticultural production present challenges to water security in the GRW, especially in terms of water accessibility and quality.

4.3.5 Visual Comparison between Agricultural, Environmental and Anthropogenic Trends

This section contrasts visual trends in agricultural production in the GRW with the various climatic, hydrometric and anthropogenic trends discussed above. To simplify the presentation of these data, select subsets of the collected data were used for each variable. Total field crop production in Wellington county was used for this analysis. This county was chosen because it exhibits very high production for the three field crops chosen, and is located primarily within the GRW, so it is representative of field crop growth within the watershed. Total field crop production within Wellington county was compared with climatic data observed at Fergus Shand Dam climate station and hydrometric data recorded at Shand Dam hydrometric station, because these stations are located closest to the centre of this county. To represent horticultural crop production, total apple production within the Haldimand and Norfolk counties was compared with climatic data from the Port Colborne climate station and hydrometric data from the Brantford hydrometric station. These trends were also compared with total population and total farm area within the entire GRW.
4.3.5.1 Climatic Variables vs. Agricultural Production

Figure 4.9(a) contrasts total field production in Wellington County with mean annual temperature at the Fergus Shand Dam climate station. The relationship between these two variables does not appear to be very consistent over the study period. At the beginning of the study period, the peak in mean annual temperature appears to coincide with low overall field crop production, while later peaks in mean annual temperature coincide with increased field crop production. Dips in mean annual temperature appear to align primarily with peaks in field crop production as well. Figure 4.9(b) shows total apple production in Haldimand/Norfolk along with mean annual temperature at the Port Colborne climate station. Apple production does not appear to illustrate a strong correlation with temperature either; however, two years in the study period are noteworthy in the comparison of these two variables. Two of the largest dips in apple production over this period occurred in 2002 and 2012 and were also aligned with two of the most substantial peaks in mean annual temperature. It is possible that apple production was significantly affected by the substantially higher overall temperatures experienced in those years.

Figure 4.10(a) compares total field crop production in Wellington County with total annual precipitation at the Fergus Shand Dam climate station. These data appear to exhibit a stronger correlation than the temperature data, with higher precipitation generally coinciding with peaks in field crop production, and lower precipitation levels coinciding with dips or plateaus in field crop production. Substantial dips in field crop production occurred in 2005, 2007 and 2009, all aligning with total annual precipitation values of 950 mm or less. Substantial peaks in field crop production occurred in 2006, 2008 and 2014, all coinciding with total annual precipitation values over 1,100 mm.

Figure 4.10(b) compares total apple production in Haldimand/Norfolk with total annual precipitation at the Port Colborne climate station. Similarly to the field crop data, very low annual apple production generally coincided with dips in total precipitation. Significant dips in apple production occurred in 2002 and 2012, both aligning with total annual precipitation levels under 900 mm. For both these years with substantially lower apple production, although mean annual temperature and total annual precipitation did not necessarily reach their highest or lowest absolute values, respectively, the combination of higher temperatures and lower precipitation likely had a significant impact on production. In the future, as climatic patterns become more extreme along
with global climate change, these incidences could become more common, resulting in more frequent dips in production of apples, or other similarly vulnerable fruits. Coinciding low precipitation and apple production were also observed in 2010 and 2015. Conversely, years with high levels of precipitation did not consistently coincide with peaks in apple production.
4.3.5.2 Hydrometric Variables vs. Agricultural Production

Figure 4.11(a) compares total field crop production in Wellington county with mean annual river discharge at the hydrometric station below Shand Dam. In general, these data also appear to exhibit a relatively strong correlation. Except for a few outlying years, total field crop production generally increased in years with peak river discharge levels and decreased in years with low river discharge levels. These results are expected, as river discharge is strongly influenced by precipitation, and precipitation also influences agricultural production. In terms of apple production, however, this relationship is slightly less consistent. Figure 4.11(b) compares total apple production in Haldimand/Norfolk with mean annual river discharge at the Brantford hydrometric station. A significant outlier in these data is the year 2007, in which apple production was high (the third highest production year in the study period), although both precipitation and river discharge reached substantial low points, suggesting that water availability was not extremely high. This also suggests that, although higher levels of precipitation do seem to increase apple production, this is not necessarily a requirement for high apple production. Other years with lower overall water availability (2002, 2010, 2012 and 2015) all coincided with dips in total apple production.

4.3.5.3 Anthropogenic Variables vs. Agricultural Production

Figure 4.12(a) shows total field crop production in Wellington county along with total population and total farm area in the GRW. Total field crop production appears to increase steadily along with the rising population in the region, suggesting that demand for these agri-food products is generally being met to the same degree as the beginning of the study period. Total field crop and total farm area, however, display a negative correlation. Although total farm area appears to be decreasing steadily, total field crop production continues to increase. This suggests possible shifts in land-use from other agri-food products to field crops. These trends could also be explained by technology trends and increased efficiency in production methods over the 16-year study period.

By contrast, apple production appears to decrease steadily along with total farm area during the study period. Figure 4.12(b) shows total apple production in Haldimand/Norfolk with total population and total farm area in the GRW. Together these trends could be an indication that some of the land that was previously used to grow horticultural crops such as apples was converted to land for field crops production. The overall trend in total apple production is also negatively
correlated with total population in the GRW, indicating that overall production may not be meeting demands to the same degree as at the beginning of the study period. Again, this suggests that externally-sourced fruit products are likely contributing to a higher percentage of the total apple supply in the region than at the beginning of the study period.
4.4 Discussion

The agricultural, environmental and anthropogenic changes observed in the GRW have implications for future food and water security within the watershed. These trends indicate that water availability could be at risk, especially during periods with high overall temperatures and low precipitation (which could occur more frequently or at higher extremes if climatic patterns continue to intensify). As the population within the watershed continues to grow and pressure increases on the water supply to meet residential, commercial and agricultural demands, this risk would also become greater. If the system does not continue to meet environmental water requirements, local species and ecosystems could be under threat as well. Conversely, during periods with lower overall temperatures and high precipitation, water availability could present other challenges due to flooding and other flood-related issues. Both these scenarios have implications for agricultural production, which could also face more frequent and more substantial fluctuations as a result.

Water access and quality are other factors that will continue to be affected as the GRW population and land continues to be developed. These changes tend to alter the overall hydrological cycle, diverting water to different areas and decreasing the quality of stormwater runoff, especially in urbanized areas. Additionally, although total farm area in the watershed is decreasing, which could have a positive effect on water quality, increased production and utilization of existing farmland could be detrimental to water quality.

In terms of food availability, the abundance of agricultural production within the GRW suggests that this is not an imminent threat for most watershed residents. More recent climatic patterns do suggest, however, that annual precipitation and temperature fluctuations could become more severe, meaning that more extreme weather events or seasons could cause periodic issues with agricultural production (as evidenced with the extreme dips in apple production coinciding with hotter and drier years). Additionally, the agri-food industry in Ontario is heavily impacted by international trade, which presents additional challenges for food access and availability.

The trends discussed in this study could also have significant implications for food and water security in the SNGR and MNC First Nations communities. Located next to the Grand River, SNGR territory is especially vulnerable to flooding during seasons with peak precipitation and
river discharge. The community also faces additional challenges to water access and quality, with most residents relying on groundwater and the rest relying on supply from the Grand River. Water access and quality are still very much a concern for certain members of this community and these challenges could continue to be exacerbated by the changes going on within the watershed. In terms of food resources, localized agri-food production efforts that aim to improve food security within the SNGR and MNC First Nations communities could be affected by the climatic patterns that influenced severe dips in agricultural production in this study. Access to healthy foods that help to continue cultural traditions, practices and ways of life remains a challenge for many members of these communities as well.

4.5 Conclusion

This study directly analyzed historical climatic, hydrometric, anthropogenic and agricultural data and discussed the potential implications of historical trends for present and future food and water security within the GRW. The results of the study found that recent, localized temperature and precipitation patterns could result in substantial or more frequent fluctuations in agricultural production and water availability. Population growth and land-use changes could also negatively impact water availability and quality and affect supply and demand for various agri-food crops in the GRW. The GRW is the largest watershed in Southern Ontario and could provide an indication of future challenges to food and water security and the overall sustainability of current management practices.

The objectives of this study were achieved despite several constraints that should also be considered for future analyses. The primary limitations for this study, and the previous analysis by McNeill et al., include the following:

- Limited timeline and limited temporal scale; and
- Limited availability of reliable data within the GRW and surrounding counties, both spatially and temporally (especially for specific crops in certain counties, climatic data and hydrometric data).

One of the primary factors that could improve future studies in the GRW region is data availability. Consistency in terms of monitoring, recording and reporting observations for all variables would
vastly improve the data set available for research. Specific recommendations for improvements to help future studies include the following:

- Address inconsistencies in monitoring and recording observations for climatic and hydrometric data in order to limit daily data gaps;
- Increase the number of climate stations to help improve understanding of localized spatial trends, in precipitation especially, throughout the watershed;
- Address inconsistencies in recording or reporting agricultural observations especially for crops such as sweet corn or tomatoes in the Dufferin, Wellington and Waterloo counties;
- Increase the overall timeline of future studies to 25 or more years, if possible; and
- Analyze monthly data as well as annual data to capture seasonal variations.

Although various conceptual, analytical or simulation-based modelling frameworks and indicators can provide useful information for understanding current and future trends in food and water availability, direct analyses of real, historical data are also important. Visual analyses of these historical data can also allow researchers to use background knowledge, experience and intuition to evaluate possible patterns and develop a more comprehensive understanding of a region or situation before utilizing statistical or simulation-based methods. These types of analyses, along with discussion about the socioeconomic and political factors that influence these trends, have the potential to address all three dimensions of food and water security from an interdisciplinary point of view.
5 Modelling Crop Production in the Grand River Watershed: a Statistical Regression Analysis

5.1 Introduction

Southern Ontario is the centre for social, economic and agricultural activity in Canada, supporting more than one third of the national population and a substantial portion of agri-food production in the province. Agricultural production is a key contributor toward food and economic security in the region, supplying a sizable share of the province’s $14.9 billion in agri-food exports in 2017 (Ontario Ministry of Agriculture Food and Rural Affairs 2018a). Production may be highly influenced by a number of anthropogenic and environmental stressors including population growth, land development, water security and factors associated with global climate change. In order to continue to properly manage agricultural resources and maintain overall food, water, social and economic security in the future, it is necessary to understand how these stressors influence production.

A variety of methods to investigate the impacts of climatic variables on crop production in North America have been investigated recently. Rosenzweig et al. 2002 used a dynamic crop model (modified CERES-Maize) to assess the impact of heavy precipitation on crop damage in the U.S.A.. The model estimates crop yield based on climate, solar radiation, crop genetic traits and management practices. Steduto et al. 2009 introduced the Food and Agriculture Organization of the United Nations (FAO) crop model AquaCrop, which simulates crop yields based on water consumption under both rainfed and irrigated scenarios. The model converts computed transpiration to biomass and then estimates crop yield as a function of biomass and harvest index (Steduto et al. 2009). These are examples of process-based models that rely on theoretical knowledge of physiological processes to predict yield responses to altered environmental scenarios. Process-based models can be very useful for predicting the effects of global changes on crop production and influencing broader management decisions, however they do rely on simplifying assumptions and cannot necessarily account for complex factors such as pests, weed control or other management-related challenges. Challinor et al. 2014 performed a meta-analysis combining data from multiple studies to determine the potential impacts of different climate scenarios on crop yields. This type of analysis can be used to validate or explain results from multiple studies, and in doing so answer broader research questions.
Many studies have also used empirical methods to develop statistical models that rely on past observations to identify key relationships and predict future crop yields. These types of models can be very useful for understanding historical relationships between crop yields and various stressors (Lobell, Cahill, and Field 2007). They may also be able to incorporate the effects of factors that are less well understood and difficult to incorporate in other models (Lobell, Cahill, and Field 2007). Lobell & Asner 2003 analyzed statistical relationships between corn and soybean production in the U.S. and temperature, precipitation and solar radiation variables over a 17-year period. Lobell et al. 2007 developed statistical regression models to estimate yields for 12 major crops in California over a 24-year period based on three important climatic variables: minimum and maximum temperature and total precipitation. The findings of this study demonstrate that relatively simple, three-variable regression models were able to explain over 70% of the variation in crop yield for most crops over the study period (Lobell, Cahill, and Field 2007).

Although various different methods have been used to investigate the impacts of climate on crop production, water availability and food and water security in the U.S.A and other countries, fewer have been applied in Canada in recent years. The Grand River Watershed (GRW) is the largest watershed in Southern Ontario, Canada and is representative of the diversity of human activity and agricultural production in the region. The GRW spans a 6,800 km² area located west of the Greater Toronto Area and just north of Lake Erie (Grand River Conservation Authority 2018b). This study aims to develop an understanding of the relationships between anthropogenic and environmental stressors and crop production in the GRW and model these effects to aid future management decisions. Rather than using more complex, process-based models like the modelling platforms reviewed in Chapter 2 of this thesis, this analysis utilizes simpler, less data-intensive (in terms of number of parameters) statistical methods to model lesser known parameter effects on crop production in the GRW.

The objectives of this study include the following: (1) examine the relationships between eight crop production variables and annual predictor variables; (2) identify the most statistically significant factors (from 86 monthly and annual predictor variables) for each crop production variable; (3) develop a unique, statistical regression model for each crop production variable.
5.2 Methodology

5.2.1 Data Collection

5.2.1.1 Study Area and Timeline

The study timeline was limited to 2000-2015 to capture more recent trends in the GRW in the early 21st century and comply with restrictions on data availability. The total study area comprises the GRW, seven overlapping counties including Dufferin, Wellington, Waterloo, Brant, Haldimand, Norfolk and Hamilton, as well as Indigenous territories of the Six Nations of the Grand River (SNGR) and Mississaugas of the New Credit (MNC) First Nations communities (see Figure 5.1). Both Norfolk and Hamilton counties do not lie primarily within the GRW, however they were each included in the analysis for the following reasons. Norfolk County statistics are reported jointly with Haldimand County, so this region was automatically included in the analysis with Haldimand County. Part of Hamilton County is located within the GRW and this county also hosts a significant population and industrial area located directly east of the watershed. Hamilton County was therefore included in order to capture the impacts of changes in this region on the GRW.

This study incorporated data for several field and horticultural crops in its analysis. The analysis of field crop production was centred in Wellington County as this region has some of the highest historical production values for field crops. The analysis of horticultural crop production focused on the Haldimand and Norfolk counties, as these areas produce the most fruits and vegetables in the watershed area.

5.2.1.2 Historical Climate Data

Daily climate data were collected from historical archives retained by Environment and Climate Change Canada (Government of Canada 2018a). These archives contain data observed and recorded by the Meteorological Service of Canada at over 8,700 climate stations throughout the country. Data for mean, maximum and minimum temperature, as well as total rainfall, snowfall and precipitation were collected for the two climate stations located within, or closest to, the two regions under analysis (Wellington and Haldimand/Norfolk counties). These two stations were chosen as they encompass the most valuable, reliable and complete climatic datasets within these study areas. The Fergus Shand Dam (FSD) climate station is located close to the centre of Wellington County, while the Port Colborne (PC) climate station is located approximately 15 km
east of the Haldimand/Norfolk counties (see Figure 5.2). Although this station is not located within either Haldimand or Norfolk County, it is the closest option with a full, available dataset and is also able to capture some of the weather effects of nearby Lake Erie.

Overall mean, maximum and minimum temperature, as well as total rainfall, snowfall and precipitation were computed for each climate station on both a monthly and annual basis for the 16-year study period. Both climate stations exhibited some missing data during the study period, which could be attributed to human error or equipment malfunction. A protocol was used to evaluate the reliability of these data and reduce seasonal bias due to unavailable data. On an annual basis, years missing more than 60 days of data were automatically eliminated and remaining years missing more than 15 consecutive days of data were also eliminated. Both the FSD and PC climate
stations had limited missing data values, therefore all data for these stations was able to be retained for the analysis.

### 5.2.1.3 Population and Farm Area Statistics

Total population and total farm area statistics were collected from the Census Program, operated by Statistics Canada (Statistics Canada 2001; Statistics Canada 2006; Statistics Canada 2011; Statistics Canada 2016; Ontario Ministry of Agriculture Food and Rural Affairs 2018a). This program observes and reports national, provincial and municipal demographics and agricultural data every five years. These data were collected for the closest available years to the study timeline: 2001, 2006, 2011 and 2016. Population data were collected for all counties located within the

Figure 5.2: Climate stations and hydrometric stations located within the GRW study area.
GRW study area and summed to provide a total population estimate. Total farm area data were collected for the Wellington and Haldimand/Norfolk counties only.

5.2.1.4 Grand River Discharge Data

Monthly hydrometric data were collected from the Ministry of Environment and Natural Resources Canada (Government of Canada 2018b). These records report historical hydrometric data for over 7,700 hydrometric stations throughout the country. Monthly mean river discharge data were collected for the ‘Grand River at Brantford’ (GRB) hydrometric station, located in Brantford, Ontario (see Figure 5.2). This station was chosen as it is the southernmost hydrometric station along the Grand River (therefore receiving flow from the majority of the watershed) and has the most reliable and complete dataset of all the stations located along the Grand River.

Mean annual river discharge was computed at this station over the 16-year study period. A similar protocol to the one used for the climate data was used to assess the reliability of these data. On an annual basis, years missing an entire month of data or more were eliminated. The GRB station did not exhibit missing monthly data during this period, therefore all data for this station was able to be retained for the analysis.

5.2.1.5 Agricultural Data

Crop-related agricultural statistics were collected from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) (Ontario Ministry of Agriculture Food and Rural Affairs 2018b). The OMAFRA partners with the Agriculture Division of Statistics Canada to record and report annual agricultural and agro-economic data for the province of Ontario. Various representative field and horticultural crops were chosen for this analysis based on the total area dedicated to growing each crop in Ontario (data availability was also a factor). Aside from hay, the three major field crops historically grown in Ontario are soybean, winter wheat and grain corn. These three crops accounted for 78-87% of the total farmland dedicated to field crops (excluding the area dedicated to hay production) in Ontario between 2001 and 2016. These crops also exhibited the highest production values for field crops in Ontario. Total annual production data were compiled for these crops for the 16-year study period. Total field crop production (in this study comprising total soybean, winter wheat and grain corn production) was also computed and analyzed for each year in the study period.
The two major fruit crops historically grown in Ontario, grape and apple, were chosen to represent horticultural fruit crops. Due to data availability and production limitations within the GRW study area, the first and fourth most-grown ‘vegetables’, sweet corn and field tomato, were also chosen for this analysis. In terms of total production, grape and apple crops exhibit the highest fruit production values, while tomato and sweet corn exhibit the first and third highest vegetable production values, respectively. Total annual production data were compiled for these four horticultural crops for the 16-year study period.

5.2.2 Exploratory Analysis

The purpose of this study was to evaluate the relationships between predictor variables and the eight yearly, agricultural dependent variables listed in Table 5.1, in order to develop a unique, multiple regression model for each agricultural variable. Nine predictor variables that influence food and water security within the GRW are also shown in Table 5.1.

The basis for each of these statistical models is the same, where the annual value of each agricultural variable can be approximated by unique relationships with the annual values of each predictor variable. A generalized, univariate, quadratic regression model with nine annual predictor variables was therefore used as a conceptual starting point in the creation of each of eight statistical models (one for each dependent variable). This equation, where \( Y_m \) is the estimated value of the dependent variable, \( x \) represents the value of each of nine predictor variables (see Table 5.1) and \( \alpha \) and \( \beta \) are constants, is given as follows:

\[
Y_m = \alpha_{1,1} x_1 + \alpha_{1,2} x_1^2 + \alpha_{2,1} x_2 + \alpha_{2,2} x_2^2 + \cdots + \alpha_{9,1} x_9 + \alpha_{9,2} x_9^2 + \beta
\]  

(5.1)

In order to develop statistical models that are easy to interpret and have the best possible prediction accuracy, it is important to minimize the number of variables in a final model. To avoid over-fitting the data and develop more reliable statistical models, analyses were performed to reduce this equation from its initial nine-variable form to include only the two to three most statistically significant predictor variables per univariate model. It was first necessary to determine appropriate predictor variables for each dependent variable. This was initially investigated using a preliminary exploratory data analysis to assess which annual variables were most significant for each
In the preliminary analysis, independent, univariate, quadratic regression analyses were performed between nine annual predictor variables and each agricultural variable. The resulting adjusted coefficient of determination (adjusted $R^2$) values for each independent regression were compared to determine the three most significant overall factors that influence production for each agricultural variable. The general coefficient of determination ($R^2$) is a measure of the proportion of the variance in a dataset that can be explained by the inputs of a given model. The adjusted $R^2$ value is a variation of the general $R^2$ that changes based on the number of terms in the model. The adjusted $R^2$ value increases only if the terms being added to a model are statistically significant for the dependent variable in question (Massachusetts Institute of Technology 2006). The following equation, where $x$ and $y$ are the coordinates of each data point in the sample data set, $n$ is the total number of data points in the data set, and $k$ is the number of predictor variables in a given model, computes the adjusted $R^2$ value for a univariate regression model.

$$Adjusted\ R^2 = 1 - \left[ \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{n\Sigma x^2 - (\Sigma x)^2}[n\Sigma y^2 - (\Sigma y)^2]} \right]^2 \frac{n}{n - k - 1}$$

In the secondary analysis, independent, univariate, quadratic regression analyses were again performed between two annual and 84 monthly predictor variables (12 months for each of mean,
maximum and minimum temperature, total rainfall, snowfall and precipitation and mean annual river discharge) and each agricultural variable. The resulting adjusted $R^2$ values for each regression were again compared and, based on the unique results for each variable, up to 15 predictor variables with sufficiently high adjusted $R^2$ values were chosen for model development. Since the total number of possible univariate regression models for ‘p’ predictor variables is equal to $2^p$, an upper limit of 15 predictor variables was chosen in order to maintain a manageable number of models to choose from in the next stage of the analysis.

5.2.3 Model Development

Using JMP statistical software, all possible univariate, quadratic regression models with up to six terms were evaluated for each agricultural variable and corresponding predictor variables chosen during the secondary exploratory data analysis. Two and three-variable models with the highest adjusted $R^2$ values were further evaluated and compared based on their root mean square error (RMSE), F-test and plot of residuals vs. predicted values. The RMSE is the standard deviation of residual values (i.e. measures how close the predicted values tend to be to observed values) (Massachusetts Institute of Technology 2006). The following equation, where $z_r$ represents predicted data points on the regression curve, $z_o$ represents observed data points and $n$ is the total number of observations/predictions, computes the RMSE value for a regression model.

$$RMSE = \sqrt{\frac{\sum(z_r - z_o)^2}{n}}$$ (5.3)

In regression analysis, the F-test can help to determine whether a regression model has statistically significant predictive power. The F-test evaluates the hypothesis that all regression parameters, except the intercept, are equal to zero. An F-ratio is computed by dividing the overall model mean square by the error mean square. If the model in question is statistically significant, then the F-ratio should be higher than expected by chance alone. This is determined by computing the probability of obtaining a larger F-ratio by chance ($P > F$), if the model is not a better fit for the data than the overall response mean (JMP 2007). Generally, if this probability is equal to or less than 5% then there is at least one significant regression factor in the model.
A plot of residuals vs. predicted values helps to identify potential issues with a regression model. In an ideal model, the ‘error’ or numeric value of a residual should not be predictable based on the estimated value of the data point. An acceptable plot shows data points scattered relatively evenly in distance from the x-axis and distributed evenly between positive and negative values. At this stage of the analysis, the models were also evaluated based on general knowledge of crop phenology and water resources systems. Any models with unrealistic or impractical predictor variables (for example, a model for soybean production that relies on mean temperatures in January although soybeans are harvested in the fall) were eliminated from further analysis.

For each agricultural variable, the statistical model with the highest adjusted $R^2$ value and lowest RMSE value was chosen to fit the data, provided that the P > F and plot of residuals vs. predicted values was acceptable. The final statistical model chosen for each agricultural variable took the following form, where $Y_m$ is the estimated production value of the agricultural variable, $x$ represents the value of each predictor variable and $\alpha$ and $\beta$ are constants:

$$Y_m = \alpha_{1,1} x_1 + \alpha_{1,2} x_1^2 + \alpha_{2,1} x_2 + \alpha_{2,2} x_2^2 + \alpha_{3,1} x_3 + \alpha_{3,2} x_3^2 + \beta$$  

(5.4)

In some cases, certain values of $\alpha$ were equal to zero where quadratic terms for specific variables were not required.

5.3 Results & Analysis

5.3.1 Exploratory Analysis

5.3.1.1 Preliminary Analysis with Annual Data Values

The first stage of the exploratory data analysis used to develop the nine unique statistical models aimed to determine which annually-measured predictor variables were most statistically significant in relation to each dependent variable. Independent, univariate quadratic regression analyses performed with these datasets produced the results given in Table 5.2, showing the three predictor variables with the highest adjusted $R^2$ values for the eight agricultural dependent variables.

For the field crop variables, predictors such as total population and mean annual river discharge tended to be most highly correlated with crop production. Examining the datasets for these
variables, it is clear that overall production for all of these field crops increased over the study period along with the total population of the GRW. Soybean, wheat and grain corn products are all consumed in simpler forms that include wheat flour, corn starch, soybean oil, corn syrup and soy protein isolate, but are also found in many processed food products including breads, breakfast cereals, canned soups and gravies, fried foods, salad dressings and high-protein products (Center for Advanced Medicine 2016). These three agri-food staples, along with rice, account for approximately two thirds of human caloric intake (Long, Marshall-Colon, and Zhu 2015). The steady population growth in the GRW during the study period may therefore account for most of the general upward trend in field crop production and is consistent with general knowledge about human agri-food consumption. The statistical relationships between several of these crop variables and mean river discharge may also indicate that many of these field crops are highly sensitive to overall water availability within the GRW. According to the Food and Agriculture Organization of the United Nations maize (corn), wheat and soybean each require between 450 and 800 mm/growing period of water, a higher water requirement on average than crops such as beans, cabbage, melon or onions, and lower than others including sunflower, sugarcane, alfalfa or banana (Food and Agriculture Association of the United Nations 2018).

The fruit crops (grape and apple) were most highly correlated with variables related to water availability (mean river discharge and total precipitation, respectively). During their peak water requirement in July, grape and ground-covered apple crops in Southern Ontario may require up to 3.7 and 5.8 mm/day, respectively (Ontario Ministry of Agriculture Food and Rural Affairs 2018b). The vegetable crops (sweet corn and tomato) both displayed positive correlations with total

Table 5.2: Most significant annual variables based on $R^2$ values in independent, univariate quadratic regression analyses.

<table>
<thead>
<tr>
<th>Most Significant Annual Variables</th>
<th>Soybean</th>
<th>Total Population</th>
<th>Minimum Temperature</th>
<th>Mean Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter Wheat</td>
<td>Mean River Discharge</td>
<td>Total Precipitation</td>
<td>Total Population</td>
<td></td>
</tr>
<tr>
<td>Grain Corn</td>
<td>Total Population</td>
<td>Mean River Discharge</td>
<td>Maximum Temperature</td>
<td></td>
</tr>
<tr>
<td>Total Field Crop</td>
<td>Total Population</td>
<td>Mean River Discharge</td>
<td>Total Farm Area</td>
<td></td>
</tr>
<tr>
<td>Grapes</td>
<td>Mean River Discharge</td>
<td>Total Snowfall</td>
<td>Minimum Temperature</td>
<td></td>
</tr>
<tr>
<td>Apples</td>
<td>Total Precipitation</td>
<td>Total Farm Area</td>
<td>Total Population</td>
<td></td>
</tr>
<tr>
<td>Sweet Corn</td>
<td>Total Population</td>
<td>Total Farm Area</td>
<td>Total Snowfall</td>
<td></td>
</tr>
<tr>
<td>Tomatoes</td>
<td>Total Population</td>
<td>Total Farm Area</td>
<td>Maximum Temperature</td>
<td></td>
</tr>
</tbody>
</table>
population and negative correlations with total farm area. Tomatoes especially are consumed frequently and in many different food products while sweet corn is consumed in both fresh and canned or processed forms throughout the year. The steady increase in population within the GRW is therefore a likely contributor towards the overall upward trend in production for these variables.

5.3.1.2 Secondary Analysis with Monthly Data Values

The second stage of the exploratory data analysis evaluated the nine predictor variables in more detail, aiming to determine which specific months for the climatic and hydrometric variables were most statistically significant in relation to each agricultural variable. Independent, univariate quadratic regression analyses performed between each of the 86 predictor variables and eight agricultural variables revealed which predictor variables, based on their $R^2$ values, were most likely to be related to the production trends observed for each crop variable. Table 5.3 displays the most significant predictor variables and corresponding $R^2$ values for each agricultural variable. For the field crops, only those variables with $R^2$ values equal to or higher than 0.20 were selected for further analysis, while for the horticultural crops, most variables with $R^2$ values equal to or higher than 0.10 were selected.

Some of the variables appear to display relationships with predictor variables outside their growing seasons (for example, Dec. total snow for soybean or Aug. min. temp. for winter wheat). One possible explanation for this is that some of these variables may be indirectly related to the dependent variable in that they may be correlated with a different variable that affects production variability.

5.3.2 Model Development

Using the results provided in Table 5.3, all possible univariate, quadratic models with up to three predictor variables and six terms were evaluated for each agricultural variable. Models were eliminated if predictor variables were inconsistent with current knowledge about crop phenology. The growing season for soybean, grain corn, sweet corn and tomato crops typically extends from early May to mid-October depending on the region, although seeding dates could also occur in late April in some cases. For these crops, climatic and hydrometric variables from April to October were therefore considered acceptable for modelling these variables. For winter wheat in Southern
Ontario, the growing season can extend anywhere from September into July, so variables between these months were considered acceptable for modelling.

In terms of grape and apple crops, although the growing season for fruit production generally occurs between April and September, these plants are not seeded every year and must withstand...
fall and winter climates as well. Winter weather can have severe implications in terms of injury to fruit crops including dead buds, bark or root damage, blackheart injury and sunscald (Huffman and Carter 2018). Due to these implications, climatic and hydrometric variables for all months were considered acceptable for grape and apple modelling. Finally, variables for all months were also considered acceptable for modelling total field crop production, as this variable includes production for crops that are grown throughout the year.

For each dependent variable, a best-fitting, unique statistical model was identified based on its adjusted R² value, RMSE, P > F and plot of residuals vs. predicted values. These eight statistical models are given by Eqs. (5.5) through (5.12). Table 5.4 shows the numeric value of each α and β parameter along with relevant statistical parameters including the adjusted R², RMSE and Prob > F for each model.

For all agricultural variables except total grape production, a simple, three-variable model was able to explain over 80% of the variation in the data. Some models gave a better fit for the data than others. For instance, the data used to develop models for the field crops appeared to be a better fit, and produce higher adjusted R² values, than the models developed for the horticultural crops. This could be partially attributed to the fact that the placement of the climate station (PC) that was used in the horticultural crop analysis is not ideal, in that it is not centred in the Haldimand/Norfolk region. Figure 5.3 illustrates the ‘fit’ of each model as compared to the real observations over time. This figure shows that most models are able to capture the major trends in production over time, as well as most major fluctuations in the data. This suggests that despite the relatively limited 16-year timeline, most models are able to capture the effects of variables that have considerable influence over crop production.

Based on these analyses, the following relationships appear to be most significant and are discussed, along with a brief analysis of the potential mechanisms driving each relationship.

(a) Soybean

Soybean production in Wellington County generally favoured moderate-to-high October maximum temperatures (which would tend to occur at the beginning of the month), between about 22 to 26 °C. In the month of October soybean crops in Southern Ontario are generally in their final
reproductive stages of development and depending on seeding date, harvest may occur in the latter half of this month and potentially into November. During this time, soybean crops typically go through the R6, R7 and R8 final reproductive stages (University of Wisconsin 2015). In this period, seeds are reaching pod capacity and root growth is reaching completion. The rate of nutrient accumulation also slows during this period, after which the plants begin to shed their leaves and pods reach full maturity (University of Wisconsin 2015). During this time temperature and

<table>
<thead>
<tr>
<th>Total soybean production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{1,2} (\text{Population} - 1,497,630)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{2,1} \text{Oct. max. temp.} + \alpha_{2,2} (\text{Oct. max. temp.} - 23.9)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{3,1} \text{Jul. mean riv.} + \alpha_{3,2} (\text{Jul. mean riv.} - 35.72)^2 + \beta$</td>
</tr>
<tr>
<td>(5.5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total winter wheat production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{2,1} \text{Feb. max. temp.} + \alpha_{2,2} (\text{Feb. max. temp.} - 6.03125)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{3,1} \text{Sep. mean riv.} + \alpha_{3,2} (\text{Sep. mean riv.} - 32.9)^2 + \beta$</td>
</tr>
<tr>
<td>(5.6)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total grain corn production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{1,2} (\text{Population} - 1,497,630)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{2,1} \text{May min. temp.} + \alpha_{3,1} \text{Jun. mean temp.} + \alpha_{3,2} (\text{Jun. mean temp.} - 17.9862)^2 + \beta$</td>
</tr>
<tr>
<td>(5.7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total field crop production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{1,2} (\text{Population} - 1,497,630)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{2,1} \text{Sep. mean riv.} + \alpha_{3,1} \text{Dec. total rain} + \alpha_{3,2} (\text{Dec. total rain} - 41.86)^2 + \beta$</td>
</tr>
<tr>
<td>(5.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total grape production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Apr. mean temp.} + \alpha_{1,2} (\text{Apr. mean temp.} - 7.62324)^2 + \alpha_{2,1} \text{Oct. total rain}$</td>
</tr>
<tr>
<td>+ $\alpha_{2,2} (\text{Oct. total rain} - 102.363)^2 + \alpha_{3,1} \text{Jan. total snow}$</td>
</tr>
<tr>
<td>+ $\alpha_{3,2} (\text{Jan. total snow} - 33.8375)^2 + \beta$</td>
</tr>
<tr>
<td>(5.9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total apple production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Nov. total prec.} + \alpha_{2,1} \text{May mean temp.} + \alpha_{2,2} (\text{May mean temp.} - 13.9425)^2$</td>
</tr>
<tr>
<td>+ $\alpha_{3,1} \text{Sep. min. temp.} + \alpha_{3,2} (\text{Sep. min. temp.} - 6.125)^2 + \beta$</td>
</tr>
<tr>
<td>(5.10)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total sweet corn production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{1,2} (\text{Population} - 1,489,924)^2 + \alpha_{2,1} \text{Sep. max. temp.}$</td>
</tr>
<tr>
<td>+ $\alpha_{2,2} (\text{Sep. max. temp.} - 29.6875)^2 + \alpha_{3,1} \text{Aug. min. temp.} + \beta$</td>
</tr>
<tr>
<td>(5.11)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total tomato production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= \alpha_{1,1} \text{Population} + \alpha_{1,2} (\text{Population} - 1,489,924)^2 + \alpha_{2,1} \text{May min. temp.}$</td>
</tr>
<tr>
<td>+ $\alpha_{2,2} (\text{May min. temp.} - 2.34375)^2 + \alpha_{3,1} \text{May total rain}$</td>
</tr>
<tr>
<td>+ $\alpha_{3,2} (\text{May total rain} - 90.0563)^2 + \beta$</td>
</tr>
<tr>
<td>(5.12)</td>
</tr>
</tbody>
</table>
Soybean production also favored moderate July mean river discharge, between approximately 30 and 45 m³/s. In this month soybean plants would likely be nearing the end of the vegetative growth cycle and beginning reproductive development, in stages generally referred to as V5, R1, R2 and R3. During this time trifoliate leaves are fully developed and flowering begins (University of Wisconsin 2015), marking the start of rapid growth and nutrient accumulation in vegetative plant

Table 5.4: Statistical modelling parameters and values of model constants.

<table>
<thead>
<tr>
<th></th>
<th>Soybean</th>
<th>Winter Wheat</th>
<th>Grain Corn</th>
<th>Total Field Crop</th>
<th>Grape</th>
<th>Apple</th>
<th>Sweet Corn</th>
<th>Tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adj. R²</td>
<td>0.90</td>
<td>0.90</td>
<td>0.92</td>
<td>0.89</td>
<td>0.69</td>
<td>0.85</td>
<td>0.83</td>
<td>0.86</td>
</tr>
<tr>
<td>RMSE</td>
<td>11.7</td>
<td>16.0</td>
<td>20.0</td>
<td>43.2</td>
<td>188.6</td>
<td>6870.3</td>
<td>6283.1</td>
<td>10613.8</td>
</tr>
<tr>
<td>Prob. &gt; F</td>
<td>0.02%</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
<td>0.64%</td>
<td>0.01%</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>α₁₁</td>
<td>4.718E-04</td>
<td>3.418E-04</td>
<td>8.310E-04</td>
<td>1.221E-03</td>
<td>1.331E+01</td>
<td>3.347E+02</td>
<td>1.495E-01</td>
<td>3.992E-02</td>
</tr>
<tr>
<td>α₁₂</td>
<td>2.253E-09</td>
<td>-</td>
<td>2.404E-09</td>
<td>4.527E-09</td>
<td>8.625E+01</td>
<td>-</td>
<td>-1.450E-06</td>
<td>-4.176E-06</td>
</tr>
<tr>
<td>α₂₁</td>
<td>-1.072E+00</td>
<td>-1.426E+00</td>
<td>5.321E+00</td>
<td>2.233E+00</td>
<td>-3.168E+00</td>
<td>-1.315E+03</td>
<td>6.651E+02</td>
<td>-7.029E+02</td>
</tr>
<tr>
<td>α₃₁</td>
<td>6.106E-01</td>
<td>2.822E+00</td>
<td>1.855E+01</td>
<td>2.171E+00</td>
<td>-3.776E+00</td>
<td>-3.524E+03</td>
<td>-2.237E+03</td>
<td>-2.397E+01</td>
</tr>
<tr>
<td>α₃₂</td>
<td>-8.498E-02</td>
<td>-7.199E-02</td>
<td>-1.335E+01</td>
<td>7.900E-02</td>
<td>-9.392E-02</td>
<td>1.828E+03</td>
<td>-</td>
<td>3.532E+00</td>
</tr>
<tr>
<td>β</td>
<td>-5.933E+02</td>
<td>-4.658E+02</td>
<td>-1.332E+03</td>
<td>-1.605E+03</td>
<td>8.223E+02</td>
<td>6.830E+04</td>
<td>-1.784E+05</td>
<td>2.279E+04</td>
</tr>
</tbody>
</table>

moisture levels are very important because pods need to reach a certain moisture level (<15%) in order to maximize yield during harvest (University of Wisconsin 2015). Additionally, soybean crops that face issues due to infections, insect feeding or environmental stresses during this period may be subject to Green Stem Syndrome during this growth period, which causes plants to have green stems long after pods have matured and may have severe implications for harvest yield (Dupont Pioneer 2018).

A study performed by Zheng et al. 2009 in Northeast China over a 21-year period revealed a strong relationship between daily maximum temperatures during the seed filling growth stage (estimated to begin during the R5 growth stage and end in R7 (Nelson 1986)) and soybean yields for most field samples. The results of this study indicated that a 6-10% increase in soybean yield occurred per 1°C increase in daytime temperature during seed filling over this period (Zheng, Chen, and Han 2009). Based on this research, the finding that October maximum temperature may be a significant factor for modelling total soybean production is therefore consistent with literature.

Soybean production also favoured moderate July mean river discharge, between approximately 30 and 45 m³/s. In this month soybean plants would likely be nearing the end of the vegetative growth cycle and beginning reproductive development, in stages generally referred to as V5, R1, R2 and R3. During this time trifoliate leaves are fully developed and flowering begins (University of Wisconsin 2015), marking the start of rapid growth and nutrient accumulation in vegetative plant
parts (Knott and Lee, n.d.), followed by pod development in R3. In these stages of growth, soybean crops are beginning to reach peak levels of evapotranspiration (i.e. water use) (Monsanto Company 2018b). Peak evapotranspiration and the most critical stage for water stress typically begins in R3. Water usage peaks and water availability becomes very important around this time. Mean river discharge along the primary channel that conveys water throughout the GRW could be a general indicator for water availability in the region. Some sensitivity to July water availability for soybean plants is therefore also consistent with literary findings.

Figure 5.3: Actual production (solid line) vs. simulated production (dotted line) based on statistical regression modelling for individual crops within the GRW study area from 2000 to 2015 (total production in Wellington county for soybean, winter wheat, grain corn and total field crop, total production in Haldimand/Norfolk county for grape, apple, sweet corn and tomato).
(b) Winter Wheat

Winter wheat production in Wellington County displayed a strong relationship with September mean river discharge. In Ontario winter wheat crops are generally planted in September, and then require about 8 to 12 weeks of growth to develop winter hardiness (Government of Manitoba 2018). During these first weeks after planting, crops require warm temperature and adequate water supply to provide energy for the cold acclimation process after emergence (Government of Manitoba 2018). Crop development in the fall impacts winter survival as well as overall yield potential (Government of Manitoba 2018). September mean river discharge is an indicator for water availability during this time throughout the watershed (especially upstream of the GRB hydrometric station), and therefore may be an indication of the importance of water availability for winter wheat crops during this period.

(c) Grain Corn

Grain corn production in Wellington County correlated positively with May minimum temperature. Early to mid-May (or end of April in certain cases) is usually when grain corn seeding occurs in Southern Ontario, closely followed throughout the rest of this month by preliminary stages of development (generally referred to as the VE, V1, V2 and V3 growth stages). In the early days after planting, temperature and moisture levels are very important in order for germination to occur (Monsanto Company 2018a). Extra care must be taken to observe soil temperatures as well as air temperatures, since soil generally takes longer than air to warm up (Silva 2013). Soil temperatures below 50°F (10°C) during this time cause delayed and uneven germination and emergence (Silva 2013). Plant emergence (VE) from the soil may occur 4 or 5 days after planting or may be delayed several weeks based on temperature and moisture conditions (Monsanto Company 2018a). During stages V1 to V3, leaves begin to emerge and eventually the plants start to rely heavily on the nodal root system (Monsanto Company 2018a).

According to Sánchez et al. 2014, who summarized the various responses of crops to temperature during different stages of development, the lethal minimum temperature for corn is -1.8°C while the minimum temperatures for leaf initiation and shoot growth are 7.3°C and 10.9°C, respectively. Soil temperature during this first growth period after seeding is known to be one of the most relevant growth-limiting factors for grain corn crops and is directly related to air temperature
These findings are consistent with the statistical model developed in this study, illustrating that grain corn production in Wellington County was favoured by higher May minimum temperatures over the study period.

Grain corn production also displayed a strong relationship with June mean temperature. Production was highest for June mean temperatures ranging between 18 and 19.5°C and diminished with lower and higher temperatures in this month. During the month of June, grain corn crops in Southern Ontario typically go through stages V3-V10 or V12, depending on the seeding date. From V3 to V7 soybean plants initiate leaf and ear shoots, begin absorbing greater amounts of nutrients and tassel formation begins, along with rapid stem elongation (Ransom 2013). At this time lower soil temperatures may increase time between leaf stages, increase the number of leaves formed and reduce nutrient availability (Ransom 2013). Between stages V8 and V12 potential ear shoots may form, nutrient and water demand is high and new leaves appear every two to three days (Ransom 2013). During this period frost or hail may reduce yields by removing unfurled leaves and flooding, especially accompanied by higher temperatures, may have severe implications for plant survival (Ransom 2013).

This research is consistent with the model developed in this study, in that production declined with lower June temperatures. Less is known about the specific impact of temperature on crop growth/yield after tassel initiation (V5) than before tassel initiation, however the correlation between the highest June temperatures and lower production could potentially be linked to another variable, such as water availability.

(d) Grape

Grape production in Haldimand/Norfolk counties showed a strong relationship with April mean temperature. In April, grapevine buds usually begin to burst and green shoot tips become visible (Lorenz et al. 1995). At this time, grapevines are highly sensitive to temperature due to the risk of frost damage. In a similar study, Lobell et al. 2007 demonstrated that grape yields were statistically favoured by warmer April night time temperatures as well. In this study, total grape production displays a parabolic relationship with April mean temperature. The lowest production values are correlated with mid-range April mean temperatures, while the highest production values occurred with lower, or higher mean temperatures. It is therefore possible that both very low and very high
April mean temperatures indicate decreased risk of injury due to frost, as grapevines experiencing much cooler temperatures may delay the sprouting growth stage in favour of warmer temperatures.

Grape production was also strongly favoured by lower January total snowfall. In January grapevines are dormant, and leaves are pruned back so that the plants can survive the colder temperatures. Even so, grapevines can sustain severe injury due to cold temperatures during this time. According to Goffinet 2004, winter snow may intensify light exposure, causing plant trunks to warm and potentially de-acclimate plant tissues. Consequentially, grapevines could be more susceptible to injury following sudden cold temperatures (Goffinet 2004). This is one possible explanation for the negative correlation between grape production and January total snowfall.

(e) Apple

Apple production in Haldimand/Norfolk counties showed a strong relationship with May mean temperature. At the beginning of May apple trees show new leaves and individual buds, which then typically transition to full blooms by the end of the month. According to Harrington 2017, spring temperatures are important because apple trees begin to bloom as temperatures rise, but if cold weather returns after blossoms appear yields will be negatively impacted. This could help to explain the apple crop’s apparent sensitivity to overall May temperatures during the 16-year study period.

(f) Sweet Corn

Sweet corn production in Haldimand/Norfolk counties displayed a direct negative correlation with August minimum temperature during the study period. During this time sweet corn crops are typically in reproductive stages of development, including the silking stage and kernel fill, before they are ready for harvest (Seminis US 2018). During the silking stage sweet corn crops can be very vulnerable to moisture stress, which can result in the desiccation of silks and pollen grains and reduce seed set (Seminis US 2018). Sweet corn production in Haldimand/Norfolk counties was lowest with high minimum temperatures in August, suggesting that higher temperatures did not favour production during this growth period. This could be explained by the fact that higher overall temperatures increase evapotranspiration, thereby potentially inducing moisture stress in the sweet corn crops.
(g) Tomato

Field tomato production in Haldimand/Norfolk counties showed strong relationships with May minimum temperature and May total rainfall. In this region tomatoes are typically seeded indoors weeks before the last frost and transplanted into the fields around or before mid-May. Within these first two weeks after planting, field tomato plants go through a stage of vegetative growth before they begin flowering (The Canadian Encyclopedia 2018). At this time most of the plants’ energy is used to create new leaves and roots so they are sensitive to lower temperatures and may not set fruit, especially if night temperatures fall too low (The Canadian Encyclopedia 2018). Once the first flowers begin to appear, tomato plants are also very sensitive to extreme temperatures, which can result in loss of blossoms and fruit (Delp 2018). Lower May minimum temperatures, even before tomatoes are planted, could impact production by lowering the soil temperature as well. In a similar study by Lobell et al. 2007 it was found that tomato yields in California increased with warmer maximum temperatures in April, reflecting the influence of temperature on tomato crops close to planting date.

For each of these crop variables, a fairly reliable (based on statistical parameters and output) statistical model was able to account for most of the variation in the datasets. Many of the patterns observed between predictor variables and crop variables were consistent with current crop knowledge or findings from other studies. While the literature supports many of the relationships observed in this study, there are a few patterns that are not necessarily supported by a depth of crop knowledge. For instance, the impacts of September water availability (mean river discharge) and February maximum temperature on winter wheat production have not been widely examined, to the authors’ knowledge. The impact of these variables on winter wheat production can be explained to some degree by crop phenology but have not been thoroughly investigated.

For grain corn, although the finding that lower June mean temperatures correlated with decreased production is consistent with crop phenology, production also decreased with the highest June mean temperatures as well, which is not necessarily supported by current knowledge. Other similarly unsupported relationships include October total rain and grape production and November total precipitation and apple production. In an independent, univariate quadratic regression analysis, November total precipitation was able to explain 50% of the variation in apple production
over the study period, suggesting that some of these relationships may require further investigation to determine their significance.

5.4 Conclusion

This study analyzed the relationships between eight crop variables and 86 predictor variables to better understand the impact of various anthropogenic and environmental stressors on crop production in the GRW study area and develop predictive, statistical regression models for each crop. Univariate, three-variable quadratic regression models were able to explain most of the variation in crop production (more than 80% for all variables except total grape production).

These objectives were achieved despite several limitations. First, some variables that could affect crop production may not have been included in this study, for reasons related to both data availability and overall complexity (for example, wind speed, solar intensity, soil moisture/temperature, etc.). Agricultural management, agro-economic and technological changes could also impact crop development and production but are more difficult to quantify in this type of analysis. Additionally, night time temperature data was not available for this particular study, therefore the potential impacts of cooler night time temperatures, especially during transitory months such as April and November, were not incorporated in this analysis.

In terms of the predictive power of the statistical models, it is also important to understand that predictions are constrained within the boundaries of data variations between 2000 and 2015. It is therefore not prudent to rely on predictions when data values exceed these boundaries. One potential exception is total population. While it is expected that the total population within the GRW and surrounding areas will continue to increase, the quadratic nature of many of these relationships, combined with relatively slow and steady population growth likely indicates that there is some leeway for short-term predictions in the near future.

Finally, future changes in climate, management, crop diseases or other variables may slowly cause crops to be affected by predictor variables differently than was demonstrated for this 16-year study period. This factor also impacts the predictive power of these statistical models and emphasizes their value for shorter-term, rather than long-term predictions. Recommendations for future similar studies include the following:
▪ Expand statistical regression analyses over all seven counties in the GRW study area;
▪ If possible in the future, use multiple climate stations spread over each county to develop more comprehensive and accurate datasets for each analysis;
▪ If possible in the future, incorporate night time temperature data into the analysis; and
▪ When possible, increase the overall timeline of the analysis (more data points may improve the predictability and reliability of statistical models).

This study offers a basis for understanding historical impacts of changes in climate, water availability and other anthropogenic factors on agricultural production in one of the most influential watersheds in Southern Ontario. These types of analyses are important to develop a broader understanding of how these factors influence trends in crop production and also emphasize the importance of data collection and availability. Future studies that are able to incorporate more comprehensive datasets with many predictive variables and a higher level of detail (ex. night time temperatures) as well as longer timelines will continue to improve the understanding of relationships between environmental and anthropogenic stressors and agricultural production.


6 Conclusions and Recommendations

Food and water resources are essential for human survival and influence every aspect of our daily lives. The interrelated concepts of food and water security are of paramount global concern, as many people across the globe face considerable challenges accessing these resources. Food and water security dictate economic, political and social security as well as human health and prosperity. In order to prepare communities to face obstacles to food and water security and work toward global security, it is necessary to explore the systems that govern access to these resources. A number of conceptual, empirical, analytical and simulation-based modelling frameworks and assessment tools have been used to evaluate food and water security at different spatial scales. The primary aim of this research was to evaluate recent water and food-related trends within the Grand River Watershed (GRW) and develop a statistical framework to model the impact of various climatic, anthropogenic and water availability-related variables on food production in the region.

6.1 Food and Water Security: Analysis of Integrated Modelling Platforms

An extensive literature review covering food and water security and various interdisciplinary modelling platforms was presented in Chapter 2 to determine the extent of the research and case studies that have been performed in this field. This research identified ten established interdisciplinary modelling platforms that assess food and water security-related parameters from regional to global scales. Many of these modelling approaches differ in terms of consideration given to environmental water requirements, green versus blue water and international trade, as well as in their estimation of non-irrigation water requirements and range of crop commodities used. This review highlights the importance of green water, as most crops around the world are rainfed. It also stresses that more modelling platforms should be capable of performing on a sub-national level to analyze food and water security in greater detail, especially for larger countries. Finally, this review suggests that for regions where data availability may be limited, less data-intensive models may be required.

6.2 Food and Water Security in the Grand River Watershed

The remainder of the analysis in this thesis addressed some of these challenges using empirical methods to evaluate food and water security on a smaller, watershed scale. Rather than using other process or simulation-based modelling techniques, this analysis used real, historical data to
evaluate recent trends within the Southern Ontario GRW. A multi-phase study was conducted beginning with a direct analysis of these historical data, followed by the development of a statistical modelling framework to assess future trends.

6.2.1 Trend Analysis for Water Security in the Grand River Watershed

Chapter 3 directly evaluated recent patterns in climate variability, water availability and anthropogenic changes within the GRW. These data illustrated that mean annual temperatures in the GRW fluctuated consistently but reached higher extremes toward the end of the 16-year study period. The magnitude of yearly fluctuations in mean river discharge also increased over the study period at various points along the watershed’s primary conduit, the Grand River. These results suggested several discussion points with regard to planning and objectives for the GRCA, implications for local Indigenous communities and general security concerns for the watershed population.

In terms of flooding and erosion protection, as well as preservation of infrastructure and human life, the somewhat erratic nature of fluctuations in annual temperature, precipitation and river discharge, increasingly influenced by the effects of global climate change, could pose a threat to water security in the region. Over the study period mean annual river discharge trended upward, which could make it more difficult to adapt and protect current infrastructure during the peak river discharge season. In terms of overall watershed health, the increasing population and land development changes in the GRW could have negative implications for drainage and maintenance of the hydrological cycle. Agricultural production is also a considerable threat to water quality, especially during the peak precipitation and river discharge season.

These trends have implications for Indigenous communities within the GRW as well, particularly since food and water security in many of these communities have been severely affected by historical relocations, removal of traditional territories and other colonial practices that have impacted cultural connections to food and water resources. The Six Nations of the Grand River (SNGR) and Mississaugas of the New Credit (MNC) First Nations communities are both located in the southern GRW, along the path of the Grand River. Changes in water level along the Grand River can have considerable flooding implications for members of these communities. Risk of flooding and damages to these communities could increase if mean annual river discharge
continues to trend upward. Additionally, some members of the community rely directly on the Grand River for fresh drinking water supply. Changes in climate and water availability could have severe implications for water access and availability for these members of the community, as well as for those who rely on private wells, and others who do not have direct access to fresh drinking water at all.

### 6.2.2 Trend Analysis for Agri-Food Production in the Grand River Watershed

Chapter 4 analyzed trends in agricultural production and discussed implications of the previously-evaluated trends in climate variability, water availability and anthropogenic changes for crop production in the GRW. These data illustrated that overall soybean, winter wheat and grain corn production in the GRW’s Wellington County increased over the study period, although production for these crops also showed yearly fluctuations. Total sweet corn and tomato production in the GRW’s Haldimand/Norfolk counties also increased over the study period, while total grape and apple production in Haldimand/Norfolk counties decreased substantially over this time.

These trends in agricultural production indicate that water availability could pose a threat to crop production in the future, especially during seasons where higher overall temperatures coincide with lower precipitation. Conversely, cooler years with high precipitation could also have adverse implications for crop production due to flooding. If these fluctuations increase in magnitude or align more frequently in the future, the sustainability of current crop production growth trends could be threatened. It also appears that agricultural management practices and efficiency within the GRW are likely improving. These changes could be accompanied by increased concentrations of fertilizer or pesticide use and could have negative implications for water quality.

Food availability is not an issue for residents of the GRW, as far more food is produced than consumed by the current watershed population (this could be attributed to trade practices with other regions in Southern Ontario and internationally). Even so, the trends illustrated by recent climatic patterns combined with the uncertainties of global climate change suggest that current production patterns may not be as stable in the future. This could result in periodic issues with agricultural production in the GRW if temperature and precipitation patterns become more erratic and extreme weather events become more frequent in the future.
These trends also have implications for the SNGR and MNC First Nations communities. The SNGR community faces many historical, cultural, social and economic barriers to food security. Loss of traditional hunting, fishing and foraging territories, generational gaps in culturally significant traditional knowledge and a lack of access to affordable local grocery options have led many residents to procure food from external, off-reserve sources. Within the SNGR community, although there are efforts to encourage community gardening and growth and consumption of traditional foods, these efforts could be affected by environmental and anthropogenic changes in the GRW as well. In 2012, a combination of warmer temperatures and low precipitation levels resulted in very low apple production. Since crop production occurs on a much smaller scale in the SNGR community, this type of weather has the potential to affect traditional food procurement efforts and overall food security in the community more than in other areas.

6.2.3 Modelling Crop Production in the Grand River Watershed: a Statistical Regression Analysis

Chapter 5 modelled the data previously presented in Chapters 3 and 4 using statistical regression analyses in order to identify specific indicators for the production of various crops and facilitate future estimations of crop production in the GRW. This analysis utilized independent, univariate, quadratic regression analyses to identify the most significant climatic, water availability-related and anthropogenic factors (from a possible 86 monthly and yearly predictor variables) influencing the yearly production of each crop within the GRW. Using these ‘significant’ predictor variables, all possible two and three-variable univariate, quadratic regression models were evaluated for each crop. A suitable model was chosen to fit the data for each crop variable based on statistical parameters (including adjusted $R^2$ and RMSE) and knowledge about crop phenology.

For each crop variable, a three-variable statistical model was able to account for most of the variation in the datasets (with an adjusted $R^2$ value over 80% for seven of eight crop variables). Many of the statistical relationships observed between crop variables and predictor variables were consistent with current knowledge about crop phenology or findings from other similar studies. Several of these relationships have not necessarily been studied comprehensively and may indicate areas for further research or investigation to determine their significance. In terms of the predictive power of these statistical models, it must be known that the most reliable predictions are constrained within the boundaries of the original dataset. Additionally, as anthropogenic and
environmental changes occur, the effect of certain variables on crop production may also evolve, emphasizing the value of these models for short-term, rather than long-term predictions.

### 6.3 Recommendations

The overall objectives of this thesis were achieved despite several limitations that constrained the scope of the investigation and analysis. These limitations are summarized as follows:

- Data gaps and inconsistencies limited the availability of useful climatic, hydrometric and agricultural data;
- Due to data availability and consistency, the timeline of this analysis was restricted;
- Limited spatial coverage for climate stations affects ability to capture detailed, localized changes in precipitation;
- A lack of consistency in river water level observations meant that this variable could not be used in the analysis;
- Agricultural management practices and agro-economic or technological changes could influence patterns in crop production but were unable to be directly incorporated into the statistical analysis; and
- Night time temperature data was not available for most climate stations (other studies performing similar statistical analyses have obtained useful results by incorporating both day and night time temperatures in statistical modelling analyses).

These limitations have led to the development of specific recommendations for future studies in similar areas, or with similar methods. Recommendations for future research are as follows:

- Address inconsistencies in monitoring and recording observations for all data types in Southern Ontario and the GRW region;
- Address the possibility of recording multiple daily observations for more climate stations in Southern Ontario and the GRW region (i.e. day and night time recordings);
- For similar studies, increase the number of climate stations used (if/when possible) to improve understanding of spatial trends;
- When possible, increase the overall timeline of similar studies to improve the reliability of modelling efforts; and
- Incorporate groundwater and other components of the hydrological cycle in future analyses to improve overall understanding of water availability and security.

This thesis provides a basis for future research and evaluations of food and water security within the GRW. The discussion of interdisciplinary food and water modelling frameworks gives future researchers an essential overview of current platforms to facilitate preliminary research in future modelling efforts. The trend analyses provide the necessary foundation for understanding localized patterns in climate, water availability, crop production and anthropogenic changes in the GRW, and will be a useful starting point for further studies in the same region. This thesis also provides a general methodology for analyzing and empirically modelling food and water security-related variables in other similar locations. The methods used in this research could be readily replicated in other locations, especially where many specific data types (for instance soil, plant or other climate variables that may be required for certain process or simulation-based models) may not be available.

Although other analytical, simulation or process-based modelling frameworks can be useful and are important for making longer-term predictions, studies using more direct, empirical methods can address aspects of food and water security research that other types of analyses cannot. Future studies that can incorporate more variables, more comprehensive datasets and longer overall timelines will continue to improve our understanding of environmental and anthropogenic impacts on food and water security.
REFERENCES


Lobell, David B, Kimberly Nicholas Cahill, and Christopher B Field. 2007. “Historical Effects of

Demand of the Future by Engineering Crop Photosynthesis and Yield Potential.” Cell 161

Stages of the Grapevine: Phenological Growth Stages of the Grapevine (Vitis Vinifera L.
Ssp. Vinifera)—Codes and Descriptions According to the Extended BBCH Scale.”

Multifunctional Character of Agriculture and Land.” In Documento de Trabajo,
FAO/Netherlands Conference on the Multifunctional Character of Agriculture and Land


Massachusetts Institute of Technology. 2006. “Quantitative Reasoning and Statistical Methods

Agricultural Production System Simulation Model for Operational Research.” Mathematics

“APSIM: A Novel Software System for Model Development, Model Testing and

McKinney, Daene C, Ximing Cai, Mark W. Rosegrant, Claudia Ringler, and Christopher A.

McNeil, Mark. 2014. “$41-Million Water Treatment Plant Opens in Six Nations, but Water
million-water-treatment-plant-opens-in-six-nations-but-water-woes-ongoing/.

Meehl, Gerald A, Francis Zwiers, Jenni Evans, Thomas Knutson, Linda Mearns, and Peter
Modeling Extremes in Projections of Future Climate Change.” Bulletin of the American

Monsanto Company. 2018a. “Corn Growth Stages and Growing Degree Units.”


University of Wisconsin. 2015. “Corn Agronomy.”


### APPENDIX

Table A1: Availability of sufficient temperature data for climate stations in this study between 2000 and 2015.

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Table A2: Availability of sufficient precipitation data for climate stations in the study between 2000 and 2015.

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Table A3: Availability of sufficient river discharge data for river stations in this study between 2000 and 2015.

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<td>PODIUMSim</td>
<td>Sub-National River Basin</td>
<td>Food and water security scenarios for the year 2025</td>
<td>India, China, Uzbekistan</td>
<td>(Amarasinghe 2005)</td>
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<tr>
<td>CERES &amp; VIC</td>
<td>National</td>
<td>Direct effects of climate change and other key drivers on future cereal production and water availability</td>
<td>China</td>
<td>(Wei et al. 2009)</td>
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<tr>
<td>CAPRI (Extended)</td>
<td>Regional</td>
<td>Impacts of climate change and water availability on agricultural production</td>
<td>Europe*</td>
<td>(Blanco, Van Doorslaer, and Britz 2012)</td>
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<td>GFWS</td>
<td>Global</td>
<td>Pressures, threats and risks to global food and water availability for irrigated agriculture</td>
<td>Global Applications</td>
<td>(Grafton, Williams, and Jiang 2015)</td>
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*Proposed application
Table A5: Primary drivers of joint food and water security modelling platforms.

<table>
<thead>
<tr>
<th>Primary Drivers</th>
<th>IMPACT-Water</th>
<th>GLASS</th>
<th>WATER-SIM</th>
<th>GEPICT</th>
<th>LPJmL</th>
<th>GCWM</th>
<th>PODIUMSim</th>
<th>CERES &amp; VIC</th>
<th>CAPRI</th>
<th>GFWS</th>
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<tr>
<td><strong>Water Demand</strong></td>
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<td>General Water Demand (Domestic, Industrial)</td>
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<td>(Hard or Soft Constraints)</td>
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<td>Economic Factors</td>
<td>Food/Water Prices</td>
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<td>International Trade</td>
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</table>

*,** present in proposed extended model framework, not original CAPRI model or individual crops

***Unknown whether GLASS model uses crop categories
Table A6: Primary limitations of joint food and water security modelling platforms.

<table>
<thead>
<tr>
<th>Food &amp; Water Security Models</th>
<th>Limitations</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IMPACT-Water</strong></td>
<td>• Assumes minimal water shortages within a river basin</td>
<td>(Rosegrant et al., 2008)</td>
</tr>
<tr>
<td></td>
<td>• Uses historical climate data - assumes that historical climate patterns will be repeated, and climate is not correlated between years</td>
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<td></td>
<td>• Assumes environmental stress is proportional to % of area with 'substantially below normal' crop yield or water availability</td>
<td></td>
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<tr>
<td></td>
<td>• Oversimplifies by using GDP per capita to determine poverty-level of each nation and determine state susceptibility to crisis</td>
<td>(Alcamo et al., 2001)</td>
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<tr>
<td></td>
<td>• Uses a country's 'most important' crop to compute environmental stress - new and better-adapted crops may be introduced</td>
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<tr>
<td><strong>GLASS</strong></td>
<td>• Global scale of the model limits level of detail and complexity</td>
<td>(de Fraiture, 2007)</td>
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<tr>
<td></td>
<td>• Assumes that % of total river flow dedicated to in-stream environmental requirements remains equal on a monthly basis</td>
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<td></td>
<td>• Modeling requires computationally-intensive calibration process</td>
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<tr>
<td><strong>WATER-SIM</strong></td>
<td>• Lack of land use maps giving spatial distribution of specific crops simplifies simulations</td>
<td>(Liu et al., 2007)</td>
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<tr>
<td></td>
<td>• Does not address effects of pests on crop yield</td>
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<tr>
<td></td>
<td>• Model should be calibrated and validated at a sub-national scale for large countries (U.S.A, China, etc.)</td>
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<tr>
<td><strong>GEPIC</strong></td>
<td>• Lack of management data available at regional scale - inconsistencies with published results in the USA and Australia</td>
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<td>• Uncertainties in published estimates of global biomass - LPJmL simulations for total soil carbon are merely plausible</td>
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<td></td>
<td>• Model appears to overestimate total crop and grazing harvest intensity across the globe</td>
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<td></td>
<td>• Does not consider technological or management changes over time (except irrigation)</td>
<td>(Bondeau et al., 2007)</td>
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<td></td>
<td>• Assumes that relative crop distribution within a grid cell is constant throughout the 20th century</td>
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<td></td>
<td>• Requires additional diversity in grouping crop functional types (CFTs) for food production assessments</td>
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<td></td>
<td>• Model currently simulates only CO₂ fluxes - does not currently simulate other greenhouse gases</td>
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<tr>
<td>Model</td>
<td>Uncertainties / Inconsistencies / Discrepancies</td>
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<td>-------------</td>
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<tr>
<td>GCWM</td>
<td>• Uncertainties associated with:</td>
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<tr>
<td></td>
<td>− data set on monthly crop growing areas and cropping calendars</td>
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<td></td>
<td>− parameters used to compute daily crop coefficients</td>
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<td></td>
<td>− methodology used to compute reference evapotranspiration</td>
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<td></td>
<td>− spatial and temporal resolution of climate input data</td>
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<tr>
<td></td>
<td>• Inconsistencies with published statistics for irrigation withdrawal water use in some European countries</td>
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<tr>
<td></td>
<td>• Discrepancies with other models (FAO) for computation of irrigation water requirements for some countries</td>
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<tr>
<td>PODIUMSim</td>
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<tr>
<td>CERES &amp; VIC</td>
<td>• Standard concentration scenarios used do not account for climate-carbon cycle feedbacks</td>
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<td></td>
<td>• Model results likely slightly optimistic due to large precipitation increases in PRECIS</td>
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<td></td>
<td>• Effects of CO2 on crop yields remain uncertain</td>
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<td></td>
<td>• Unlikely to capture full spatial and temporal detail of extreme climate events</td>
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<td></td>
<td>• Crop production simulations do not consider effects of distribution changes, pests, and diseases, changes in management practices, crop variety and type or the multiple cropping index</td>
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<tr>
<td></td>
<td>• Assumess that farmers apply optimum inputs</td>
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<td></td>
<td>• Assumes continuation of water management and efficiency of use at current levels</td>
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<tr>
<td></td>
<td>• Uses observed planting and irrigation area to calculate future potential production</td>
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<td></td>
<td>• Water use does not consider non-grain production and livestock requirements</td>
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<td></td>
<td>• Does not incorporate decreasing groundwater levels due to abstractions for irrigation and urban water use or declining soil fertility</td>
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<tr>
<td>CAPRI (Extended)</td>
<td>• Development of the irrigation module is limited by the lack of homogeneous and accurate data at the EU-level for major variables (ex. irrigation costs, irrigation water use by crop, etc.)</td>
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<td>• Currently limited in the ability to account for competition between agricultural and non-agricultural water uses</td>
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<tr>
<td>GFWS</td>
<td>• Does not incorporate expected future contributions of animal production to diets (likely underestimating future crop food requirements)</td>
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</table>