8-21-2013 12:00 AM

A system dynamics approach to water resources and food production in the Gambia

Jordan T. Atherton, *The University of Western Ontario*

Supervisor: Slobodan Simonovic, *The University of Western Ontario*
A thesis submitted in partial fulfillment of the requirements for the Master of Engineering Science degree in Civil and Environmental Engineering

Recommended Citation

Atherton, Jordan T., "A system dynamics approach to water resources and food production in the Gambia" (2013). *Electronic Thesis and Dissertation Repository*. 1550.
https://ir.lib.uwo.ca/etd/1550

A SYSTEM DYNAMICS APPROACH TO WATER RESOURCES AND FOOD PRODUCTION IN THE GAMBIA

(Thesis format: Monograph)

by

Jordan Atherton

Graduate Program in Civil and Environmental Engineering

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Engineering Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

Abstract

The Gambia, a country in West African, faces an increasingly daunting situation. They do not produce enough food needed to feed the population, yet population growth remains high, and the current area of land under cultivation is approaching total arable land available. Climate changes complicate matters further as the majority of farms lack irrigation and are dependent on rainfall to provide water to their crops. The purpose of this thesis is to provide the first 1st iteration of a system dynamics model that could be useful as a tool to assist decision in the Gambia better understand long-term implications of policies before they are implemented. Contained within this thesis is the foundation of a system dynamics simulation model designed specifically for the Gambia that incorporates five interconnecting sectors: climate, population, land use, food production, and water resources. The model is demonstrated through four simulated scenarios over a 100-year period and an analysis of the long-term model behaviour of the model is provided. The simulated scenarios include the reduction in total fertility rate, increased irrigation, increase in crop yields, and extreme reduction in precipitation. The simulations unanimously show the long-term dangers posed by population growth and climate change in the Gambia.

Keywords

Water Resources Management, System Dynamics, Gambia, Climate Change, International Development

Table of Contents

List of Tables

List of Figures

List of Appendices

1 Introduction

1.1 Research Objectives and Contributions

In comparison to the developed world, little research is being conducted into how climate change will impact developing countries such as those of West Africa (Washington, 2006). This thesis provides the first iteration of a regional system dynamics simulation model developed specifically for the conditions of the Gambia. The model consists of five interconnected sectors, representing: climate, population, land use, food production, and water resources. The purpose of the model is to examine the long-term behavior of the overall system when fitted with government policies and simulated using different projected climate change scenarios. The model was also constructed with the intention that it be freely available, to be used and expanded on, by anyone with the interest.

1.2 Project Background

In 2009, I spent the summer in the Gambia and was given the opportunity to visit agriculture sites across the country with Soil and Water Management Services of the Gambian Ministry of Agriculture. It was an eye opening experience to see the importance agriculture played in so many people’s lives. For most living in Canada, agriculture has largely been removed from our daily reality, but in the Gambia 75% of the workforce is directly employed in agricultural sector (FAO, 2013).

The Gambia is classified as a least developed, low income food deficit country, and is currently ranked 165 out of 177 countries according to UNDP’s Human Development Index (HDI) (UNDP, 2013). One of the most significant problems facing the Gambia is they lack the ability to produce enough food required to feed their population. In fact, less than 60% of food consumption is produced domestically making the country reliant on food imports to feed the population (FAO, 2013).

A number of interconnecting factors keep the Gambia from becoming food self-sufficient, both social and physical, that progressively become more difficult to rectify the longer nothing is done. For one, while population growth rate is high, the area of land currently under cultivation is approaching the country’s total available arable land. With a growing number of people to feed and shrinking land availability, agricultural land practice techniques that were once common, such as crop rotation and leaving land fallow, are no longer practiced. Crop rotation and long fallow periods are methods of replenishing the soil nutrients crops need to maintain healthy yields each year. Not maintaining these land use practices is counterproductive as less fertile land will result in less food over the long term. Deforestation is another negative land use practice caused by population pressure (Kuyu, et al., 2006).

Another barrier to achieving food self-sufficiency is the wide spread use of rain-fed agriculture, since crops can only be grown during the rainy season. It is estimated that only 2,800 hectares of land is currently under irrigation, representing less than half of 1% of the total land area under cultivation throughout the country (FAO, 2013). With crops not receiving the water they require to reach their potential yields, less food is produced per hectare and the pressure to put more land under cultivation will increase (Allen, et al., 1998). Even though agriculture is reliant on rainfall, most farms do not have the infrastructure to handle increased runoff from heavy rainfall events resulting in the loss of fertile top soil to water erosion. It has been estimated that 12 tons/hectares/year are eroded from frequency cultivated soils with a 2% slope (Republic of The Gambia, 2003).

Compounding these barriers to food self-sufficiency is climate change. The Gambia has already experienced the effects of a changing climate, since 1960 precipitation has become increasingly variable, both interannuall and interdecadal, and during the rainy season has been decreasing at a rate of 8.8 mm per decade (McSweeny, et al., 2008) (Republic of The Gambia, 2008). As global mean temperatures are set to continue increasing, the long-term impact of climate change has yet to be felt.

1.3 Literature Review

1.3.1 Climate Change

The climate has influenced humans significantly since throughout our history; from where we live, what we wear, what we eat, and possibly played a major role in our evolution (Behrensmeyer, 2006). However, since the industrial revolution human produced greenhouse gasses released into the atmosphere have had resulted in a significant impact on the climate; more specifically, human greenhouse gas emissions have caused an increase in mean global temperature. (IPCC, 2007)

Of the human produced greenhouse gases, carbon dioxide (CO_2) is considered the most threatening to the climate because of its high atmospheric concentration and its ability to survive in the atmosphere for periods of over one hundred years. Atmospheric concentrations of CO_2 have increased from the pre-industrial levels of around 280 ppm to the current value of 398.5 ppm as of June 2013 (Tans & Keeling, 2013). To put this in perspective, atmospheric concentrations of CO_2 only increased by 20 ppm in the 8,000 years prior to the industrial revolution. The primary sources of CO_2 emissions have been the use of fossil fuels and results of land use change. As seen in Figure **1**, the past 25 years have seen an unprecedented rise in global mean temperature (IPCC, 2007).

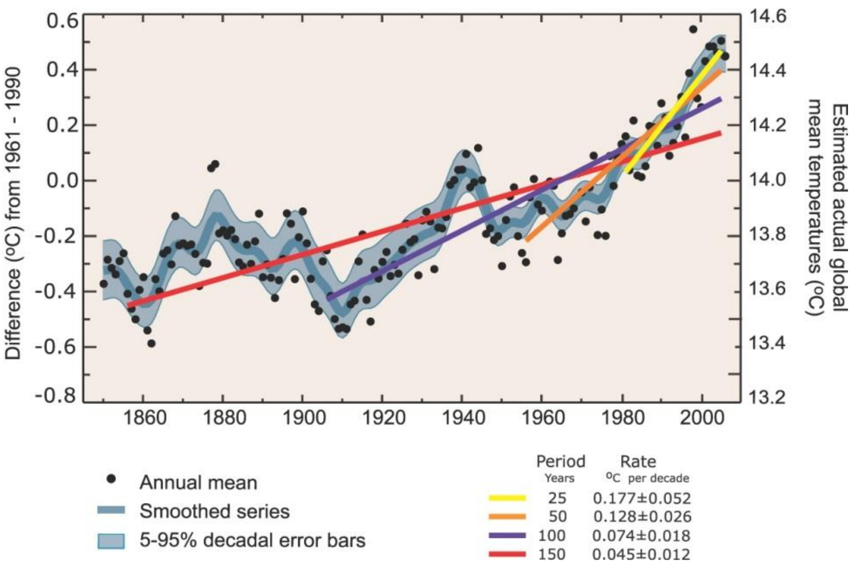


Figure 1: Global annual mean temperature for the duration 1856-2005 (plotted in black dots). Left hand axis shows temperature anomalies with respect to average temperatures recorded in the period 1961-1990 while right hand axis shows absolute temperature values
(IPCC, 2007)

By 2080, it is expected that atmospheric concentrations of CO2 will double resulting in a temperature increase of 4° C. As a response to the global rise in temperature, it is expected that the hydrological cycle will be accelerated as a result of increases in the rate of evaporation from both land and sea. This will result in increased rainfall in the tropics and higher latitudes, but decreases in dry semi-arid to arid mid-altitudes and in the interior of large continents. Temperature and rainfall are both predicted to become more variable, resulting in increased occurrences of drought and floods (Turner, 2008).

Coupled Atmosphere-Ocean Global Climate Models (AOGCMs) are the state of the art in complex climate models that are used for predicting future climate in response to increasing concentration of greenhouse gases. They use a standard set of plausible emission scenarios from the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Emission Scenarios (SRES) as inputs. The models simulate climate variables (temperature, precipitation, humidity, wind, surface pressure and others) on a daily or monthly time step (IPCC, 2013).

Emission scenarios are based represent future conditions that are based on assumptions including patterns of economic and population growth, technological development, and many other factors These assumptions are what determine the rate in which greenhouse gasses are released into the atmosphere. The emission scenarios are used to establish baseline conditions across models (Nakicenovic, 2000).

AOGCMs represent the climate as a three dimensional grid over the globe with horizontal resolutions usually ranging between 200 and 500 kilometers and 10 to 20 vertical layers are used to represent atmosphere. The spatial resolution of the model projections is too large to be useful for examining the impacts of climate change on individual river basins or agriculture. It is therefore necessary for AOGCM projections to be downscaled to provide regional climate projections more appropriate for use in climate change studies in a smaller scale (IPCC, 2013).. A major problem encountered when downscaling model projections for developing countries is that there is little available historic data that can be used to calibrate the downscaled projections (Turral, et al., 2011).

1.3.2 System Dynamics

System dynamics, as an academic discipline, is a computer based simulation approach to understanding how the structure of a system perpetuates the behavior exhibited by the system overtime (Simonovic, 2009). Since being developed in the 1960s for better understanding of economic and industrial systems, system dynamics has been applied in the analysis of social, economic, physical and biological systems (Sterman, 2000). In water resources management, system dynamics is used to integrate physical, social and economic factors that influence water resources to address long term planning (Winz, et al., 2009).

Some definitions are helpful in an explanation of system dynamics. A system is as a collection of interacting components that form a unified complex whole, that are physical or abstract. The underlying relationship between components making up a system is known as the structure of the system. The term dynamic refers to a constant change over time. Therefore, a dynamic system is a system in which components interact to stimulate changes within the system overtime. The way in which the components making up a system interact overtime is known as the behavior of the system (Simonovic, 2009).

1.3.2.1 System Dynamics and Water Resources

In 1966, Crawford and Linsley created The Stanford Watershed Model, the first comprehensive watershed simulation model. It only simulated the hydrological processes, not incorporating any social or economic factors. The first time the interdependencies between water resources and their management were simulated in conjunction with measurable social and economic factors was in the Susquehanna River Basin Model (Hamilton, 1969). Considering the limited computational capabilities of the time period, the additional complexity of the model was considered exceptionally ambitious and came at the cost of increased data aggregation and larger spatial scale (Winz, et al., 2009).

Eventually, the underlying concepts of system dynamics modeling became heavily intertwined with the systems approach to water resources management (Biswas, 1976). Grigg's (1977) defined the systems approach as “a systematic method to conceptualize the water resources ‘system’ and use the tools of systems analysis to identify and evaluate strategies.” In the 1980s just following the systems, Integrated Water Resources Management (Bowden & Glennie, 1986) came into use. Integrated water resources management took account for the integrated nature of water resources problems and saw the need to incorporate multiple objectives and also to involve multiple stakeholders in the decision making process (Winz, et al., 2009).

With developments in water resources management, the applications of system dynamics have gone in a number of directions over the last 50 years. In a comprehensive literature review, Winz et al. (2009) have documented the modern trends in which system dynamics has been used as a tool for regional water resources analysis:

> *While spatial scales have shifted from* ***regional*** *(Camara et al. 1986; Cartwright and Connor 2003; Cohen and Neale 2006; Connor et al. 2004; Den Exter 2004; Den Exter and Specht 2003; Guo et al. 2001; Leal Neto et al. 2006; Passell et al. 2003; Sehlke and Jacobson 2005; Xu 2001; Xu et al. 2002) to* ***national***

> *(Simonovic and Fahmy 1999; Simonovic and Rajasekaram 2004) to* ***global*** *(Simonovic 2002a, b, 2010, 2011), so too have the number of socio-economic factors included, mirroring improved computer capabilities as well as changing problem foci (global water crisis and social impacts). Simonovic and Rajasekaram (2004) note a recent trend in the reduction of spatial scales to basin and watersheds with the aim of identifying regional and local solutions.*

Population growth and urban encroachment onto floodplains have resulted in an increase in the frequency of urban flooding have required a larger focus to be put onto managing urban water resources (Akhtar, 2011). The changing water management focus has made it necessary to increase the complexity of models to account for these developments. Recent research has also focused on the integration of groundwater with surface water (Roach, 2007; Tidwell & van den Brink, 2008) and irrigation. Within these areas of research, models have increasingly aimed to investigate spatial outcomes (Ahmad & Simonovic, 2004) and operational planning over shorter temporal scales.

Participatory methods have also been incorporated into system dynamics modeling for regional and urban watersheds (Beall, et al., 2011) allowing public-centered decision making and getting local stakeholders to participate to better understand a long term vision of the management of water resources.

Ahmad and Simonovic (2006) have developed an intelligent decision support system for flood management in the Red River basin in Manitoba, Canada. It is intended to be used as a training tool for entry-level flood managers and as an interactive problem-solving and advisory tool for experienced managers. System dynamics is one component of the overall modelling framework; it also includes artificial neural networks, hydrological models, and geographic information systems (GIS).

Building on the ANEMI model developed by Davies (Davies, 2007; Davies & Simonovic 2008; 2009; 2010; 2011), Akhart (2011) has brought forth a global nine-sector integrated assessment model (ANEMI version 2) with a regional version (ANEMI_CDN) developed specifically for Canada. The models introduce the integration of an optimization scheme within a system dynamics simulation structure, where the optimal plan is updated at each time step of the simulation interval. The models also implements a disaggregation modelling technique within the system dynamics simulation framework which will allow the ANEMI_CDN model to be regionalize the global model.

1.3.3 The Gambia

The Gambia is located on the West Coast of Africa nestled inside much larger Senegal. It is the smallest country on main land Africa with a total area of 11,300 kilometers ^{2}, of which 1,180 kilometers ^{2} can be considered wetlands. The River Gambia, flowing east to west, bisects the country into northern and southern strips of land that are each 25 kilometers to 50 kilometers wide and about 400 kilometers long. (FAO, 2005)

The Gambia has a Human Development Index (HDI) of 0.439, which ranks it towards the bottom of 186 countries in the 165th position. In comparison, the average HDI of sub-Saharan African countries is 0.475, showing that The Gambia is even lagging behind regionally. (UNDP, 2013)

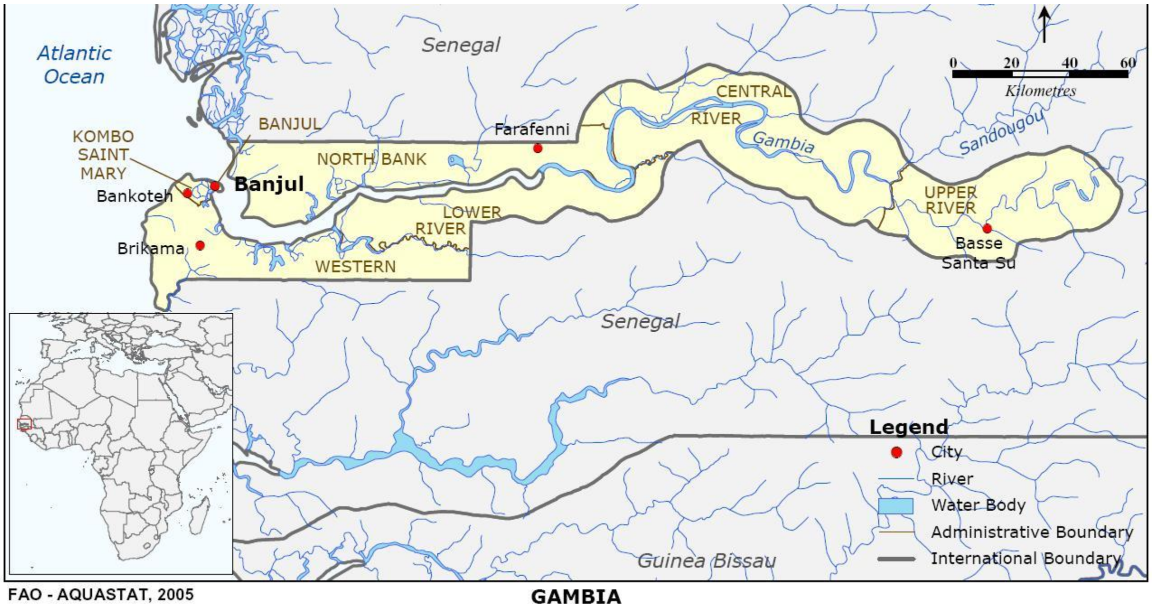


Figure 2 Map of the Gambia

(FAO, 2013)

1.3.3.1 Climate

Located between latitudes of 13° and 14° N and longitudes 13°40' and 16°50' W, the Gambia is just south of the sub-tropical and semi-arid belt known as the Sahel, with a tropical climate with two distinct seasons. There is a wet season of variable length usually between May and October and a long dry season from November to May. Precipitation ranges between 850 to 1,200 millimeters a year. Average temperatures range from18 to 30 in the dry season and 23 to 33 in the wet season. Relative humidity is about 68% along the coast and 41% inland during the dry season, and around 77% throughout the country during the wet season (Republic of The Gambia, 2003).

The rainy season is of variable lengths from May to November, with 80 percent or more of the total precipitation occurring in short heavy storms between July and September, making water conservation necessary for crop security (FAO, 2005). There is a significant north-south gradient in total annual rainfall with over 1,000 mm falling in the south to less than 800 mm in the most northern parts of the country where rainfall is less reliable (Njie, 2009).

The rainfall season is controlled by the movements of the tropical rain belt (Inter-Tropical Conversion Zone, ITCZ) which oscillates between northern and southern tropics affecting the Gambia while it is in its northern position. The year-to-year variation in latitudinal movements of the ITCZ is responsible for a large inter-annual variability of precipitation during the wet season (McSweeny, et al., 2008).

The high variability of precipitation on both an interannuall and interdecadal timescale has made it difficult to identify long-term trends. Though a steady decrease in rainfall has been observed since 1875, most strikingly, linear trends show that rainfall for July, August, and September has decreased at an average rate of 8.8 millimeters per decade between 1960 and 2006. There is limited number of rainfall observations available for the Gambia, making it difficult to determine changes in extreme incises of rainfall. (McSweeny, et al., 2008)

The Gambia's climatic pattern allows for only a short agricultural season, usually averaging around three months. The short season coupled with recent low rainfall and its poor distribution has resulted in drought conditions during the past three decades, affecting vegetation cover and food production potential (National Climate Committee, 2003).

The Gambia has a longitudinal spatial distribution of temperature, with temperature increasing from the coast towards the west. During the hottest month of May, temperature in the coastal city of Banjul can range from 13 to 36°C, while 400 kilometers directly east in Basse, temperatures can range between 23 and 43°C. During the wet season, cloud and rainfall have a cooling affect resulting in similar temperatures distribution across the country (Njie, 2009).

As a result of the El Niño Southern Oscillation (ENSO), there also exists an inter-annual variability in temperature across the Gambia. Since 1960, the mean annual temperature has increased by 1°C at an average rate of 0.21°C per decade. The highest rate of increase in temperature has been between October and December at 0.32°C per decade. Like with precipitation, there is a lack of quality temperature observations to identify daily temperature extremes (McSweeny, et al., 2008).

1.3.3.1.1 Climate Change Projections

Downscaled climate projections for the Gambia can be obtained through the United Nations Development Program's (UNDP) Climate Change Country Profile for the Gambia. Multimodel projections, from the World Climate Research Programme (WCRP) Coupled-Model Intercomparison Project (CMIP3), are downscaled to 2.5° for 52 developing countries, with the objective of increasing the availability of projected climate data for areas where little climate change research is conducted (McSweeney, et al., 2010). Time series data for precipitation and temperature from 15 model projections under three SRES emission scenarios (A2, A1B, and B1) are provided for the Gambia (McSweeney, et al., 2008).

The annual and seasonal trends in mean temperature in the Gambia for the recent past and for the 15 model projections under the three emission scenarios are shown in Figure 3. All 15 models projected an increase in average temperature for the Gambia of between1.8 to 5° C by 2090s, with a rise of at least 1 to 2° C under any of the three emission scenario simulated.

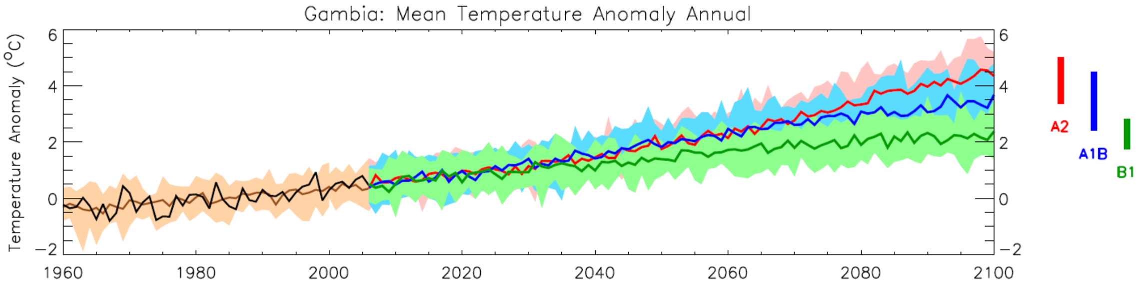


Figure 3: Annual mean temperature anomaly projections

(McSweeny, et al., 2008)

Figure 4 show the annual and seasonal trends in precipitation in the for the recent past and for the 15 model projections under the three emission scenarios There no consensus between the 15 models on mean annual precipitation projections with a wide range increases and decreases in precipitation, but three is more of a tendency for a decrease. A decreasing trend is more noticeable in precipitation during the wet season, which corresponds with historic observations. The projected annual change in precipitation ranged between -23 and 18% by the 2090s, with ensemble means between -7 and -20% (McSweeny, et al., 2008).

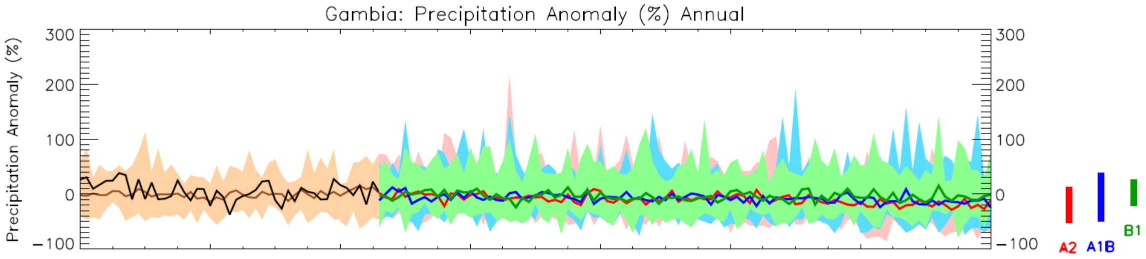


Figure 4: Annual monthly precipitation (%) anomaly

(McSweeny, et al., 2008)

Values in the Figure 3 and Figure 4 show anomalies relative to the 1970-1999 mean climate. The black curves at the beginning of the graphs show the mean observed data from 1960 to 2006 and the brown curve (line) and range (shading) of model simulations of the recent climate across an ensemble of 15 models. The coloured lines from 2006 onwards show median (solid line) and range (shading) of the ensemble projection of climate under the three emission scenarios (A2, A1B, and B1). The Couloured bars on the right of the figures summarise the range of mean 2090-2100 temperature and precipitation simulated by the 15 models for each emission scenario (McSweeny, et al., 2008).

1.3.3.2 Population

As of 2013, the Gambia has a population of 1,849,000 up from 1,360,681 in 2003, with population densities of 173 and 127 persons per square kilometer respectively, making it one of the most densely populated countries in Africa. Population growth continued at the current annual rate of 2.3% will result in a doubling of the population in 22.6 years (United Nations, 2013).

The Gambia has one of the faster growing urban populations in Africa, and urbanization is expected to increase greatly at a rate of 3.7% annually (United Nations, 2013). The urban population constitutes 58% of the total population and now outnumbers the rural population, in comparison to an urban population of 41% in 2003 and 37.1% in 1983.

The majority of the urban population lives in the Greater Banjul Area which occupies just 93 square kilometers, eight percent of the country's total land mass. In rural areas, the number of people is less than 500 in 77% of settlements, and only four towns (Barra-Kanuma, Farafenni, Soma, and Basse) in the rural countryside having a population over 10,000 (Njie, 2009).

A large percentage of the population lives below the poverty line and suffer from food insecurity. It was reported that in June 2006 approximately 57.9% of the population lived in poverty, 39% in extreme poverty. About 46% of rural households fall below the food poverty line, compared with 15% in urban areas and 4% in the Greater Banjul Area. Approximately 91% of extreme poor and 72% of the poor are dependent on agriculture for their survival (Fatajo, 2010).

Like many countries in sub-Saharan Africa, the population age-structure of the Gambia is significantly skewed to the youth. It has the tenth youngest in the world with a mean age of 17.8. In 2010, 45.9% of the population is under the age of 15, increasing from 43.6% in 2000. The population under the age of 18 is 56.6%, while the population over 65 consists of just 2.5% of the population. The young population, lack of current opportunities and high fertility rates (4.81 births per woman as of 2011) will have significant implication for future development of the country (United Nations, 2013).

As of 2012, infant mortality is 55.3 per 1000 live births, down from 73 per 1000 live births in 2000. The under-five mortality is 100.4 deaths per 1,000 births. The current (2012) birth rate is 32.59 births per 1,000 people and the death rate is 7.38 deaths per 1,000 people (United Nations, 2013).

Abortions are illegal in the Gambia except when the life of the mother is at risk during child birth. Family planning services have been available in the Gambia since the late 1960's. Though, it wasn't until 1994 that a national population policy was included in the national health program. The policy was focused on reducing the number of abortions and maternal deaths and to improve maternal and child nutrition. Contraceptives are available in Government health care centers, private pharmacies and civic organizations such as the Gambian Family Planning Association. Yet, contraceptive and other modern family planning methods are only used by seven percent of women of reproductive age. The UN’s Population Division (2003) states that the low use of contraception in the Gambia can be attributed to a number of factors such as: contraceptive services are not provided to women under age 21, unmarried mothers must obtain parental consent in order to receive family planning services, illiteracy, traditional practices, the low status of women, inadequate and under-trained medical personnel, low morale among family planning workers, poor communication and insufficient funding (United Nations, 2003).

1.3.3.3 Agriculture and Land Use

Agriculture in The Gambia is characterized as subsistence rain-fed agriculture mostly of food crops comprising of cereals (early millet, late millet, maize, sorghum, and rice) and cash crop production (groundnuts, and horticulture). With a food self-sufficiency ratio of around 0.5, food production remains the primary role of agriculture (Fatajo, 2010). The importance of agriculture can’t be overstated; the sector generates 40% of total foreign exchange earnings, accounts for 23% of the GDP, and employs 75% of the population The farming system is mixed, but crops account for a greater share of production than livestock, accounting for 13.6% of the GDP wile livestock accounts for 4.4%. Fishing and forestry make up the rest of the agricultural GDP providing 4.4% and 0.5%, respectively. (FAO 2005; The World Bank 2012)

Farmland in the Gambia can be classified into upland and lowland, and with the exception of most rice and vegetables, the majority of crops are grown in the uplands. Men are responsible for farming **upland crops**. Crops include groundnut, early millet, maize, sorghum, late millet, and upland rice. Water conservation is rare and farming is kept to the wet season. Soils in the uplands are weathered with low fertility and water retention capacity but have good drainage. Lowland farming is the responsibility of women. During the wet season, the primary crop is rice, mostly located along the middle and lower reaches of River Gambia. In the dry season vegetables have begun to be cultivated in the lowlands. Soils in the lowlands are fine textured and poorly drained resulting in the risk of developing into acid sulfate soils in the Lower Valley. (FAO, 2005)

Total cultivated land has increased from 280,000 hectares in 2000 to 450,000 hectares in 2011, representing a 60% increase and covering 44% of total country (Figure 5). The majority of farmers are small holders owning less than 3 hectares of land and there is high agricultural density with 104 agriculture workers per kilometers ^{2} of agricultural land. It is estimated that 555,240 hectares of land are suitable for agriculture throughout the country, with 326,340 hectares for upland agriculture and 81,120 hectares for irrigation. A caveat for the suitable irrigated land is that a dam must be constructed in Senegal for it to be feasible. (Njie 2010; FAO 2013)

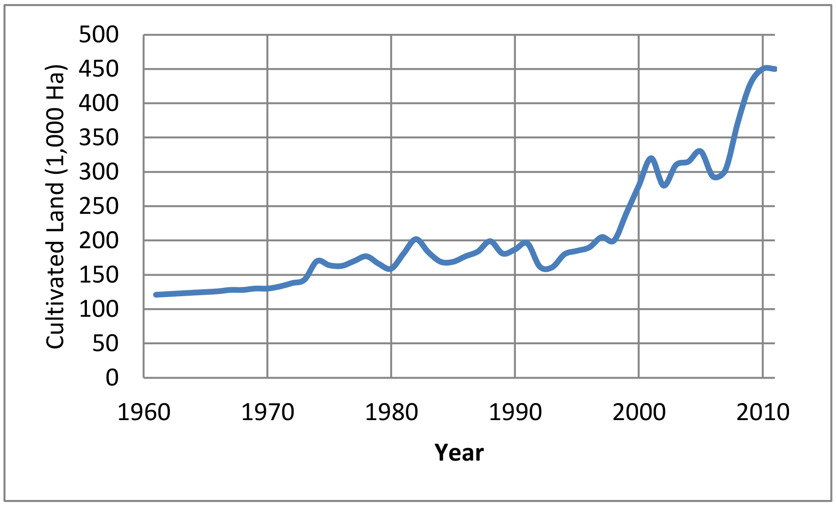


Figure 5 Cultivated Land in the Gambia, 1960-2011

(FAO, 2013)

Between 1968 and 1990, the country experienced recurrent episodes of drought, erratic rainfall and high population growth. The erratic rainfall reduced yields and in order to feed the growing population farmers responded by intensifying land use. Fallow periods for groundnut cultivation were reduced from seven years to less than 2, and occasionally completely eliminated. During this time, deforestation and erosion of top soil became a significant problem. In rural areas land degradation was more pronounced because of agricultural practices such as slash and burn, fires, overgrazing and increased cutting down of trees to fulfill the urban demand for fuel wood. (Kuyu, et al., 2006)

Up to the turn of the century, dense forests covered the Gambia, but because of the problems facing the country in the late 1960s and the population's high reliance on wood as a simple source of energy accelerated deforestation. In 2003, the use of fuel wood for energy was still practiced by 85% of the population. Forest cover was calculated as 493,400 hectares in 1989 and classified into four broad categories: closed forest (26,800 hectares), open forest (62,600), tree and shrub savannah (347,000 hectares), and mangroves (68,000 hectares). To get a sense of the rate of deforestation, in 1972 there was 333,200 hectares of open and closed forest, a decrease of 243,800 hectares in 17 years. The FAO (2013) currently reports forest area at 481,000 hectares but it is unknown the quantities of each forest category. Current rates of deforestation are estimated to be about six percent per year, but a government initiated reforestation program is trying to counter this. Though.it is not known how successful the reforestation program is as deforestation is still significant (Republic of The Gambia, 2003).

Historically, farmers realized that there was a diminishing return on soil fertility after several years of cultivation. Therefore, they would farm one piece of land for several years and then move on to a new area of land, leaving the former to a fallow period for up to 20 years while the soil reclaims its fertility. Along with a fallow period, they also once practiced crop rotation and intercropping. This allowed them to maintain the balance of the nutrient content of the soils with the crops requirements. An example crop rotations would be planting groundnut the first year, millet the second year, sorghum the third year, and groundnuts again for the fourth year, all on the same piece of land (Kuyu, et al., 2006).

Currently, traditional and improved farming methods are practiced side by side, although there has been an ongoing transition towards improved methods. Animal traction utilizing the Sine Hoe is well established but fully-fledged mechanization with conventional tractors has yet to be adopted. Farming still entails a lot of labour as many of the tasks are performed physically or manually. As of 2002, 73.4% of all farm work in The Gambia is carried out with animal power, 24.9% by human power and 1.7% by mechanized power (Kuyu, et al., 2006).

1.3.3.4 Significant Crops

Typically, farmers begin ploughing their fields after the first rains in mid-May or early June. In a good season harvesting of the crops would begin in late October or early November. Once harvested, crops are transported home either by donkey or on their head to be dried on rooftops or specially constructed platforms. (Kuyu, et al., 2006)

Groundnuts are the main cash crop of the Gambia, accounting for 5.3% of the total GDP (The World Bank, 2012). They account for 30% of all cultivated land (FAO, 2013). Land is prepared and cleared between late-April to early-June and ploughing commences following the first rains. The plants flower after approximately eight to nine weeks and they begin to mature approximately 90-130 days after planting, with harvesting usually beginning in late October (Doorenbos & Pruitt, 1975). Seeds collected following the harvest are selected, treated with pesticides and stored at home or the village seed store for the next season. Groundnuts are extremely vulnerable to irregular weather, extremes in temperature, moulds and pest infestations (Kuyu, et al., 2006). Groundnut yields have been decreasing since for the past two decades, with the average yield throughout the 1980s of 1.26 tons/hectares, 1990s 1.01 tons/hectares, and the 2000s with 0.91 tons/hectares (FAO, 2013).

The cereal crops grown in the uplands are maize, millet and sorghum, accounting for 10%, 31%, and 6% of total cultivated land, respectively (FAO, 2013). All cereals share the same land preparation techniques including burning unwanted vegetation on the site then planting the seeds and plough the land once the rains commence (Kuyu, et al., 2006). Maize usually is ready for harvest after 125 days, millet 105 days, and sorghum 130 days (Doorenbos & Pruitt, 1975). Yields have stayed consistent since 1983 in the Gambia averaging: 1.6 tons/hectares for maize, 1.02 tons/hectares for millet and 1.01 tons/hectares for sorghum (FAO, 2013).

Rice is the most important crop in the Gambia in terms of meeting the county’s food needs. The area of rice under cultivation has remained below 20,000 hectares for decades. Recent rice development projects in 2008 and 2009 have more than tripled the area of rice under cultivation to 73,000 hectares, but cultivation remains much lower than imports as can be seen in Figure 6(FAO, 2013)

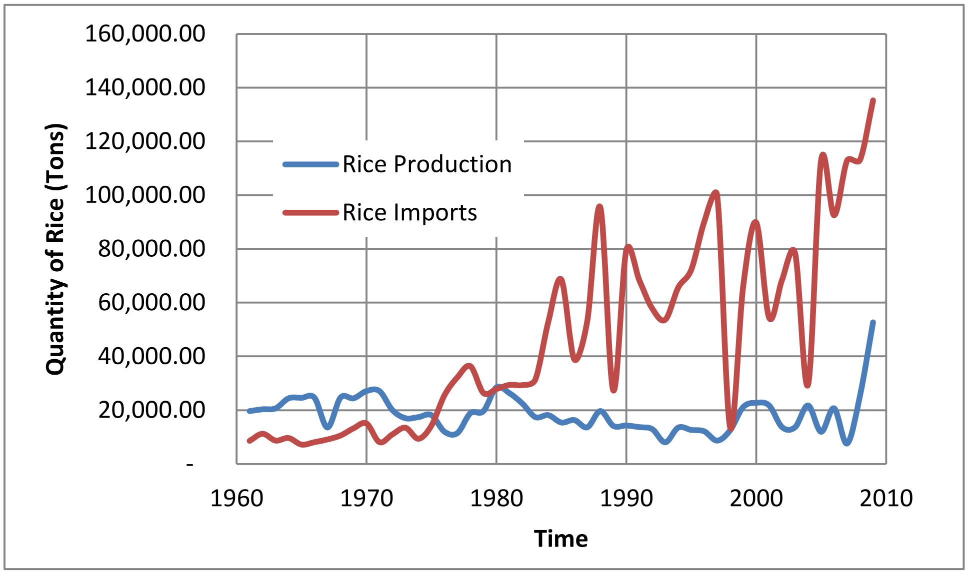


Figure 6: Rice production and imports (1960-1961)

(FAO, 2013)

Numerous rice irrigation projects, like those in Jahally Patcharr and Sankuli Kunda, have tried to increase rice production but have failed in the long-term. Most rice is grown on small-scale by woman farms who predominantly basic hand tools because they are more affordable to women (Kuyu, et al., 2006). Rice yields have fluctuated greatly since 1983, averaging at approximately 1.5 tons per hectare (FAO, 2013). The average time for rice to reach harvest in the Gambia is 150 days (Doorenbos & Pruitt, 1975).

Vegetables are another crop grown mostly by women. Vegetable production has been increasing since the 1970s to cater to the international tourist market. There are some large vegetable farms, but they mostly under 20 hectares. Currently, vegetables are cultivated on only 1,500 hectares of land. Depending upon the type of vegetables harvesting can begin within eight weeks on planting (Kuyu, et al., 2006). Yields fluctuate greatly averaging 5.6 tons/hectares but have only dropped below 4 tons/hectares since 1990 (FAO, 2013).

1.3.3.5 Irrigation

There have been approximately fifteen irrigation projects in the Gambia 1970, but most have not been sustainable, and the FAO estimates that only 2,300 hectares of land is currently under irrigation due to limited local finances and a lack of locally skilled managers, and technicians to provide maintenance (FAO, 2005). The lessons of past irrigation projects have shown that pump irrigation is not a feasible option and have started to utilize tidal irrigation. It is estimated that there is 81,120 hectares of land along the River Gambia that is suitable for tidal irrigation provided a dam was constructed just east of the Gambia in Senegal (Njie, 2010). The dam would provide a steady flow of water flow down the river, lessening the tidal influences from the Atlantic Ocean that are responsible for pushing a saline front up to 250 kilometers upriver. There are plans to start a significant irrigation project in 2020 will develop 2,800 hectares for vegetables and 15,600 hectares of land for rice with irrigation capabilities over thirty years (Njie, 2010).

1.3.3.6 Water Resources

The Gambia River Basin occupies 77,000 km^2, falling within the Gambia, Senegal and Guinea. The basin east of The Gambia is referred to as the Continental Sub Basin covering 42,000 km^2. The catchment downstream, containing all of The Gambia except for a small fraction located in Senegal, is known as the Estuarine Sub Basin and covers the remaining 35,000 km^2. The River Gambia is one of the larger rivers of the basin, and the only significant one within The Gambia (Lesack, et al. 1984; Meybeck, et al. 1987).

Figure 7: Gambia River Drainage Basin

(Musser, 2010)

The River Gambia begins in the high rainfall mountainous Fouta Djallon region in the north of Guinea and travels 1,200 kilometers through southern Senegal and The Gambia before reaching the Atlantic Ocean. The river begins with moderate gradient between 1-4% in Guinea, decreasing below 1% through Senegal, and is virtually nonexistent over the final 500 kilometers through The Gambia (Lesack, et al., 1984).

Almost 50% of the country's land area is less than 20 meters above mean sea level, one-third of which is below 10 meters above mean sea level. This results in 10 to 20 percent of the lowlands experiencing annual flooding. Only 3.8% of total land area is above 50 meters giving the county an extremely flat topography. The low elevation of the capital and most populous city Banjul puts it at significant risk of flooding from sea level rise (Cham, et al., 2007).

Tidal influences during the dry season have limited accurate collection of river flow data within the Gambia. Therefore, a gauging station in Gouloumbou, Senegal, just beyond tidal influences, has commonly been used for the measurement of flow into the Gambia.

(Lesack, et al., 1984) The lack of flow measurements within the Gambia, have made it impossible to accurately account for contribution of local tributaries and groundwater to river flow (Njie, 2010).

River flow entering the Gambia is highly seasonal, and has been recorded as high as 1,500m3/s during the rainy season and decreasing as low as 2-3 m3/s during the dry season (FAO, 2005), with an annual average flow of 164 m3/s (Njie, 2010). The characteristics of the river flow are illustrated in the 1980 hydrograph (Figure 8). Peak discharge occurs during September, dropping off as rapidly as it rose, with insignificantly small flows from December to July (Lesack, et al., 1984).

It is estimated that the total quantity of water passing from Guinea to Senegal is 3kilometers ^{3}/year and 5 kilometers ^{3}/year passing into the Gambia (FAO, 1997). Although it has been stated (Njie, 2009, 2010) that river flow data at Gouloumbou Station has been continuously measured since 1953 (Lesack, et al., 1984), I have only been able to find sporadic monthly data for periods in the 1970s (Risley, et al., 1993) and 1980s (Meybeck, et al., 1987) and nothing recent.

1.3.3.7 Saline Front

The Gambia's flat topography and seasonal changes in river flow allow tidal influences from the Atlantic Ocean to have a significant impact on the River Gambia (Risley, et al., 1993). The tidal influences push saltwater (referred to herein as the saline front) as far as 250 kilometers upstream resulting in brackish water that is unusable for agriculture or human needs.

The river can be divided into three sections based on the reach of the saline concentration of the river. The Lower Valley, where most irrigated rice schemes are located (between 100 to 250 kilometers upstream), is closest to the ocean and perennially saline for the initial 100 kilometers of the river. During the dry season this entire section of the river is saline. The Central Valley portion of the river experiences tidal influences but the water remains fresh. The Upper Valley remains fresh throughout the year and on occasion tidal influence can be detected. (Risley, et al. 1993; FAO 1995; Njie 2009, 2010)

Figure 8 shows the seasonal movements of the saline front, station between December 1972 to March 1974, for three salinity levels (1, 10 and 30 ppt) in relation to rainfall in Senegal and corresponding river flow into the Gambia at the Gouloumbou. It can be seen that in the final months of the wet season (September and October), the 1 ppt salinity front moves downstream in response to higher freshwater flows entering the country from Senegal. At the height of the dry season (May), the 1-ppt salinity front is often observed as far as 250 kilometers from the river mouth. The figure illustrates clear evidence of lags between rainfall in Senegal, freshwater flow entering the Gambia, and the movement of a given salinity level in the Gambia. It should be noted that the upper and lower migration boundaries of the 1-ppt saline front coincides with the location where irrigated rice is grown.

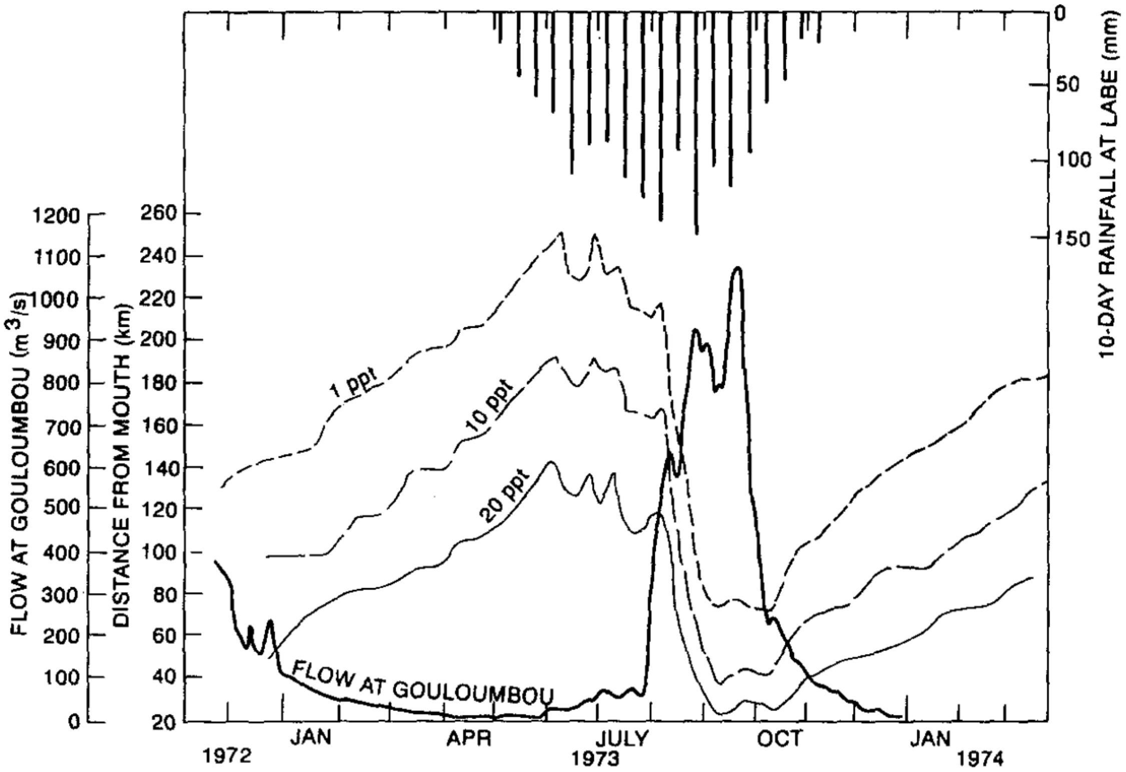


Figure 8: Graph showing Rainfall at Labe, River Flow at Gouloumbou, and Distance from River Mouth to 1-ppt Salinity Front in Estuary

(Risley, et al., 1993)

1.3.3.7.1 Ground Water

The Gambia sits on top of one of Africa's major sedimentary basins referred to as the Mauritania/Senegal Basin (FAO, 2005). It consists of two major aquifer systems that lay beneath the Gambia: a Shallow Sand Aquifer (SSA) and a Deep Stone Aquifer (DSA) (Njie, 2009).

The SSA rages in depth between 4 and 30 meters below ground level (mbgl), and is the predominate source of drinking water in the Gambia (Njie, 2010). Transmissivity values range between 20 to 4000 m^2/day, and hydraulic conductivity has an estimated range of 5 to 20 m/day. A 1983 Department of Water Resources Study estimates SSA reserves at 0.1 kilometers 3 but this is thought to be on the low side (Njie, 2009) .

The DSA is 250 mbgl and has been estimated to hold reserves in the order of 80kilometers ^{3}. And the only known recharge mechanism within the Gambia is lateral flow. Transmissivity is around 500 meters squared per day, and hydraulic conductivity is estimated between 30 and 100 m/day. Water from the DSA is not suitable for drinking without treatment as it contains anywhere from 5miligrams per liter of total dissolved solids including fluoride (Njie, 2010).

1.3.3.7.2 Water Uses

Access to drinking water and sanitation is good and improving each year. In 2003, 89% of the population have access to drinking water (92% urban; 85% rural), and 68% having access to sanitation facilities (70% urban, 65% rural) (Republic of The Gambia, 2003). Water use patterns follow a simple line: seasonal or perennial freshwater resources in the River Gambia are exclusively used for irrigation because of the saline front and groundwater is used for all other purposes, including domestic water supply. (FAO 2005; Njie 2009)

1.4 Organization of Thesis

The thesis is organized into five chapters. Chapter Two explains system dynamics methodology and discuss in detail the system dynamics model built for the Gambia, The third chapter discusses model calibration the performance of the model. The fourth chapters gives the rationale behind the four simulation scenarios and then provides an analysis of the model structure The fifth chapter concludes the thesis by providing a summary of simulation results and provides recommendation for areas of model improvement and future work.

2 Methodology and Model Description

2.1 System Dynamics Methodology

System dynamics modeling is a simulation modeling technique that describe how a system operates, and used to determine changes resulting from a specific course of action (Simonovic, 2009). System dynamics models are also referred to as causal mathematical models (Barlas, 1996) because the structure of the system gives rise to behaviour (Forrester 1968, 1987).

A system dynamic model consists of the following phases: defining the problem, decomposing and conceptualizing the system, model formation, model evaluation and testing, operation of the model, analysis of the resulting outputs and alternative inputs. These phases are done in an iterative fashion (Sterman 2000; Simonovic 2009).

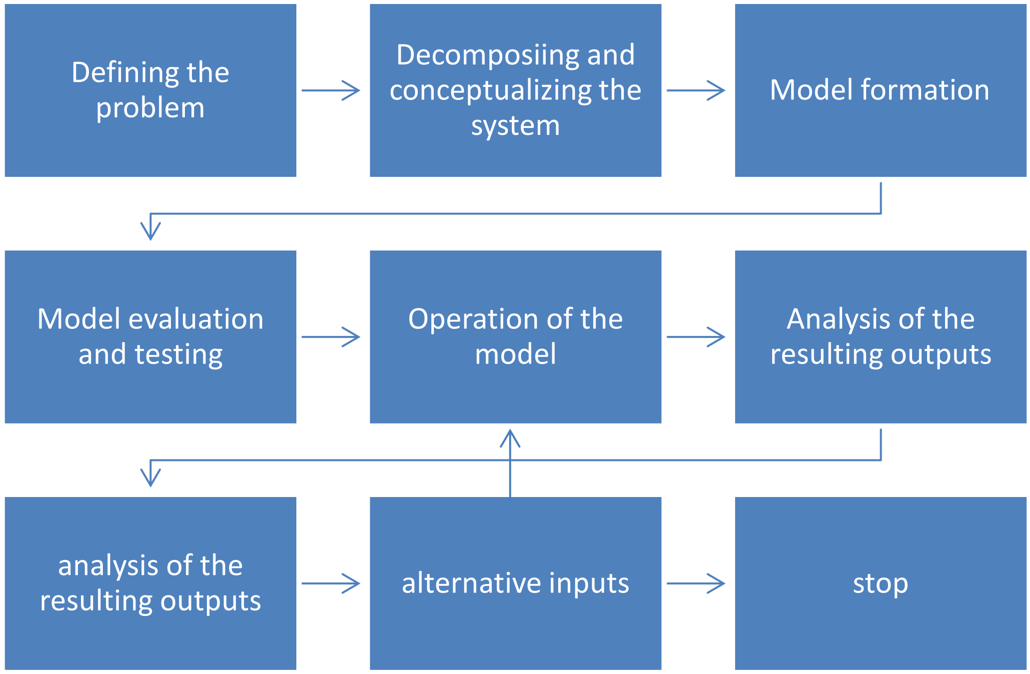


Figure 9: The simulation procedure

(Sterman 2000; Simonovic 2009)

The first step in creating a system dynamics model is determining the structure of the system that is constructed of positive and negative relationships between variables, feedback loops, and delays (Wolstenholme 1990; Sterman 2000).

System dynamics models consist of quantitative/conceptual and qualitative/numerical models (Winz, et al., 2009). The quantitative model, known herein as a causal loop diagram, is used as a starting point to develop a better understanding of the systems behaviour by graphically representing the basic feedback structure of the system. Qualitative modelling, represented by a stock-and-flow diagram, uses the causal loop diagram as a foundation and incorporates mathematical relationships into the model so that the systems behaviour can be observed (Simonovic, 2009).

A causal loop diagram, like the one in Figure 10, shows the interaction between variables within a system. Variables are connected by blue arrows and are labeled positive or negative. A positive arrow reads as an increase in Births leads to an increase in Population. A negative arc reads as an increase in Deaths leads to a decrease in population. Feedback loops are labeled (+) or (-) depending on the type of feedback loop they are, reinforcing or balancing respectively. It is these interactions between the variables that make up the complex system behaviour (Simonovic 2009; Winz, et al. 2009).

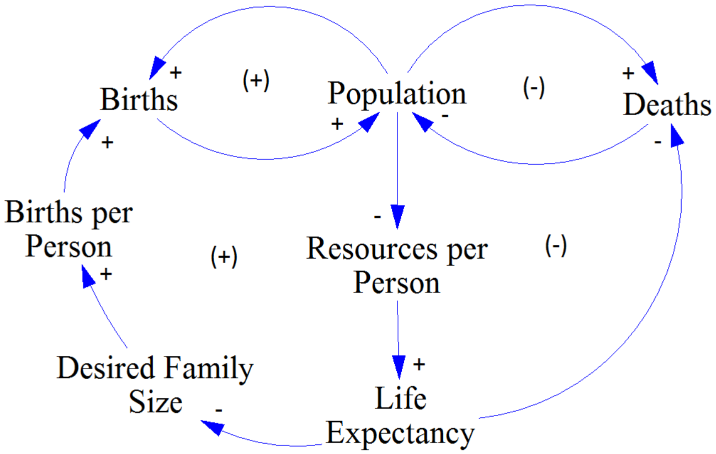
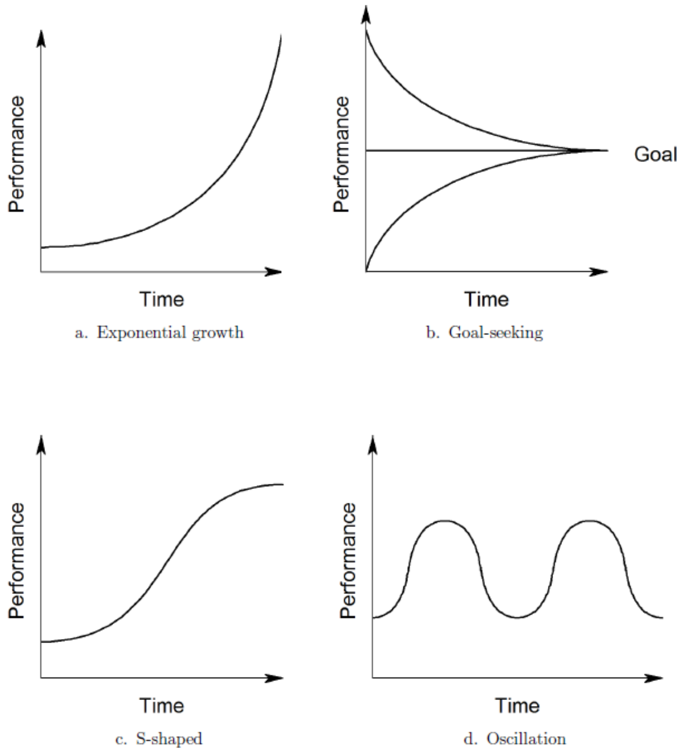


Figure 10: Example causal loop diagram

The concept of feedback plays an integral in the system dynamics approach. Feedback is when a system is influenced by its previous actions. In a feedback system, the systems past behavior are what controls its future actions; unlike an open system, where outputs respond to external inputs rather than the past behavior of the system itself (Simonovic, 2009).

Feedback loops are assigned a polarity based on the action they cause. A feedback loop that reinforces the initial action causing growth is known as a positive or reinforcing feedback loop. While a feedback loop that opposes the initial action is known as a negative or balancing feedback loop and tend to provide a stabilizing effect on the system. All closed systems consist of both balancing and reinforcing feedback loops, and the systems behavior is characterized by interaction between the two. (Simonovic, 2009) The four patterns of behavior generally observed within a system appearing individually or in combination are: exponential growth, goal-seeking, and s-shaped growth (Kirkwood, 2013).



a. Exponential growth
b. Goal-seeking
c. S-shaped
d. Oscillation

Figure 11 General patterns of system behavior (Kirkwood, 2013)

In a stock and flow diagram, stock variables, also known as accumulations or levels, are the memory of a dynamic system, and as they change overtime they characterize the state of the system at any point in time. A stocks accumulated value provides the information by which decisions are made and is the source of the systems dynamic behavior. Stocks are boxed variables, in **Error! Reference source not found.** the stock is the variable labeled "Population". Flows, the larger arrows going into and out of the stock, are a variable measured over a specific period of time, representing the increase and decrease in stock levels. Equation 2.1 shows the mathematical representation of a stock and flows. The remaining variables in **Error! Reference source not found.** are auxiliary variables and can influence any of the model components (Simonovic 2009; Winz, et al. 2009; Kirkwood, 2013).

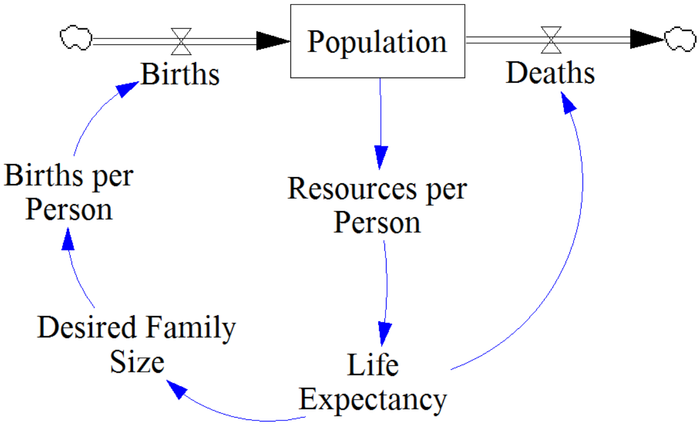


Figure 12: Example stock and flow diagram

$$Population(t) = \int_{t_0}^{t} [Births(s) - Deaths(s)]ds + Population(t_0) \tag{2.1}$$

Instead of validating the model, system dynamics models are run through a number of tests in order to gain confidence in the model (Barlas 1989, 1996). There are three classes of tests that can be used: a structure test, behaviour test, and policy implication tests. Structure tests determine how well the structure of the model corresponds to the structure in reality. A behaviour test examines how consistently a model outputs match real world behaviour. Real world behaviour can be based on historic time-series data, if available, or the correlation of mental models with established reference models

(Sterman, 2000). Policy implementation tests look at whether the observed responses to policy changes replicate model predictions. Statistical tests are not usually used for system dynamics models since the focus is on the interactions between model components and model behaviour.

2.2 Description of the Gambia Model

The system dynamics model for the Gambia is composed of five interconnecting sectors that describe climate, population, land use, food production, and water resources. The model simulates future conditions by using inputted projected climate conditions to drive the food production and water resources sectors those will impact the land use and population sectors. The model uses monthly time steps and runs for 1,404 months (100 years). Vensim is the computer program used for simulation modeling (Ventana Systems, 2010).

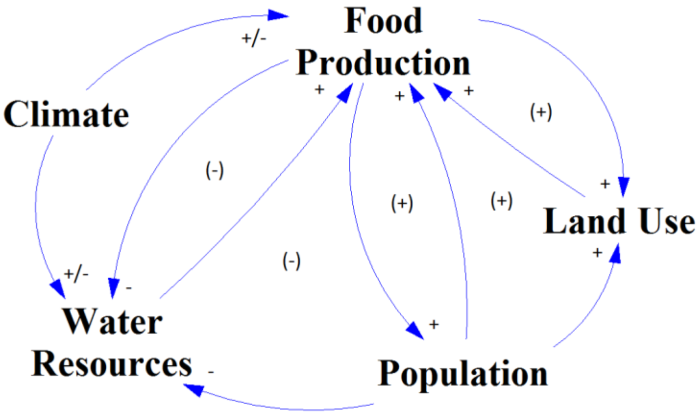


Figure 13: Causal loop diagram of model sectors

The first section discusses model assumptions, followed by a brief description of causal relationships of the model sectors and then an in-depth examination of the structure for each model sector.

2.2.1 Model Assumptions

This section provides an overview of assumptions made in the model structure assumptions made in the simulation scenarios.

2.2.1.1 Climate Sector

Climate Inputs: The precipitation and temperature inputs assume climate conditions based on ensemble mean climate projections of 15 GCMs under the A1B emission scenario from the UNDP Climate Change Country Profile for the Gambia.

Daily Rainfall: It is assumed that monthly rainfall is evenly distributed amongst every day within the month. There are therefore no dry days in any month where there is rainfall.

2.2.1.2 Population Sector

Critical Food Deficit: It is assumed that if the sum of domestic food production and food imports are less than the minimum daily food requirements, assumed to be 1,700 kcal/capita/day, the mortality rate is increased across all age groups.

International Assistance: It is assumed that international assistance, appearing in the form of food aid, occurs the year following a critical food deficit and increases with each subsequent critical food deficit and an increasing rate.

Food Demand: It is assumed that food demand increases by an annual increment of 10 kcal/capita/day when food consumption from the previous year exceeds food demand.

Life Expectancy: It is assumed that life expectancy can be calculated from food energy consumed per capita by using equations derived from their historic relationship in the Gambia and extrapolated using data from Brazil.

Total Fertility Rate: It is assumed that the total fertility rate can be calculated from life expectancy by using equations derived from their historic relationship in the Gambia and extrapolated using data from Brazil.

Age-Specific Fertility Rate: It is assumed that the age-specific fertility rate can be calculated from the total fertility rate by using equations derived from their historic relationship in the Gambia and extrapolated using data from Brazil.

Mortality Rate: It is assumed that mortality rates can be calculated from life expectancy using model life tables for developing nations created by the United Nations Population Division (United Nations, 2013).

Agricultural Work Force: It is assumed significant changes in the population do not have an impact on agricultural productivity.

2.2.1.3 Land Use Sector

Land Allocation: Land allocation procedure assumes that each crop is responsible for providing a fixed percentage of the total food energy demand per capita. Therefore, increase in food energy demand per capita is the main factor in determining the quantity of new land to be allocated to each crop,

Maximum Arable Land: It is assumed that a total of 555,240 hectares of arable land in the Gambia that can be used for food production (Njie, 2010).

Maximum Land Available to Rice: It is assumed that only 80,000 hectares of arable land provides an environment in which rice can be successfully produced (Njie, 2010).

2.2.1.4 Food Production Sector

Food: It is assumed that food is composed only of domestically produced crops supplemented by food imports. Livestock and fish are therefore not incorporated into the model as their contribution to total food energy consumption is deemed small enough to be left out

Yield: It is assumed that the only factor in determining crop yield is the degree in which crop water requirements are satisfied, expressed in the crop water production function (Equation 3.29). Other factors that may impact yield including soil fertility and farm practices are not accounted for in the calculation of crop yields

Irrigation: It is assumed that crops under irrigation receive the total quantity required to produce the maximum potential yield. Therefore, crops that are irrigated will always achieve maximum potential yield.

Food Imports: It is assumed that food is imported in the form of food energy, from no food source in particular. It is further assumed that the maximum annual quantity of food that can be imported is 900 kcal/capita/day over the length of a year no matter the size of the population.

Farming Methods: It is assumed that farming methods remain the same throughout the simulation period, therefore not impacting the yield

2.2.1.5 Water Resources Sector

Irrigation Withdrawals: As irrigation withdrawals are small and predominantly occurring during the wet season, no limits placed on the quantity of water that can be withdrawn.

Groundwater Withdrawals: It is assumed that human water consumption is the only cause of water withdrawals from the aquifer and no limit is placed on consumption.

River Base flow: It is assumed that 0.01% of the total water contained within the aquifer seeps into the surface water each month during the dry season.

Human Water Consumption: It is assumed that human consumption of water is only from groundwater and that it remains constant at 0.0139 m^3/capita/day**.**

2.2.1.6 Simulated Scenarios Assumptions

Scenario 1 assumes that the total fertility rate can be reduced to 2.2 births per woman over a 15 year period through increased family planning education. It is also assumed that the education program was so successful because of significant investments. This is an exaggerated scenario for the purpose of analyzing the performance of the model and is not meant to reflect reality.

Scenario 2 assumes that the construction of a dam just east of the Gambia in Senegal will complete in 2020, It is also assumed that the controlled release of water down the river Gambia will result in the saline front being so that that 55,000 hectares of land along the river can be equipped with tidal irrigation. Irrigation schemes are developed at at a rate of 1,740 hectares a year spread over 30 years. Only rice will be grown on the newly irrigated land.

Scenario 3 assumes that large investments in agriculture can result in an increase in maximum potential yields to maximum yields achieved in neighboring countries. It is also assumed that yields will increase at a steady rate over 30 years beginning in 2014.

Scenario 4 assumes that climate change will cause precipitation to follow the ensemble minimum climate projection under the A1B scenario, and the temperature data from the ensemble maximum climate projection also under the A1B emission scenario.

2.3 Model Sector Descriptions

2.3.1 Climate Sector

There are no causal relationships within the climate section as climate data is obtained externally. The two climate inputs are monthly precipitation and temperature, seen in Figure 14. The model is capable of using precipitation and temperature data from the ensemble minimum, mean or maximum climate projections under either of the three emission scenarios (A2, A1B, or B1). The base simulation and the first three simulation scenarios use precipitation and temperature data from the ensemble mean climate projection under the A1B emission scenario as climate inputs. The ensemble mean is the mean value across the 15 model projections in the UNDP Climate Change Country Profile for the Gambia. Scenario 4 uses the precipitation data from the ensemble minimum climate projection under the A1B emission scenario and the temperature data from the ensemble maximum climate projection also under the A1B emission scenario as climate inputs (McSweeny, et al., 2008).

2.3.1.1 Structure of the Climate Sector

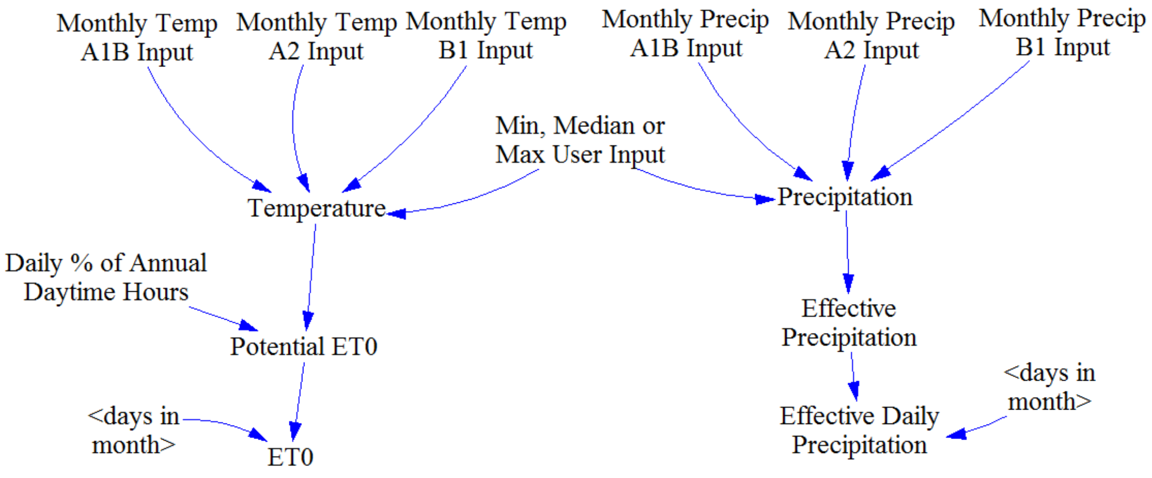


Figure 14 Model structure of the climate sector

As temperature and precipitation are the only climate projections inputted into the model, normally much more complicated relationships need to be simplified. An example of this is using the Blaney-Criddle method (Equation 2.2) to calculate reference crop evapotranspiration with only temperature and mean daily percentage of annual daytime hours. This method is recommended by the FAO in their guideline on calculating crop water requirements. With the limited climate inputs, this method is not very accurate and only provides a value for the reference crop evapotranspiration only accurate to the order of magnitude (Doorenbos & Kassam, 1979).

$$ET_0 = \rho(0.46 \times T_{mean} + 8) \qquad (2.2)$$

where, ET_0 is the reference crop evapotranspiration as an average for a period of 1 month, p is mean daily percentage of annual daytime hours, T_{mean} is the mean daily temperature (°C).

$$P \leq 250mm\colon\ P_{eff} = \frac{P \times (125 - 0.2P)}{125} \qquad (2.3)$$

$$P \geq 250mm\colon\ P_{eff} = 125 + 0.1P \qquad (2.4)$$

Calculations for effective rainfall are also simplified by using two formulas used by CROPWAT, a program developed by the FAO (Allen, et al., 1998) to calculate crop yields, when precipitation is over 250 millimeters, Equation 2.3 is used to calculate effective rainfall,, and when precipitation is less than 250millimeters Equation 2.4 is used.

2.3.2 Population Sector

The population sector contains multiple feedback loops, one reinforcing and three balancing as can be seen in the population causal loop diagram in Figure 15. The reinforcing feedback between population and births provides growth to the population. Population growth can be controlled by a reduction in fertility, life expectancy or a critical food deficit. Fertility is controlled by life expectancy unless a population policy is implemented. The population policy exists within a balancing loop with fertility and reduces as fertility reaches its goal. A balancing feedback is also used to maintain food per capita when a critical food deficit is detected by increasing international food assistance. .

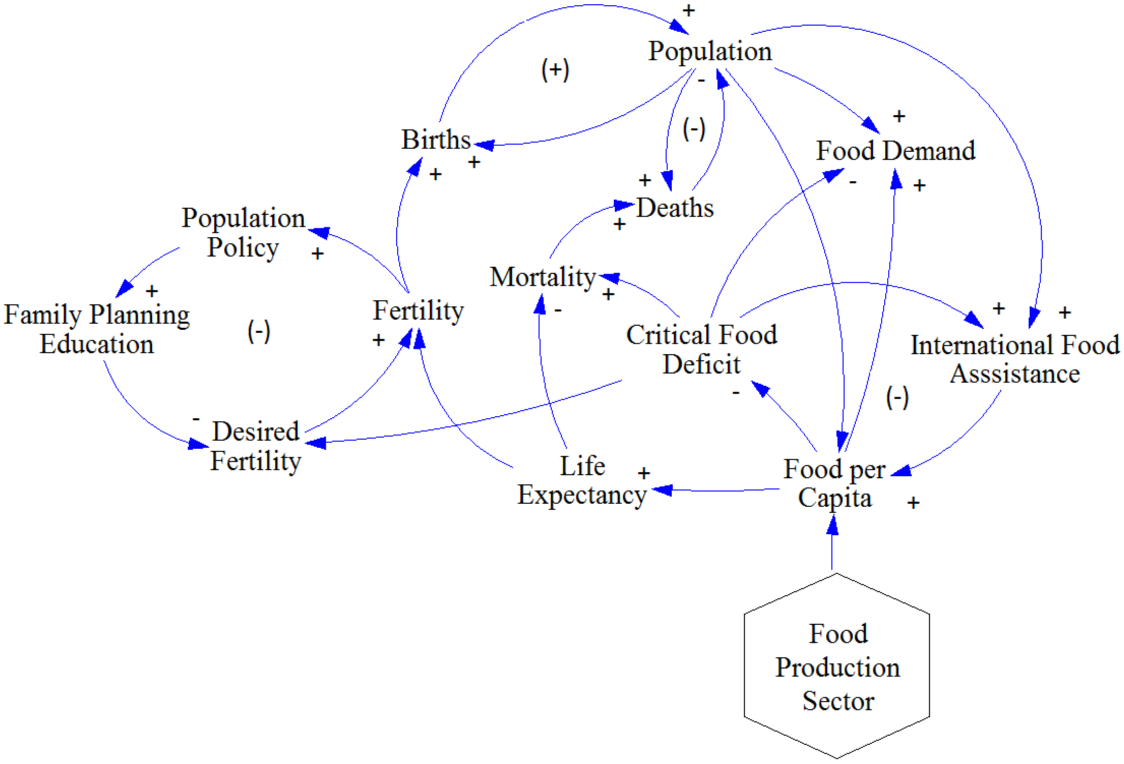


Figure 15: Causal loop diagram of the population sector

2.3.2.1 Structure of the Population Sector

The structure of the population sector is presented in four components: Population, Total Fertility Rate, Life Expectancy and Food Demand.

2.3.2.1.1 Component One: Population

The population is divided into fifteen age specific levels, each representing a five-year span, except for newborns (1 year), young children (4 years), and the elderly (65 years and above). Displayed in Figure 16 is a simplified representation of the population sector with four population levels.

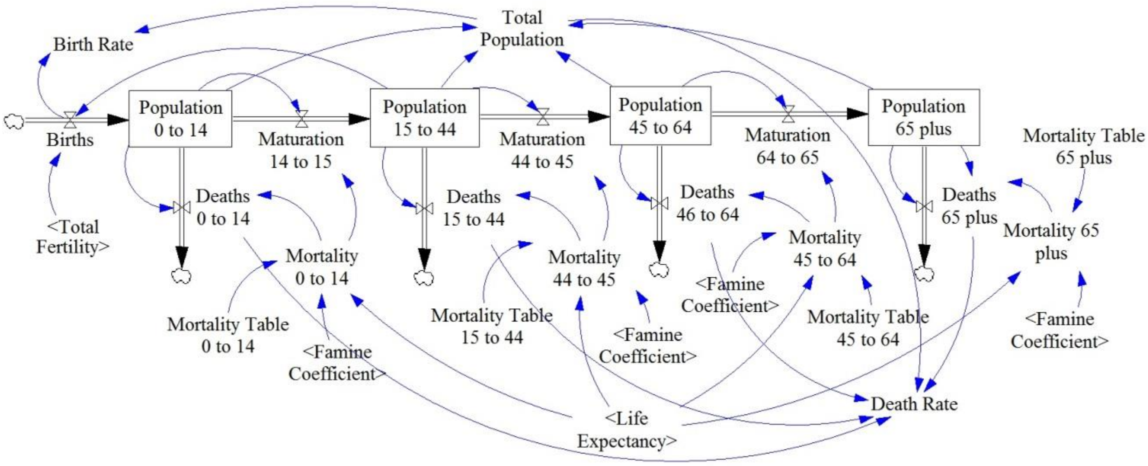


Figure 16 Model structure of the population component of the population sector

Population levels are changed through flows representing births, deaths, and the aging of the population (maturation). The total population can only be increased through increased births while population levels increase through the maturing of the younger age-groups population. Net migration was considered as another input flow, but no general pattern was observed in the historic data, nor was the annual number of migrants deemed large enough to have a significant impact.

The flow labeled death represents the number of deaths a population level has each month. The monthly number of deaths is easily calculated by multiplying the population by its age specific mortality rate, the annual number of deaths, then dividing by 12 months to get the monthly number of deaths (Meadows, et al., 1974).

$$Deat\hbar s_{0-15} = Pop_{0-15} \times \frac{Mort_{0-15}}{12} \qquad (2.5)$$

Where $\text{Deaths}_{0\text{-}15}$ is the flow representing the monthly number of deaths for the 0 to 15 population stock, $\text{Pop}_{0\text{-}15}$ represents the population stock for 0 to 15 year olds, and $\text{Mort}_{0\text{-}15}$ is the mortality rate for the 0 to 15 year old population stock.

Maturation represents the population graduating from one age group to the next each monthly time step. For example, using the four-level model in Figure 16, teenagers celebrating their 15th birthday, represented by the "Maturation 14 to 15" flow, are transferred from the "Population 0 to 14" level to the "Population 15 to 44" level. Maturation is calculated by subtracting 1 by mortality rate and multiplying it by the population, getting the number of the populations that did not die that month, then dividing by 15 (the number of ages represented in the stock) and 12 months. (Meadows, et al., 1974)

$$mat_{14-15} = \text{Pop}_{0-14} \times \frac{1 - mort_{0-14}}{15 \times 12} \tag{2.6}$$

The mortality rate is called from the mortality table with life expectancy as the input. The mortality table consists of age-specific mortality rates corresponding to life expectancy. The mortality table is made up of data from model-life tables developed for developing countries in World Population Prospects: The 2010 Revision (United Nations, 2013).

2.3.2.1.2 Component Two: Fertility

The number of births is determined by both Total Fertility (TF) and age-specific fertility rates. Total fertility is the number of children born to a woman over her lifetime if she were to conform to age-specific fertility rates and survives through her reproductive life (FAO, 2013). The fertility component of the population sector is shown in Figure 17.

There are three total fertility auxiliary variables and one stock representing total fertility. Estimated Total Fertility (ETF) is the main fertility variable because it is used in determining in calculating the age-specific fertility rates. ETF is a stock and will increases and decreases each year depending on weather a family planning education policy is in place. If there is no family planning education policy, ETF is adjusted by the

Initial Expected Fertility (IEF) variable and when family planning is in place ETF is determined by Actual Total Fertility (ATF).

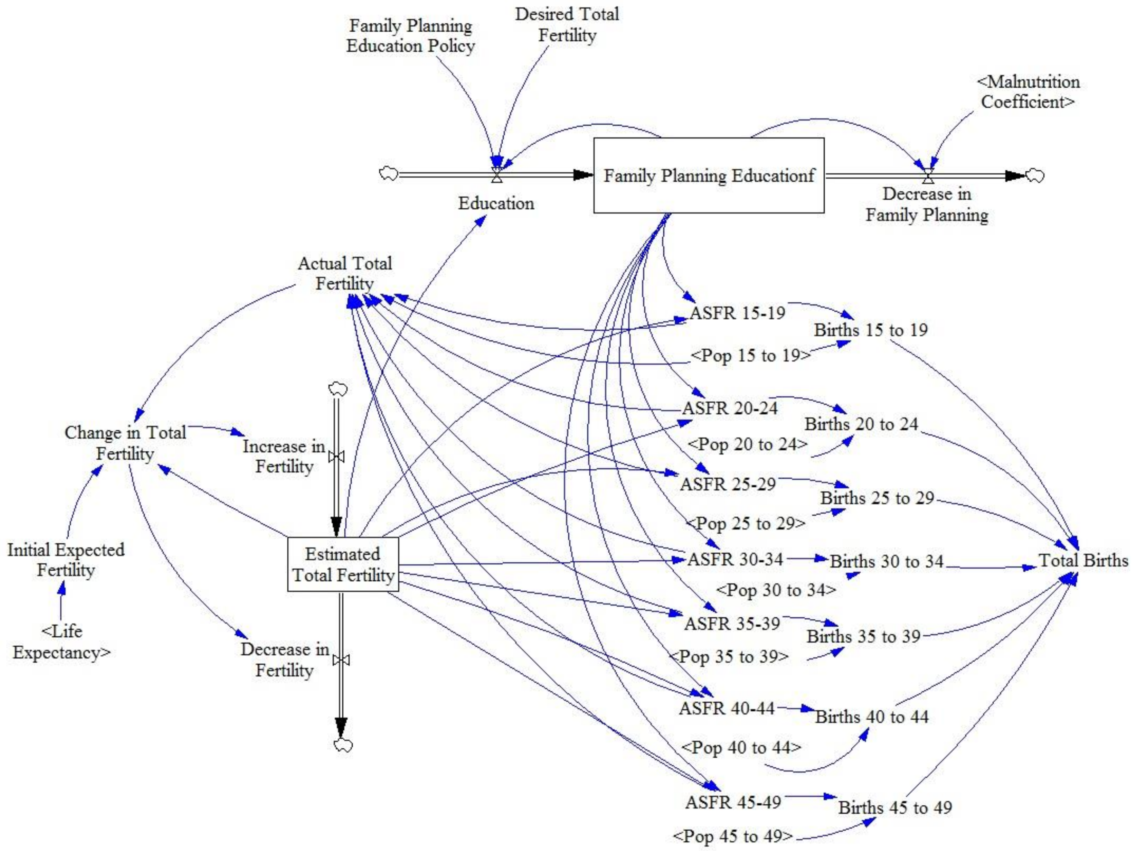


Figure 17: Model structure of the fertility component in the population sector

Life expectancy has been shown to be negatively correlated with adolescent reproduction and total fertility rates throughout the world. Though, correlation is much stronger in countries that have a stable economy and life expectancy above 60. Because of this relationship, life expectancy is originally used in calculating the IEF. (Bulled & Sosis, 2012)

The equations used to calculate the expected total fertility are derived from fertility and life expectancy data for the Gambia and Brazil. Data from Brazil was used because it is has gone through a dramatic rate of development over the last 30 years and its relationship between total fertility and life expectancy matched with the Gambia’s. Because the population of the Gambian is predominantly Muslim, one may assume the fertility-life expectancy relationship would follow a similar pattern to countries in Northern Africa or the Middle East; this is not the case. These regions have a predominantly higher fertility rate at even higher life expectancies experienced in The Gambia (United Nations, 2013).

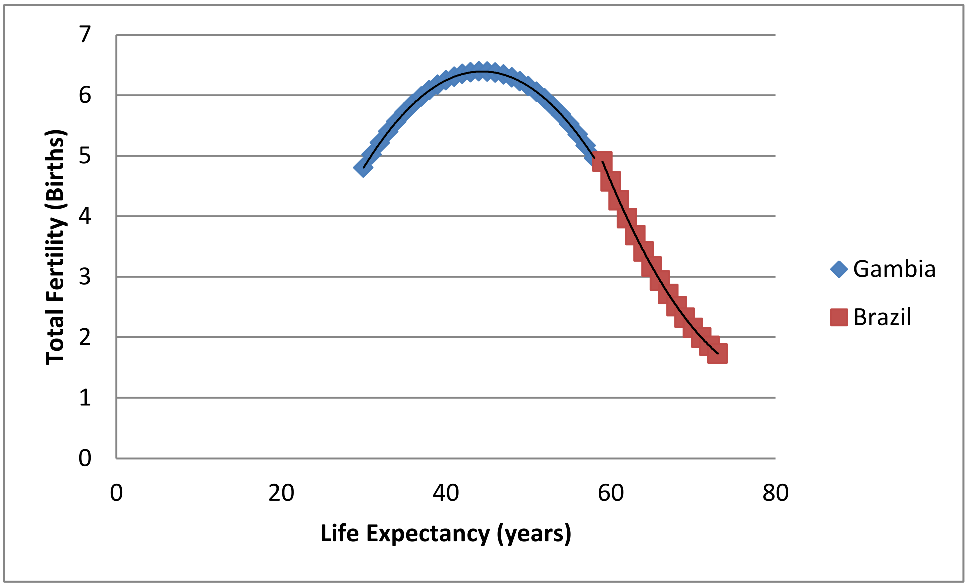


Figure 18: Total fertility-life expectancy relationship for the Gambia and Brazil

Two equations are therefore used in calculating IEF: the first, derived from data from the Gambia is used when life expectancy (LE) is below 58; the second, derived from Brazilian data is used when life expectancy is greater than 58 (United Nations, 2013). The following equations represent the total fertility-life expectancy relationships for Brazil and the:

$$If\ LE < 58:\ IEF = 0.0077(LE)^2 + 0.68(LE) - 8.7673 \qquad (2.7)$$

$$If\ LE > 58:\ IEF = 0.0078(LE)^2 - 1.26(LE) + 51.86 \qquad (2.8)$$

When the IEF is larger than ETF, there is a set increase in ETF, and if IEF is lower than ETF, there is a set decrease in ETF.

Family Planning

Family Planning Education Policy (FPEP) is used to decrease the birth rate overtime. The value used for FPEP determines how quickly the total fertility rate will be reduced to the desired total fertility rate. Once the FPEP has been initiated, the Family Planning Education (FPE) stock gradually increases towards one, with a higher value representing larger acceptance of family planning throughout the population.

Once desired total fertility has been reached, the Family Planning Education stock is emptied, but once total fertility increases above desired fertility the stock will start to be increased again until total fertility goes back down.

The model uses the Estimated Total Fertility (ETF) to determine age-specific fertility rates ASFRs. ASFRs represent the number of women, out of 1,000, within a 5-year age group that are likely to have a child during that period (FAO, 2013). As data for Brazil was used for extrapolation the life expectancy-total fertility relationship, it is also used to extrapolate the TF-ASFR relationship. Below are the equations used for calculating the ASFRs, including the reduction to ETF because of Family Planning Education (FPE).

ASFR 15-19:

If DF < 5.4

$$\text{If DF} < 5.4\text{:}\quad ASFR_{15-19} = 101.18 \times ETF(1 - FPE) - 443.21,\quad R^2 = 0.94 \tag{2.9}$$

If DF > 5.4

$$ASFR_{15-19} = 13.29 \times ETF(1 - FPE) + 38.18,\quad R^2 = 0.58 \tag{2.10}$$

ASFR 20-24

If DF < 5.2

$$ASFR_{20-24} = 88.48 \times ETF(1 - FPE) + 348.66,\quad R^2 = 0.96 \tag{2.11}$$

If DF > 5.2

$$ASFR_{20-24} = 40.2 \times ETF(1 - FPE) + 3.97,\quad R^2 = 0.74 \tag{2.12}$$

ASFR 25-29

If DF > 5.2 $$ASFR_{25-29} = -11.93 \times ETF(1-FPE) + 348.66, \quad R^2 = 0.43 \tag{2.13}$$

If DF < 5.2 $$ASFR_{25-29} = 59.07 \times ETF(1-FPE) - 20.74, \quad R^2 = 0.99 \tag{2.14}$$

ASFR 30-34

If DF < 5.2 $$ASFR_{30-34} = -29.20 \times ETF(1-FPE) + 398.59, \quad R^2 = 0.83 \tag{2.15}$$

If DF > 5.2 $$ASFR_{30-34} = 51.6 \times ETF(1-FPE) - 35.46, \quad R^2 = 0.97 \tag{2.16}$$

ASFR 35-39

If DF < 3.7 $$ASFR_{35-39} = 70.8 \times ETF(1-FPE) - 28.45, \quad R^2 = 0.86 \tag{2.17}$$

If DF < 5.4 $$ASFR_{35-39} = 27.67 \times ETF(1-FPE) - 16.61, \quad R^2 = 1 \tag{2.18}$$

If DF > 5.4 $$ASFR_{35-39} = 6.78 \times ETF(1-FPE) + 64.8, \quad R^2 = 1 \tag{2.19}$$

ASFR 40-44

If DF < 4.6 $$ASFR_{40-44} = 28.26 \times ETF(1-FPE) - 101.25, \quad R^2 = 0.57 \tag{2.20}$$

If DF > 4.6 $$ASFR_{40-44} = 5.8 \times ETF(1-FPE) + 1.11, \quad R^2 = 0.98 \tag{2.21}$$

ASFR 45-50

If DF < 5.2 $$ASFR_{45-49} = 27.94 \times ETF(1-FPE) - 135.26, \quad R^2 = 0.91 \tag{2.22}$$

If DF > 5.2 $$ASFR_{45-49} = 2.67 \times ETF(1-FPE) - 3.38, \quad R^2 = 0.99 \tag{2.23}$$

The Actual Total Fertility (ATF) is then used to adjust the ETF stock in the same way the IEF does, thereby reinforcing the reduction in total fertility. ATF is calculated using equation 3.23.

$$ATF = \frac{5}{1,000}\sum_{i=1}^{6} ASFR_i \tag{2.24}$$

2.3.2.1.3 Component Three: Life Expectancy

Life expectancy (Figure 20) is determined through a correlated relationship with food production. Food energy and life expectancy have a strong linear relationship throughout the world. Life expectancy is a stock variable that is increased or decreased by an increment of 0.2 years annually, depending upon the total food energy consumed per capita. The increment of 0.2 was chosen during model calibration. Life expectancy is also increased annually by an additional value of 0.15 to represents improvements in health care. The use of food aid will stall the increase in life expectancy.

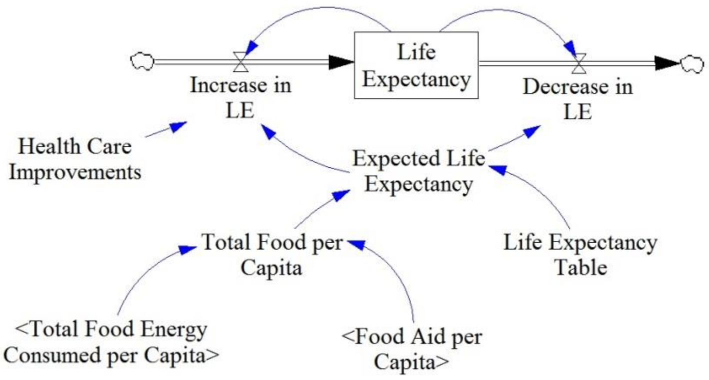


Figure 19: Model structure of the life Expectancy component in the population sector

2.3.2.1.4 Component Four: Food Demand

The food demand per capita stock (food demand), shown in (Figure 20) also plays an important role in the land use sector. Food demand is a stock and is either increased or reduced by a factor of 10 kcal once a year, except during a food deficit where it can be reduced by the value that decreases food demand to 1,800 kcal. Food demand is increased if the demand for food from the previous year is less than the quantity consumed, and decreased if consumption is less than demand.

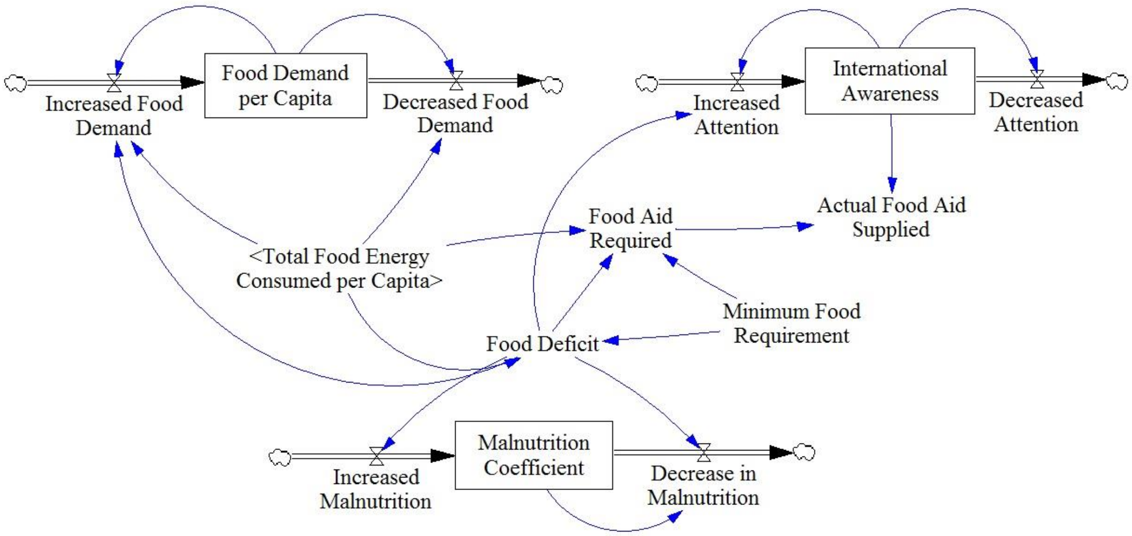


Figure 20: Model structure of the food energy demand component in the population sector

If food consumption falls below the minimum food requirement of 1700 kcal, then there is a critical food deficit which triggers an increase in the malnutrition coefficient. The malnutrition coefficient increases each year there is a food deficit. Once there is no longer a food deficit, the malnutrition coefficient is reduced by half and then removed completely the year after that. The purpose of the malnutrition coefficient is to cause an increased mortality due to critical food deficit, with a larger impact being put on the mortality of newborns and the elderly.

2.3.3 Land Use Sector

The purpose of the land use sector is primarily to determine the allocation of arable land. The main driver of the sector is food demand from the population sector. As seen in the causal loop diagram in Figure 21, an increase in food demand results in an increase in demand for new arable land and this information is then sent throughout the rest of the model. When arable land is available, the demand for new arable land will cause an increase to area of land under cultivation, and the increased area under cultivation will decrease the demand for arable, resulting in a balanced feedback. When there is no available arable land, land will be taken from meadows and pastures, which in then takes land from the forest.

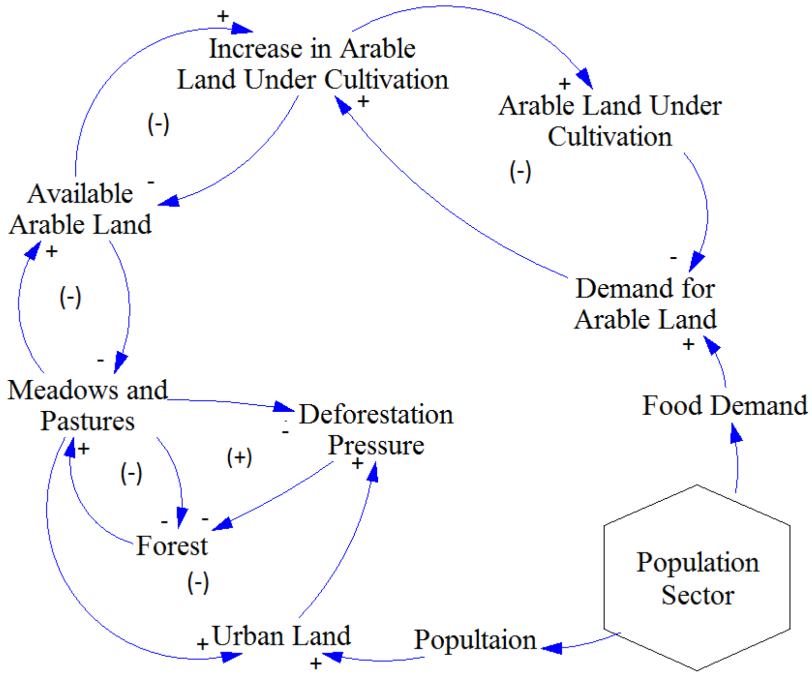


Figure 21: Causal loop diagram of the land use sector

The relationship between the three land categories: arable land, meadows, and forest are all balancing feedback loops. An increase in arable land is the direct result of a decrease in meadows and pastures, but an increase in meadows and pastures will also cause an increase in available arable land.

As land becomes scares there are increased deforestation pressures. The main increase in deforestation pressure is from the decrease in meadows and pastures, but an increase in urbanization also increases deforestation pressures. Meadows and pastures have a reinforcing feedback relationship with deforestation pressure and forest, that will result in accelerated deforestation once meadows and pastures require land.

2.3.3.1 Structure of the Land Use Sector

The structure of the land use sector comprises two components: land use and arable land.

2.3.3.1.1 Component One: Land Use

The land use component of the land use sector (Figure 22) divides land into three categories: arable land, permanent meadows and pastures, and forest cover. The Meadows and Pastures stock acts as the middle man between the Forest, Urban Land and Available Arable Land stocks. The primary role of the stocks other than Available Arable Land is to act as a place holder for quantities of land until they are demanded and transferred to the Available Arable Land stock.

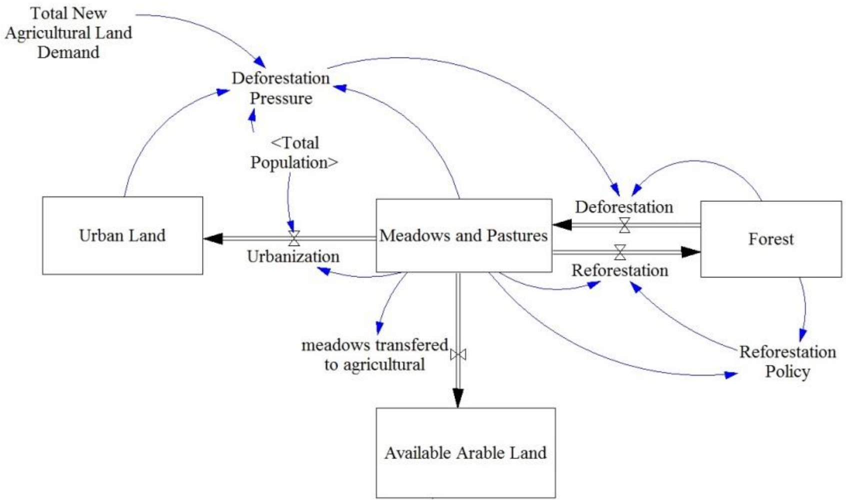


Figure 22: Model structure of the land use component of the land use sector

2.3.3.1.2 Component Two: Arable Land

The land allocation procedure determines the amount of land required each year to produce enough energy from food to satisfy the population’s demand. The procedure takes place for each of the 10 crops one time step (one month) following the crops harvest in the Food Production Sector. This means new land is allocated 11 months prior to the harvest and the population used to determine food demand is smaller than the population will be at the time of harvest. Also, because the procedure takes place 11 months prior to the determining of that years yield, the yield used in the procedure is not the same that is used in calculating the year’s harvest.

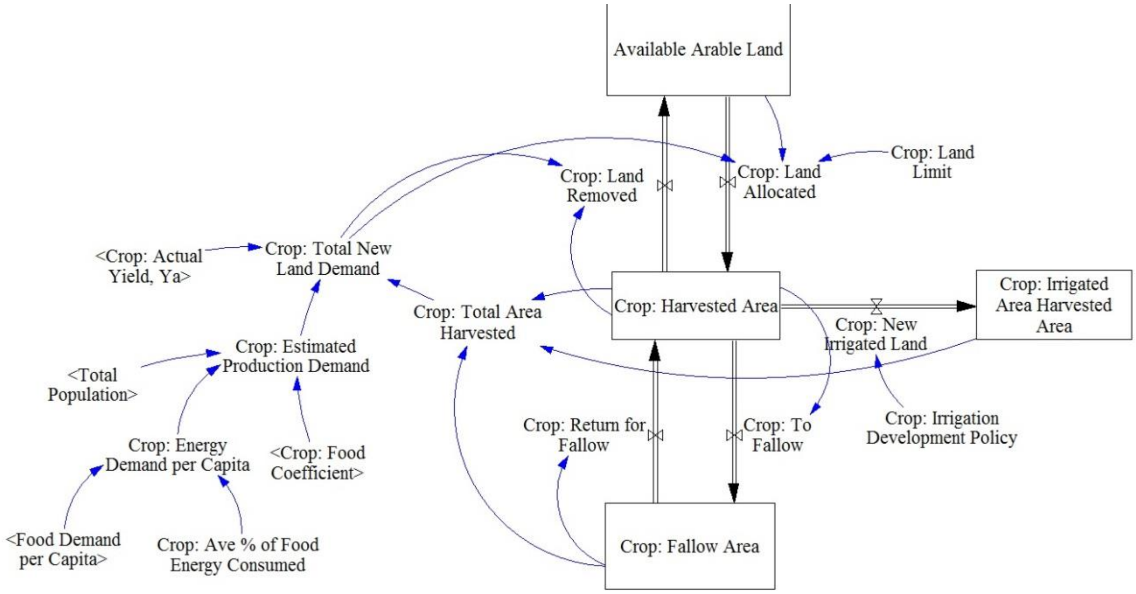


Figure 23: Model structure of the crop harvested area in the land use sector

The variable % Total Energy represents a crops percentage of the total energy produced by all crops for a season. The value is calculated externally by averaging the historic percentage of total daily energy consumption for each crop. % Total Energy could be made into a dynamic variable, but for simplicity and mostly to save time, I have decided to keep the value static for the time being. Daily Energy Demand per Capita is calculated by multiplying Energy: Demand (kcal/capita) (the total daily energy demand) by % Total Energy.

The Energy Demand is the annual total energy demanded by the population, and is calculated by dividing Daily Energy Demand per Capita by the total population and 365 days. Food Demand is then determined by dividing Energy Demand by the Energy Coefficient. Import demand is then determined by dividing Food Demand by the Food Coefficient. The Energy Coefficient and Food Coefficient are calculated externally by averaging the historic values for each crop. The variables could have been be dynamic but with the lack of reliable data static variables makes more sense.

$$Daily\ Energy\ Demand\ per\ Capita = \%\ Total\ Energy \times Energy: Demand \tag{2.25}$$

Energy Demand is the crop specific energy demand for the total populations. It is determined by multiplying the Daily Energy Demand per Capita by the current Total Population and the number of days in the year.

$$\begin{aligned} \mathit{Energy\ Demand} &\\ &= 365 \\ &\times (\mathit{Daily\ Energy\ Demand\ per\ Capita}) \\ &\times (\mathit{Total\ Population}) \end{aligned} \tag{2.26}$$

Food Demand is determined by dividing Energy Demand by the Energy Coefficient. The Energy Coefficient is introduced in the Food Production section of the model where it is used to convert food from tons into calories.

$$\mathit{Food\ Demand} = \frac{\mathit{Energy\ Demand}}{\mathit{Energy\ Coefficient}} \tag{2.27}$$

Production Demand is the quantity of a crop that needs to be produced to in order to meet the Food Demand. Only a fraction of a crops harvest becomes food, much of what is produced is lost to waste, processing, seed, and feed. The Food Coefficient is used to calculate the Production Demand by dividing Food Demand by the Food Coefficient. Like Daily Energy Demand per Capita, the Food Coefficient is calculated externally by averaging the historic daily energy consumption for each crop and could be a dynamic variable but the lack of good relevant data makes it extremely time consuming to determine.

$$\mathit{Crop}{:}\mathit{Total\ Production\ Demand} = \frac{\mathit{Crop}{:}\mathit{Total\ Food\ Demand}}{\mathit{Crop}{:}\mathit{Food\ Factor}} \tag{2.28}$$

Table 1: Crop Model Input Values

Crop	Energy Coefficient (kcal/ton)	Food Coefficient (dmnl)	Harvested Area, time step =0 (1983) (Ha)
Groundnut Oil	2,866,902	0.05	97,200
Groundnut	5,664,119	0.6451	6,900
Maize	3,165,475	0.7557	25,200
Millet	2,937,720	0.7992	6,900
Rice	3,455,866	0.8655	14,800
Vegetables	236,640	0.9234	1,500
Pulses	3,409,001	0.8404	15,000
Cassava	1,100,801	0.9574	2,000
Fruits	425,898	0.9447	750

The Total Land Area Required is calculated by dividing Production Demand by the Yield. It should be noted that the yield used for this calculation is the "current year" yield, and not the Yield that is to be used to in calculating total production for the land area being calculated.

$$Crop\!:Total\ Area\ Required\ for\ Production = \frac{Crop\!:Total\ Production\ Denabd}{Crop\!:Yield} \tag{2.29}$$

For most years, the Land Allocation Procedure results in an increase in land area, but on occasions, when yield is increasing, less land is called for. The if statements within the Unneeded Land and Land Demanded variables are used to determine if the Total Land

Required is less than or greater than the Harvested Area stock. If Total Area Required is less than Total Area Harvested, there will be a decrease in Total Area Harvested, while an increase in Total Area Harvested results when Total Area Required is greater than Total Area Harvested.

With the quantity of land to be added or removed from the harvested area determined, the Land Allocated and Land Removed flows are used to transfer land from the Arable Land stock to and from the Harvested Area Stock. Arable Land consists of all land not under agricultural use. At the initial time step, the model has 818,000 hectares of arable land not under agriculture.

2.3.4 Food Production Sector

The food production sector is where all domestic food is produced. Although fish and livestock are consumed in the Gambia, they do not make up a significant portion of total food energy consumption (Figure 24) and are therefore excluded from the model (FAO, 2013). Food produced in this sector consists only of domestically grown crops.

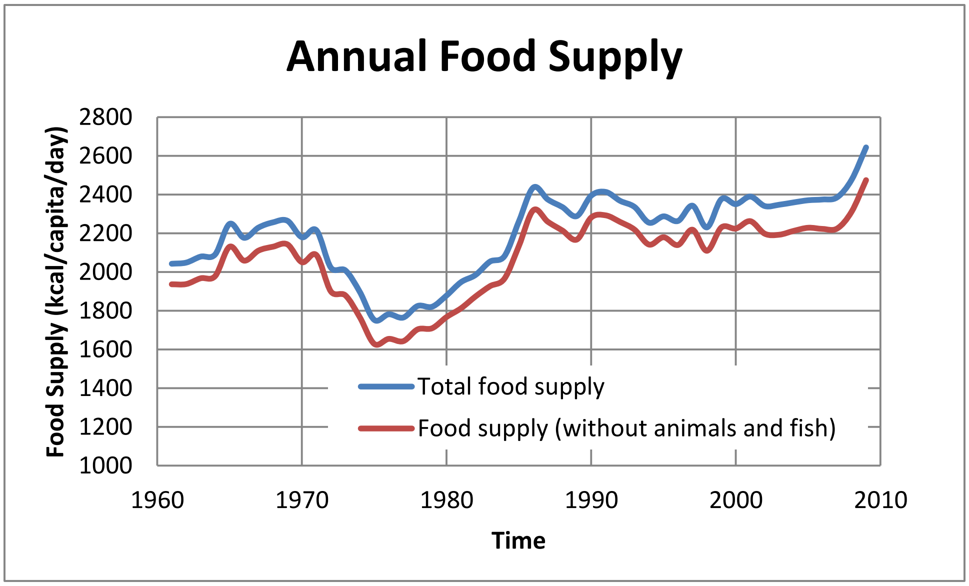


Figure 24 Annual Food Supply (kcal/capita/year)

In the causal loop diagram for the food production sector in Figure 25 it can be seen that the four other model sectors are all used as inputs. Climate input variables evapotranspiration and effective precipitation are responsible for determining crop water requirements and crop yields. The water resources sector also impacts yield through providing additional irrigation water. The cultivated land from the land use is used in addition to the yield to determine crop production. And the population sector inputs food demand.

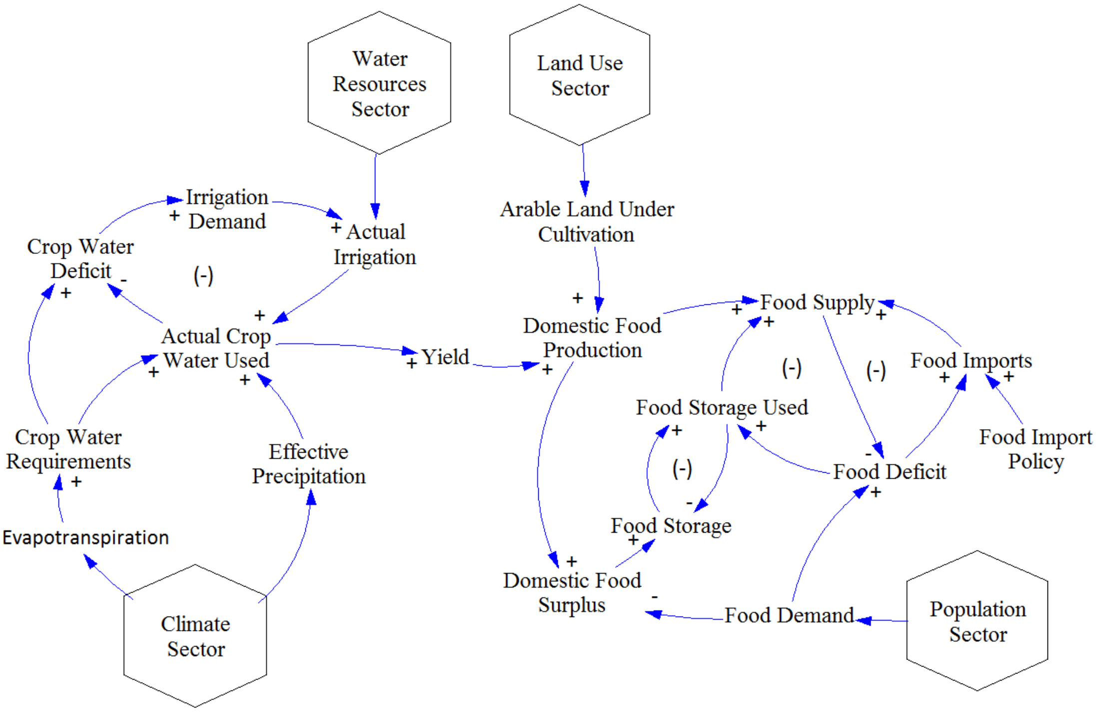


Figure 25: Causal loop diagram of the food production sector

2.3.4.1 Structure of the Food Production Sector

The Food Production model structure is composed of three components. The first determines crop water requirements and determines yields; the second component determines food energy produced; and in the third component crop food energy in combined in a stock, consumed and stored.

2.3.4.1.1 Component One: Crop Water Requirements and Yield

In the late 1970s, the FAO developed an equation expressing the relationship between crop yield and water use (Doorenbos & Kassam, 1979). The relatively simple equation, known as the crop water production function (3.29), relates the relative reduction in yield to the corresponding reduction in evapotranspiration.

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y \left(1 - \frac{ET_a}{ET_c}\right) \tag{2.30}$$

where Y_a and Y_m represent the actual yield and the maximum yield possible to achieve assuming conditions are perfect and water supply is met, ET_a and ET_c represent actual evapotranspiration and crop evapotranspiration, and k_y is a yield response factor representing the effect of a reduction in evaporation on yield losses.

The water equation is rearranged to calculate the actual yield as follows:

$$Y_a = Y_m \left[1 - k_y \left(1 - \frac{ET_a}{ET_c}\right)\right] \tag{2.31}$$

The yield response factor (k_y) captures the essence of the complex linkages between production and water use by a crop where many biological and physical processes are involved. The water production function has proven its validity and has provided a workable procedure to quantify the effects of water deficits on yield. (Steduto, et al., 2012).

Crop evapotranspiration differs from the reference evapotranspiration (ET_0) as the properties of each crop differ much from grass and other crops. The FAO (Allan, et al., 1998) uses a crop coefficient (K_c) to distinguish crop evapotranspiration from reference transpiration by multiplying it by the reference evapotranspiration (ET_0):

$$ET_c = K_c ET_0 \tag{2.32}$$

In the crop coefficient approach, the climate conditions are incorporated into ET_0 and crop characteristics into the Kc coefficient. This allows the K_c coefficient to be standardized for crops across climates. It should be noted that using the crop coefficient method to calculate ET_c no limitations are placed on crop growth or evapotranspiration from soil water and salinity stress, crop density, pests and diseases, weed infestation or low fertility. Though, ETc can be adjusted to take these factors into account but that is beyond the current scope of this thesis. (Allan, et al., 1998)

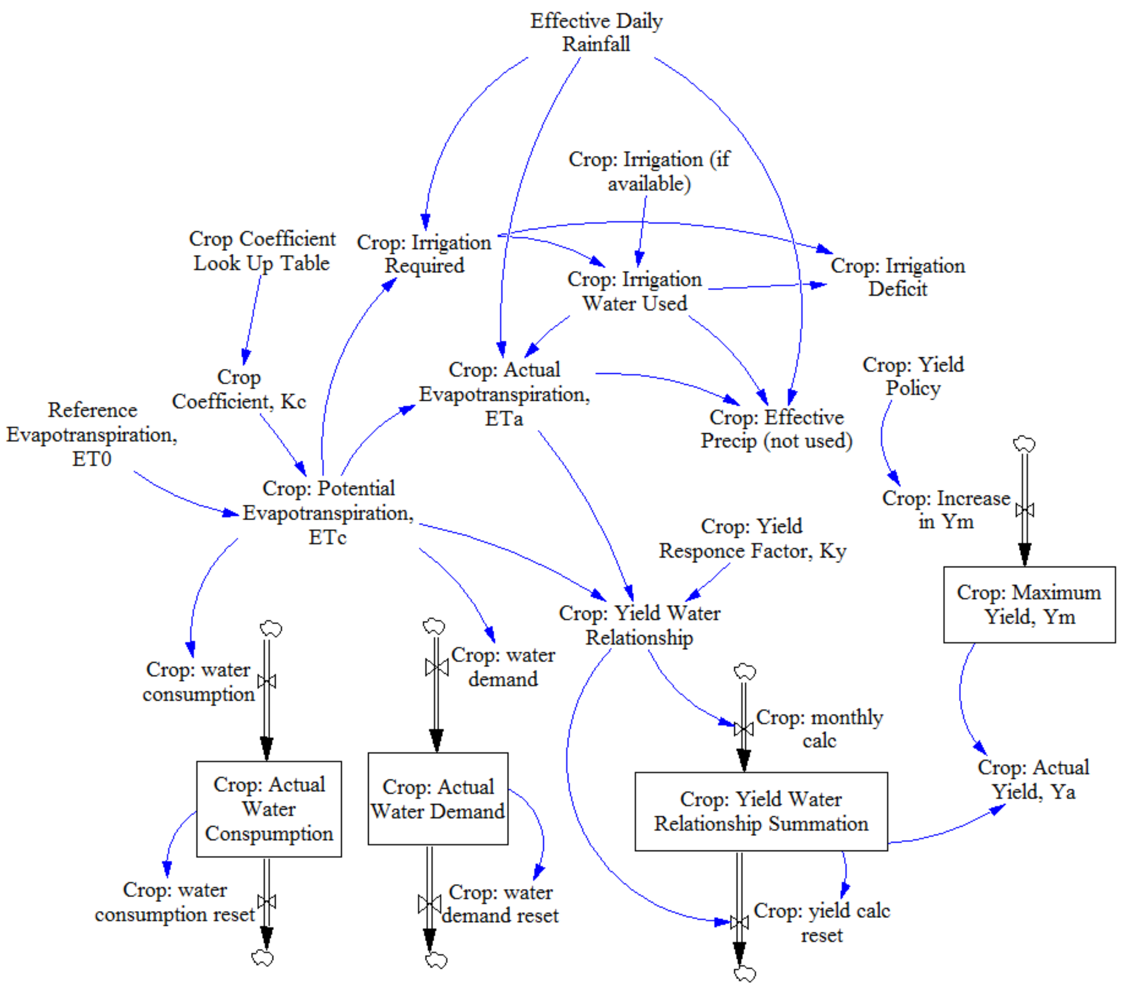


Figure 26: : Model structure of the crop water requirements and yield component of the food production sector

The change in vegetation and groundcover during the lifecycle of a crop result in a changing crop water requirement. Crop coefficient curves are constructed for each crop providing a crop coefficient value corresponding to each of the four stages of the crops life. Three values for K_c are used in constructing the curve: the initial stage ($K_{c\ ini}$), mid-season stage ($K_{c\ mid}$), and the late season stage ($K_{c\ end}$). The length of the four crop stages and corresponding crop coefficients used in the model are displayed in. **Table 2**.

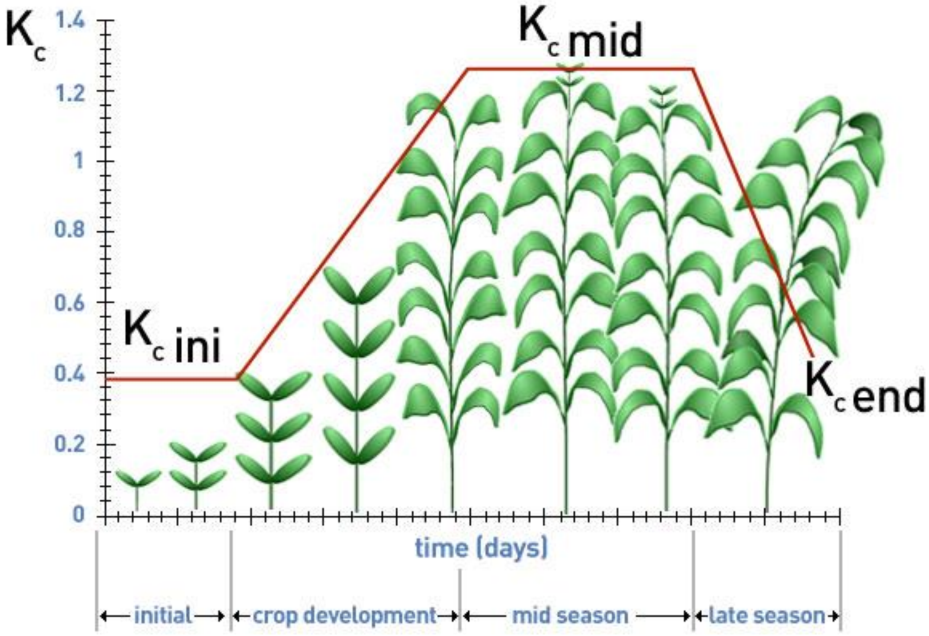


Figure 27: Generalized crop coefficient curve

(Steduto, et al., 2012)

2.3.4.1.2 Component Two: Commodity Balance

The purpose of the commodity balance (Figure 28) is to determine the food content of the total crop production. The food content is determined by multiplying the crop production by a food factor. Waste, assumed to be anything left in the domestic supply stock, is removed in the time step following the removal of food. Waste is a catch all term for any other uses of the crop than food such as processing losses, livestock feed, or actual waste.

Table 2: Lengths of crop development stages and crop coefficients

Crop	Length of Crop Development Stages						Crop Coefficients		
	L_{ini}	L_{dev}	L_{mid}	L_{late}	Total	Plant Date	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Groundnut	25	35	45	25	130	Dry Season	0.4	1.05	0.6
Maize	20	35	40	30	125	June	0.3	1.2	0.5
Millet	15	25	40	25	105	June	0.3	1	0.3
Sorghum	20	35	40	30	130	May/June	0.3	1.05	0.55
Rice	30	30	60	30	150	May	1.05	1.2	0.9
Vegetables	35	40	45	30	145	April/May	0.7	1.05	0.95
Pulses	25	30	35	30	120	May	0.3	1.15	0.4
Cassava	20	40	90	60	210	Rainy Season	0.3	0.8	0.3

Source: (Doorenbos & Pruitt, 1975).

It is assumed that the food coefficients remain constant. In reality advancements in technology may result in decrease improved crop processing resulting in more food and less waste, but this is purposely left out of the model. Food coefficients were obtained through taking an average of the percentage of food from historic commodity balances, as they remained relatively consistent. The changes in crop coefficients are relatively small and would not have made a difference in the functioning of the model.

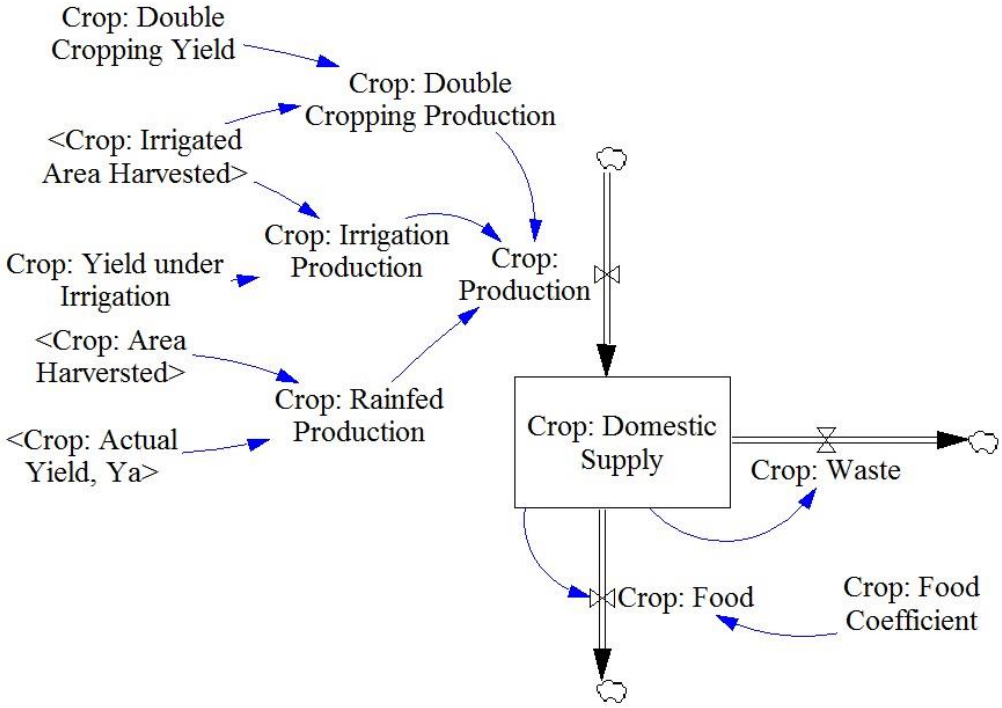


Figure 28: Model structure of the commodity balance component of the food production sector

2.3.4.1.3 Component Three: Food Energy

The only useful quantity for food in this model is the energy contained within food. The total quantity of food from each crop is multiplied by the crops corresponding energy coefficient to become an energy flow. The energy coefficients were previously shown in Production Demand is the quantity of a crop that needs to be produced to in order to meet the Food Demand. Only a fraction of a crops harvest becomes food, much of what is produced is lost to waste, processing, seed, and feed. The Food Coefficient is used to calculate the Production Demand by dividing Food Demand by the Food Coefficient. Like Daily Energy Demand per Capita, the Food Coefficient is calculated externally by averaging the historic daily energy consumption for each crop.

$$Crop\colon Total\ Production\ Demand = \frac{Crop\colon Total\ Food\ Demand}{Crop\colon Food\ Factor} \qquad (2.33)$$

Energy produced from each crop is transferred into the energy stock, labeled Total Locally Produced Food Energy in Figure 29. As some of the crops harvest during different months the food is stored until the Total Food Energy Demand variable initiates the Consumption of Local Food Energy flow on an arbitrary preselected month. If the total food energy produced happens to satisfy the total food energy demand then the energy remaining in the Total Locally Produced Food Energy will flow into the Food Energy Storage where it will remain until consumed the following year.

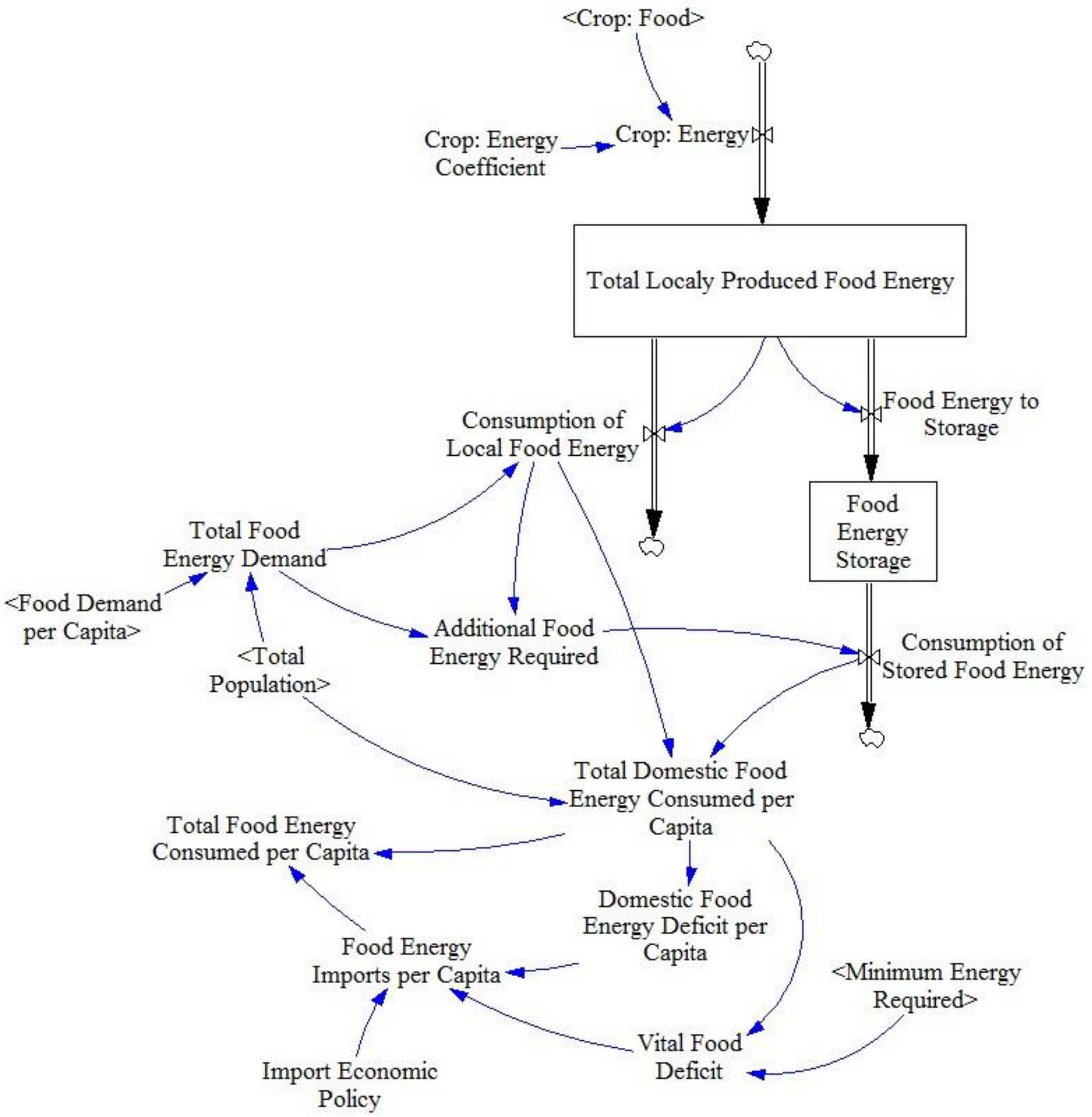


Figure 29: Model structure of the food energy component in the food production sector

The Additional Food Energy Required variable will compare the Consumption of Local Food Energy flow to the Total Food Energy Demand to detect a food energy deficit. If a food deficit is detected Food Energy Storage stock will be called to utilize the food energy in storage if available.

If the food energy produced locally including storage is still not enough to satisfy food demand, then the Food Energy Imports per Capita variable is called to determine how much food needs to be imported in the Food Energy Imports per Capita.

The Vital Food Deficit variable is to detect whether or not domestic food production has satisfied the minimum daily food energy requirements of the population. If a vital food deficit exists, imports are limited to a maximum of 700 kcal/capita/day even if this is not enough to satisfy the minimum daily food energy requirements. This is so that food shortages will have an effect on the population through the malnutrition stock in the population sector. The 700 kcal/capita/day limit was based on the historic quantities of import compared to domestic production.

2.3.5 Water Resources Sector

The water resources sector is more straight forward than the others sectors, as seen in the sectors causal loop diagram in Figure 30. This sector is largely driven by precipitation from climate sector. Water withdrawals also have balancing feedback relationships with both surface water and ground water, but the current rate of water withdrawals are not significant enough to have much of an effect. There is also a balancing feedback loop between groundwater infiltration and groundwater that shows that as groundwater capacity fills up groundwater infiltration decreases and diverted to runoff. .

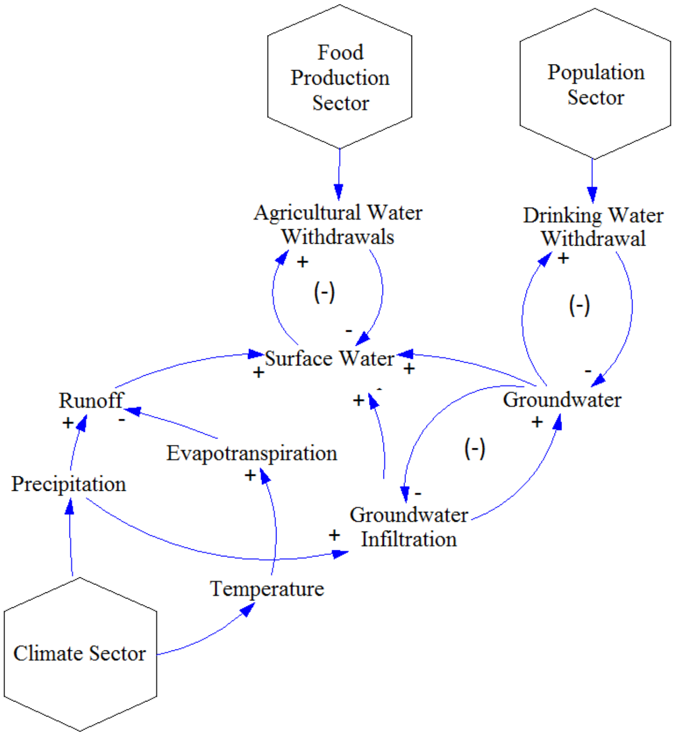


Figure 30: Causal loop diagram of the water resources sector

2.3.5.1 Structure of the Water Resources Sector

The water sector is composed of three stocks, two representing surface water and one representing groundwater (Figure 31). The Upper Basin Surface Water stock represents the area of the basin east of the Gambia that provides an inflow entering the Gambia near Gouloumbou and into the Lower Basin Surface Water Stock. The Groundwater stock represents all groundwater within the Shallow Sand Aquifer throughout the entire water basin.

Precipitation is the driver of the sector providing the inflow into the Upper Basin, Lower Basin stock and groundwater stock. Agricultural irrigation and Discharge are the only outflows from the Lower Basin stock while human water consumption and base flow are the only outflows from the groundwater stock. All of the relationships in this sector were developed from the limited historic monthly river flows into the Gambia (measured at Gouloumbou station) and historic monthly precipitation from the year 1976 to1979 Meybeck, et al., 1987; Risley, et al., 1993).

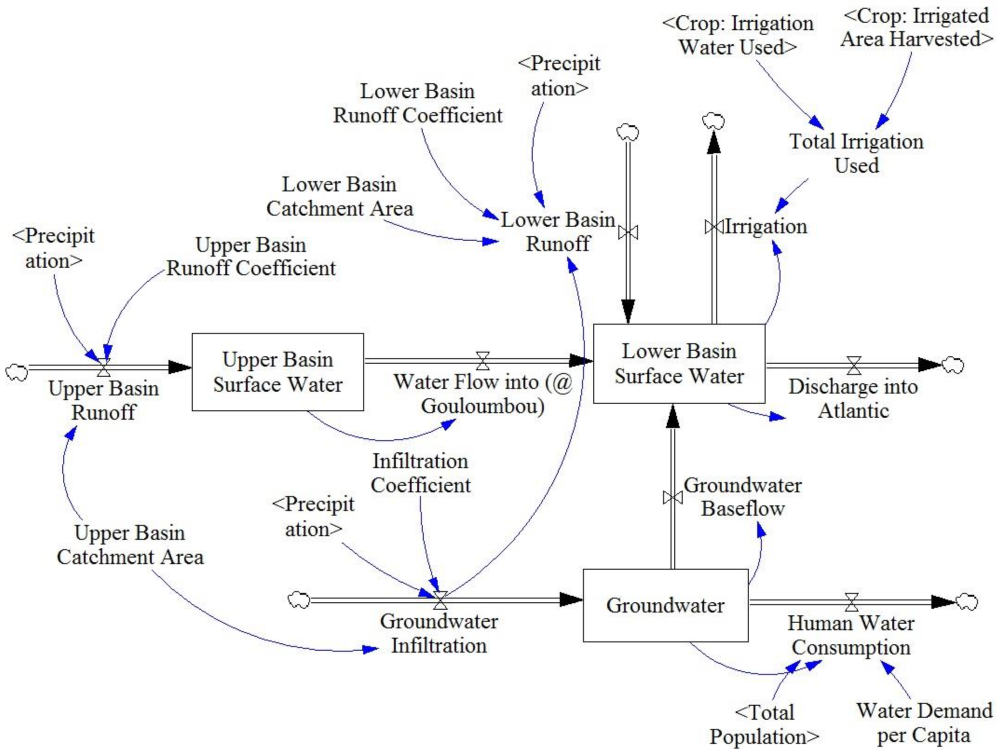


Figure 31: Model structure of the water resources sector

3 Model Performance and Clibration

In this chapter, the performance of the model is discussed by comparing model outputs for key variables to the corresponding historic data. Information about the data sources used is available in Appendix 1.

During and after construction of the model, each sector of the model was calibrated individually and then again once combined with the other sectors by comparison between outputs and historic data. The model is calibrated for the years 1983-2009; this is because most of the required historic data was available during this period. Statistical correlation methods are used sparingly as the trends and behaviour observed in graphical representation of the data are more important in determining model performance. Because of no standard way of measuring the performance of the model, personal judgment is used.

3.1 Population Sector

The performance of the population sector is much better than the performance of the others sectors. This is credited to the abundance in demographic data made available by the United Nations Population Division (United Nations, 2013). Key variables that demonstrate the performance of the population sector include: total population. Life expectancy, total fertility rate, crude birth rate, and crude birth rate.

The overall behaviour of the model outputs performed well in comparison to historic data and can be seen in Figure 32. There were some minor discrepancies such as the crude death rate (Figure 32(d)) being slightly higher than historic values, but the overall behaviour remains the same as seen historically. This is likely because generic mortality tables for developing countries are used in the model and not ones specific to the Gambia. There is also a curve early in life expectancy from the historic data that is not represented in the model.

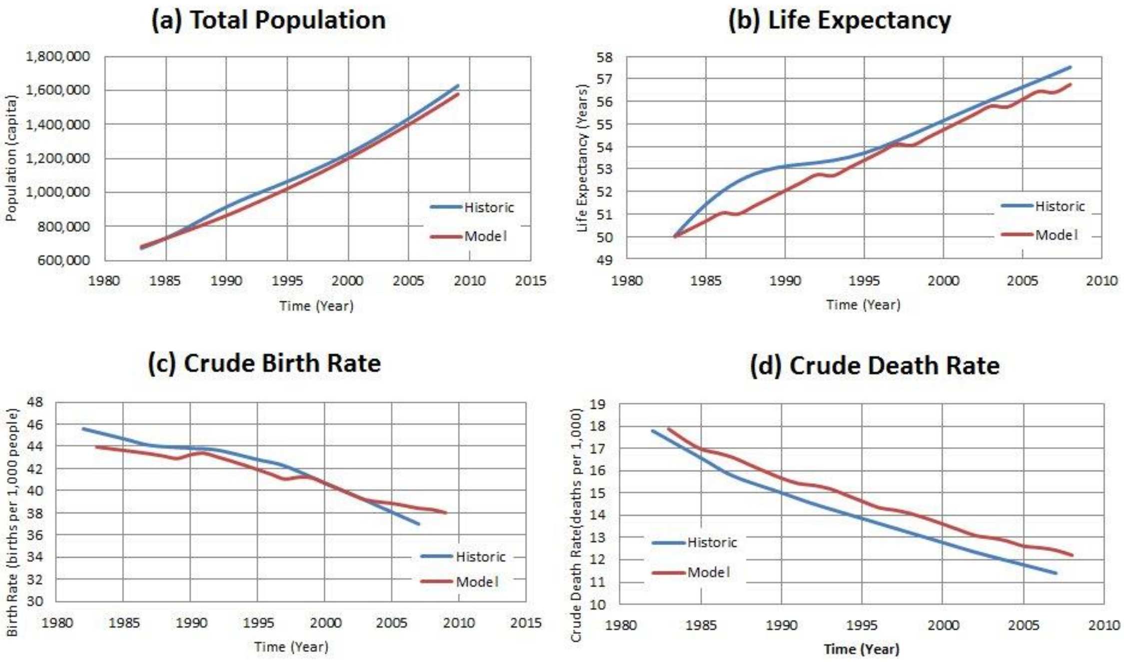


Figure 32: Comparison between historic data and model outputs of the population sector: (a) total population, (b) life expectancy, (c) crude birth rate, and (d) crude death rate (1983-2009)

3.2 Land Use Sector

The land use sector was calibrated using historic land using data made available from the FAO (FAO, 2013). The data is provided to the FAO from the government of the Gambia and there is not account of how accurate the data is, there were some inconsistencies found within in the data. The key variables used in calibration and performance evaluation are total area under cultivation, area of meadows and pastures, and the areas under cultivation for each individual crop.

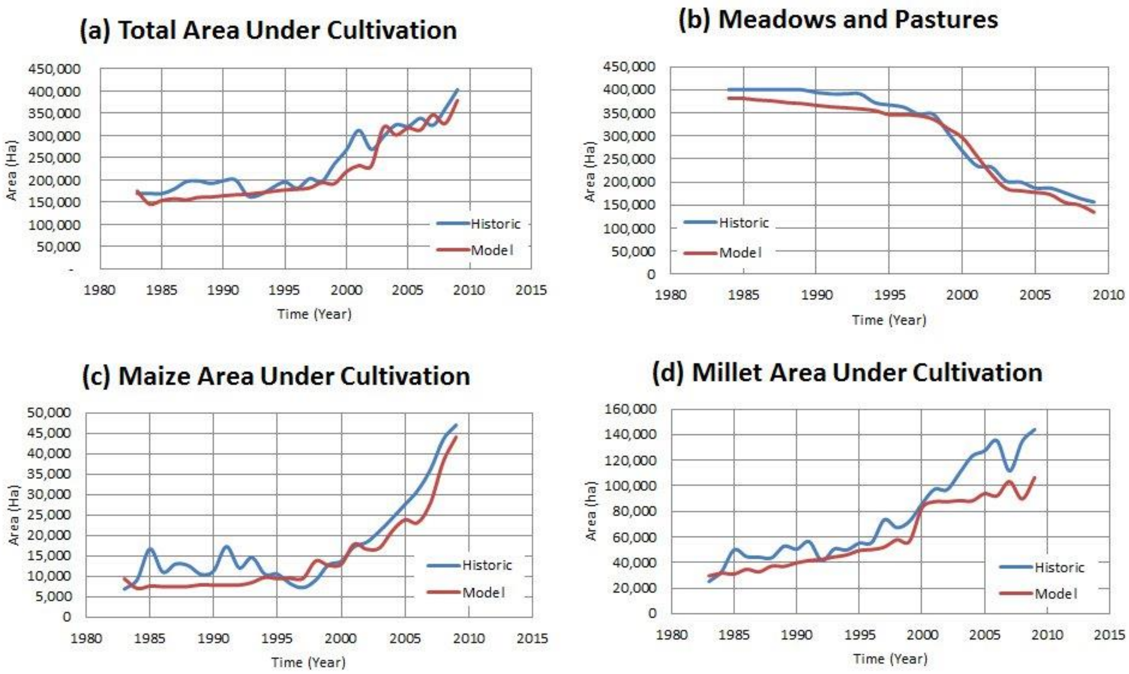


Figure 33: Comparison between historic data and model outputs of the land use sector for: (a) total area under cultivation, (b) meadows and pastures area, (c) maize area under cultivation, and (d) millet area under cultivation (1983-2009)

The behaviour of the land use sector performed slightly better for commutation’s such as total area under cultivation seen in Figure 33 (a) and meadows and pastures in Figure 33 (b). The behaviour of individual crop areas under cultivation for each crop, shown here for maize (Figure 33 (c)) and millet (Figure 33 (d)), did not match with historic data on an annual basis but the overall general pattern did, therefore making the outputs acceptable. The annual changes of area under cultivation were not determined, and therefore not represented in the model. .

3.3 Food Production Sector

The food production sector was also calibrated using historic data from the FAO (FAO, 2013). The key variables used to express model performance are: are crop yields and food energy production per capita.

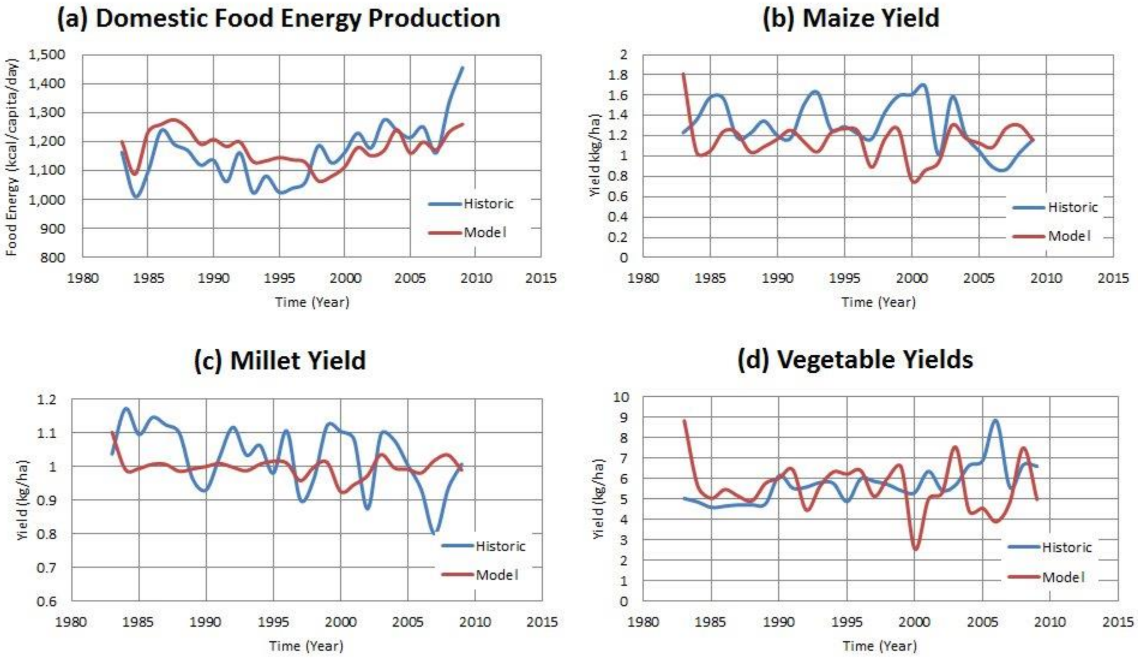


Figure 34: Comparison between historic data and model outputs of food production sector for: (a) domestic energy production, (b) maize yield, (c) millet yield, and (d) vegetable yields (1983-2009)

There were a wide range of yield behaviours both in model outputs and historically. Three crops that provide a representation of yield behaviour are maize, millet, and vegetables shown in Figure 34 (b, c, and d). Other than remaining close in value, there are is no significance in the behaviour between historic and model yields outputs,.

Yields are calculated using a limited version of the water productivity function using monthly rainfall data and not accounting for soil conditions. There is no possible way that yields could completely accurately determined using these limited inputs. However, there are no other methods available that can provide a more accurate yield calculation which is why the water productivity function remains in use.

However, total food production performed much better than model yields. As can be seen in Figure 34 (a), the behaviour of food energy per capita does show similarities to the historic behaviour. This is because food production is only partially dependent on yield, determining its order of magnitude is the area of land under cultivation is, and as seen in the land use section, land under cultivation performed extremely well.

3.3.1 Water Resources Sector

Historic data required for the water resources sector is not available in the quantity or quality seen in the other sectors. The lack of adequate recent historical data makes it impossible to properly calibrate or test the performance of the model sector. Therefore, available data was used as an indicator of the magnitude model outputs should have. A collection of sources containing historic water resources data used is available in Table 8 in Appendix 1.

4 Description and Analysis of Simulation Scenarios

4.1 Simulation Scenarios

The following four scenarios are used further examine the model. It should not be assumed that the four scenarios used for the simulations are completely realistic; some are exaggerated with the specific purpose of causing exaggerated behaviour that can be used to better understand the model structure. It should also be understood that the outputs from the simulated scenarios only represent the behaviour of the model which is based on the many assumptions below and therefore may not accurately reflect reality.

4.2 Scenario 1: Population Control

In the family planning scenario total fertility will be reduced by a total of 2.93 births per woman over 15 years. A rapid reduction in total fertility of this magnitude is not unheard of. Thailand decreased total fertility by 3.03 births per woman between 1970 and 1985 and Vietnam decreased theirs by 2.72 births per woman between 1980 and 1995 (United Nations, 2013). However, the Gambia a predominantly Muslim country with high total fertility rates and cultural attitudes towards family planning are predominantly negative, therefore it should be restated that the purpose of this scenario is used to get a better understanding of model behaviour.

4.2.1 Scenario 2: Increase in Rice Irrigation

Currently, the saline front in the river prevents water from being used for agriculture as far as 250 kilometers upstream during the dry season. Gambians see the construction of a dam as the best way of becoming food self-sufficient as it would allow for double cropping during the dry season. It should be noted that there have been numerous plans for dams at different points along the River Gambia but none have come to be (Njie, 2009).

For this scenario, the construction of a dam located at Kekreti, Senegal would open 55,000 hectares of land to rice irrigation and be completed by 2020. As there are no current realistic plans to construct the dam, he date of dam completion was chosen so that dam irrigation projects would correspond with the start of actual planned long-term irrigation project (Njie, 2010), The development of land capable of irrigation would span 30 years with 1,740 hectares being developed annually until the limit of 55,000 hectares is reached in 2050. Only rice would be able to be use the newly developed land. The rate of increase in irrigated land is developed is based on the size of successful past irrigation projects in the Gambia; any larger of an area would be unrealistic (FAO, 1997).

4.2.2 Scenario 3: Increased Yields

Yields for all crops in the Gambia are much lower than those achieved in neighboring countries due to the predominance of rainfed agriculture using traditional farming techniques and equipment, the lack of land equipped to provide irrigation, decreased soil fertility because of over cropping and decreased fallow periods and many other factors. In this scenario the maximum potential yield for each crop is increased at annually at a constant rate over a 30 year time period until the desired maximum potential yield is reached. The increased maximum potential yields used in the scenario are displayed in Table 3. They were chosen because they were the maximum yields achieved in surrounding countries.

It is assumed that the increase in the maximum potential yields would be achieved through investments in the agricultural sector by the government and NGOs. As stated earlier, the maximum potential yield, Y_m, represents the maximum yield that can be achieved when crop water requirements are met using the water productivity function (Equation 2.20).

Table 3: Increase in maximum potential yields in Scenario 4

	Original Maximum Potential Yield, Y_{m0} (ton/hectares)	New Maximum Potential Yield, Y_{m1} (ton/hectares)
Groundnut	1.53	3
Maize	1.81	5
Millet	1.1	3.5
Sorghum	1.1	4
Rice	2.57	5
Vegetables	8.8	8.8
Pulses	0.34	1.05
Cassava	5.08	15

4.2.3 Scenario 4: Extreme Climate Change

In this scenario, the precipitation and temperature data used for climate inputs are changed from the ensemble mean projections but remain projected under the A1B emission scenario. The precipitation data used as model inputs is from the ensemble minimum climate projection, and the temperature data used as model inputs is from ensemble maximum climate projections.

4.3 Analysis of Simulated Scenarios

. In the following analysis, four model outputs are used to assist in describing the four simulated scenarios as well as to provide insight into the overall behaviour of the model. The outputs are: total population, total fertility rate, life expectancy, and domestic food energy deficit. A base simulation is used as a standard source of comparison for each of the simulated scenarios. Outputs from the land use and water resources sector are discussed in summary of results sections.

4.3.1 Scenario 1: Population Control

The impact of reducing the total fertility rate to 2.2 births per woman by 2030 (Figure 35(b)) can clearly be seen in Figure 35(a) with the reduction of the population growth rate and the stabilization of the population at around 3,500,000. It could be assumed that the reduction in the population growth rate is completely the work of the reduction in the total fertility rate, but this is not the case. Life expectancy also plays a role in stabilizing the population in this scenario. As can be seen in Figure 35(c), life expectancy reaches its peak in 2037 at 62.9 years and then gradually decreases to 59.8 years over the remaining 63 years of the simulation. The importance of life expectancy to the population growth is that it is responsible for determining the mortality rate and thereby total number of deaths; with the relationship being: as life expectancy decreases mortality rates increase, and vice versa. Therefore, increased deaths caused by a decline in life expectancy in conjunction with the rapid decrease in births both play an integral role in the reduction of population growth rate and the stabilization of the population.

The behaviour of life expectancy exposed in this scenario is significant because it illustrates that an artificial decrease in total fertility rates have no significant impact on life expectancy. Under normal conditions, total fertility rate is a function of life expectancy, and as life expectancy increases the total fertility decreases.

Life expectancy is itself a function of food consumption, declining as less food is available for consumption or rising with increased food availability. In this scenario, the continued rise in the food deficit shown in Figure 35(a), illustrates why life expectancy decreases even though total fertility rates have been significantly reduced.

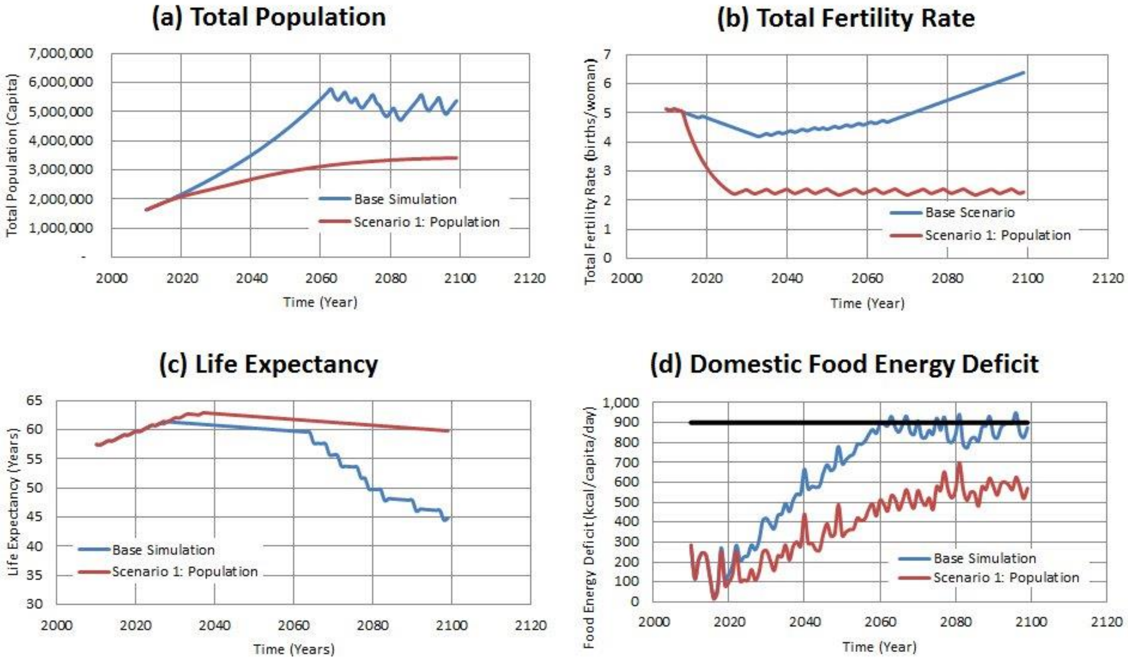


Figure 35: Model outputs for Simulation Scenario 1 (total population, total fertility rate, life expectancy, and domestic food energy deficit)

Over the course of the simulation, the decrease in the population growth rate provides some relief to the food production system by reducing overall demand preventing a critical food deficit, but it is not significant enough to avoid a food deficit (Figure 35(d)). It becomes clear that population growth is not the only factor placing a strain on food production as the rates of change between population and the food deficit are not proportional which is seen by the food deficit growing at a faster rate than total population. The other factor contributing to the food deficit is the decreasing annual rainfall and increasing temperature resulting from climate change. The rise in temperature increases crop evapotranspiration and thereby crop water requirements. Compounding the problem is the decrease in rainfall. The decrease in rainfall means that crop water requirements will not be completely satisfying which results in decreased yields and an overall reduction in food production/

In summary, the population growth was reduced by a combination of a reduction in total fertility rates and a declining life expectancy. Life expectancy stopped increasing and began to decrease due to a reduction in food availability as a result of a slightly increasing population and the effects of climate change.

4.3.2 Scenario 2: Increased Rice Irrigation

The population growth rate observed in Scenario 2 (Figure 36 (a)) does not significantly change from the base simulation, differing only by the timing of the critical food deficit. Slight changes can be seen in the total fertility rate (Figure 36 (b)) and life expectancy (Figure 36 (c)) by 2037, but these do not result significant changes to the rate of population growth. Population growth does not change from the base simulation because the increased rice production, as a result of increased yields from increased irrigation, does not result in a significant rise in overall food production. This can be seen in the slight decrease in the food deficit (Figure 36 (d)), though it still leads to a critical food deficit, only delayed by 14 years. Following the critical food deficit life expectancy tumbles and total fertility rates rise as they did in the base scenario following the critical food deficit.

Food production plays a critical role in controlling the rate of population growth. A reduction in population growth can only organically occur through a constant increase in food production, which raises life expectancy and decreasing total fertility rates. On the other hand, with no population control measures in place, food deficits and a high population growth rate have a positive reinforcing feedback relationship, as high population growth with an non-proportional increase in food production cause the food deficit to increase, which leads to a decrease in life expectancy and an increase to the total fertility rate, resulting in further population growth and the continuation of the reinforcing feedback loop. The feedback loop continues in this manner until food production cannot satisfy the minimum food requirements which results in a critical food deficit and significant increases in mortality rates.

The current structure of the model does not allow recovery of the population following its collapse from a critical food deficit. The model structure will also not allow the food deficit to increase beyond 900 kcal/capita/day because continued critical food deficits will keep increasing the mortality rate which keeps the population from growing much beyond the point triggering a critical food deficit. Therefore reaching a critical food deficit represents the end of the simulation.

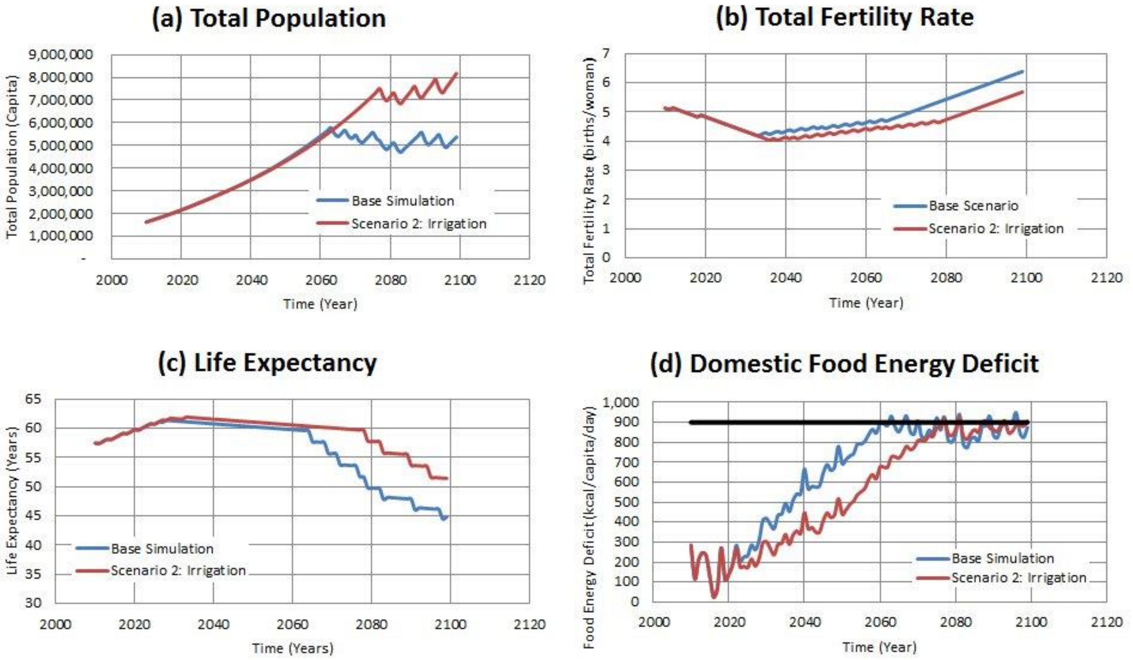


Figure 36: Key outputs for Simulation Scenario 2 (total population, total fertility rate, life expectancy, and domestic food energy deficit)

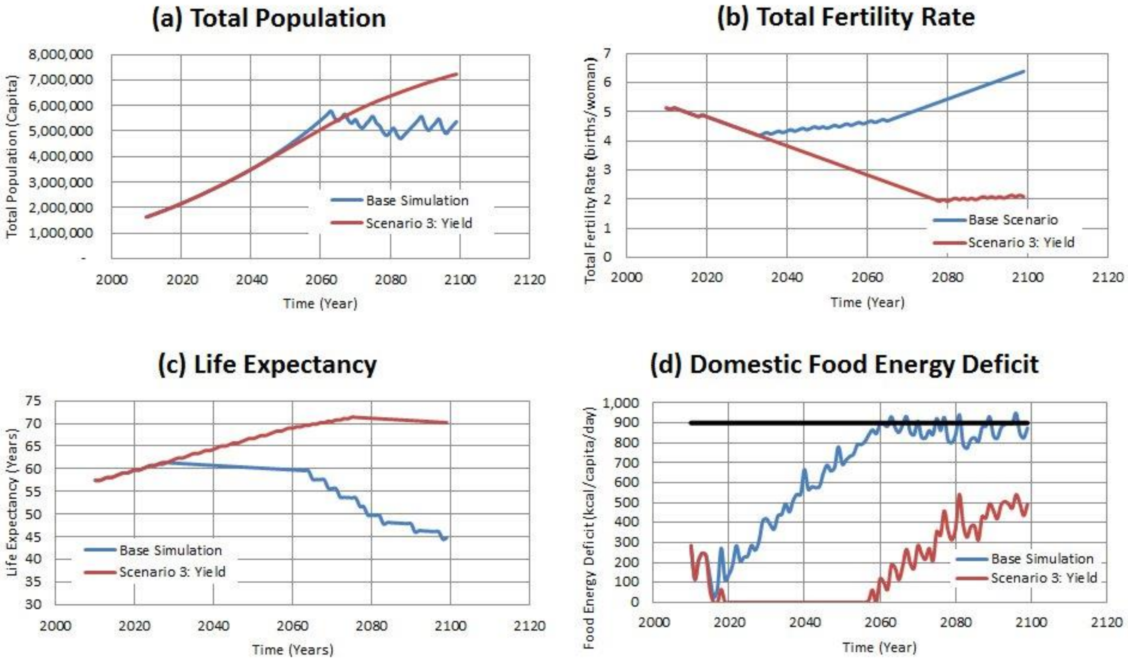
The increase in the area of rice under irrigation results in an increase in rice yields and overall food production. The impact of increased food production is a slightly reduced rate of increase in the food deficit when comparison to the base simulation as seen in Figure 36D. It can also be seen that the increase in rice production is not significant enough to result in food self-sufficiency; it only reduces the rate of increase in the food deficit until population has increased to the level where there is a critical food deficit.

In summary, scenario 2 follows the same path as the base scenario but a slight increase in food production from increased irrigation delays the critical food deficit by 14 years. Population growth, without increased food production, causes an increase in food deficits

4.3.3 Scenario 3: Increased Yields

In this scenario, the maximum potential yields for each crop are increased to the maximum yields observed in other West African countries.

As with Scenario 2, population growth, seen in (Figure 37(a)), initially mirrors the base simulation, but in this scenario the growth rate starts to decrease around 2050. The total fertility rate ((Figure 37(b)) and life expectancy (Figure 37(c)) begin deviating from the base simulation in 2030 and 2035, respectively. The change in the total fertility rate and life expectancy occur once yields and food production start increasing as can be seen by the reduction in the food deficit in Figure 37(d). The increase in yields has a dramatic impact on food production with food self-sufficiency being achieved by 2020.



(a) Total Population

(b) Total Fertility Rate

(c) Life Expectancy

(d) Domestic Food Energy Deficit

Figure 37: Key outputs for Simulation Scenario 3 (total population, total fertility rate, life expectancy, and domestic food energy deficit)

Two significant lags within the system become apparent as well. The first is the lag between increased food production and changes in life expectancy ((Figure 37(c, d)) and the second is the decrease in population growth which is lagging behind the decrease in total fertility rate and life expectancy.

As discussed in the analysis of Scenario 1, the rate of population growth is largely dependent on the total fertility rate, but life expectancy also plays a significant role and explains the previously mentioned lags. This scenario shows the other side of this with an increase in life expectancy contributes to population growth by decreasing the mortality rate. This scenario represents a more organic decrease in the population growth rate than in Scenario 1.

4.3.4 Scenario 4: Extreme Climate Change

In this scenario, model climate inputs are changed to express a more extreme climate with increased temperatures and decreased precipitation. This is the only scenario where a critical food deficit is reached sooner than the base simulation (Figure 38). The decrease in precipitation resulted in a number of years where crop yields for groundnut, maize, millet, sorghum, rice, vegetables, pulses were zero since they did not receive enough water. Cassava, on the other hand, continued producing food every year. Millet, maize and sorghum were the least affected of the crops that suffered water deficits while pulses were by far the most sensitive to the reduction in water followed by vegetables. The most important story from this scenario is the reliance the country has on a steady source of rainfall.

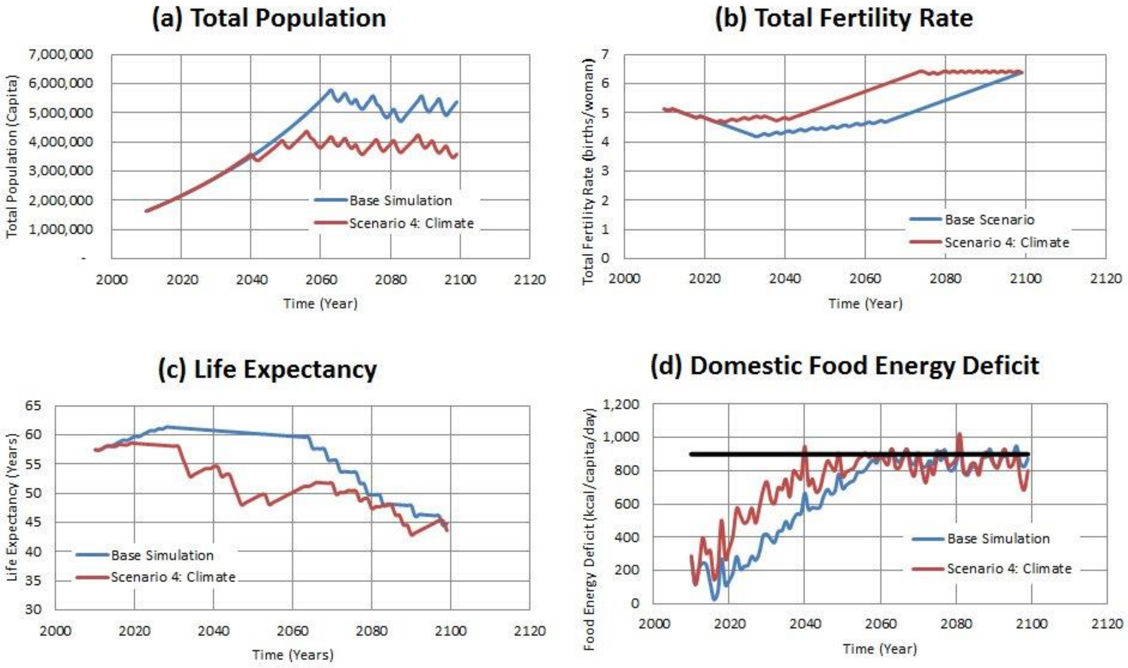


Figure 38: Key outputs for Simulation Scenario 4 (total population, total fertility rate, life expectancy, and domestic food energy deficit)

5 Summary of Model Behaviour and Recommendations

The results of the four scenario simulations show that within the model structure there was no individual policy that led to long term self-sufficiency or completely removed the food deficit. The main factor preventing long-term sustainability is population growth. And a significant increase in food production is the only way to naturally decrease the population growth rate. Even with significant increases in food production where food self-sufficiency is met(Scenario 3),, the decrease in total fertility rate takes much longer to reach replacement levels than when population control measure are used (Scenario 1),Figure 39 (b) shows the difference between natural (Scenario 3) and artificial (Scenario 1) methods in reaching replacement levels of the total fertility rate.

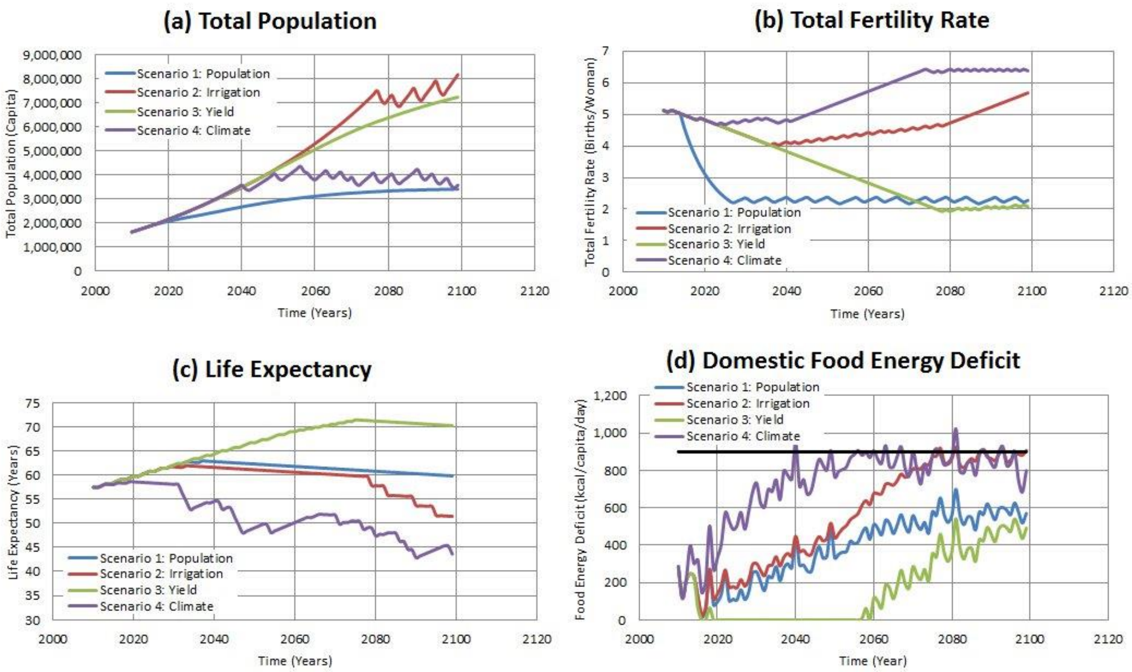


Figure 39: Comparison of key outputs of simulation scenarios 1, 2, 3 and 4 (total population, total fertility rate, life expectancy, domestic food energy deficit)

Arable land is almost fully exploited prior to the simulation. So it is no surprise that during simulation for each scenario the maximum quantity of arable land was under crop cultivation and forest land was just as quickly reduced. Forest area was significantly reduced from over 400,000 hectares to just over 150,000 hectares.

The increase irrigable land in scenario 3 was the only cause of increased surface water use. Scenario 3 was the only scenario, other than extreme climate change in scenario 1 where there is significant change in the water resources sector. Once the entire 55,000 hectares are used to irrigate rice, water withdraws from the river doubles. The model results show that withdrawals from the aquifer have no long term impact to its capacity. Scenario 3 required the largest withdrawal at just over 40 (10^6) m^3 yet still having little impact on the 1,000 (10^6) m3 capacity aquifer.

5.1 Model Limitations and Improvements

5.1.1 Model Limitations

Population Sector

Life expectancy in the population sector currently relies on the quantity of food energy consumed per capita in calculating the life expectancy ignoring other factors such as quality of healthcare, population density, gross domestic product, and air pollution. This is also true for the total fertility rate which is determined based on life expectancy and therefore also food consumption per capita.

In the current structure of the population sector a critical food deficit basically represents the end of the simulation as there is no way for the population to recover from the reinforcing feedback between food production per capita and the total fertility rate.

Land Use Sector

The fertility of arable land is not factored into the land use sector. Over cropping and erosion significantly reduces the nutrient content of topsoil and the reduced fallow periods have common in the Gambia, this leaves little time for the rejuvenation of arable land.

New land is allocated to crops based on its fixed percentage of total food energy. This limits the way in which land can be allocated, making it difficult for policies to influence change in crop patterns.

Food Production Sector

The food production sector does not account for soil fertility in determining crop yields. Yields are currently calculated based solely on the quantity of water each crop receives.

Water Resources Sector

There is a clear limitation in many aspects of the water resources sector due a large gap in available information. Measurements of river flows in the River Gambia are pretty much nonexistent within the Gambia. It is reported that the lack of stream gauges is due to the tidal influences disrupting the measurements of flow rate throughout the length of river (Njie, 2009). The only relevant records of flow rates are from the Gouloumbou station just east of the Gambia in Senegal (Njie, 2009). These records have been difficult to obtain and the water resources sector was built only using one year of monthly flow rates from the 1970s. I did eventually come across a French report containing a significant collection of flow records at the Gouloumbou station as well as additional river data. Unfortunately, the records were found during testing of the model, too late to be incorporated into the model.

5.2 Recommendations for Model Improvements

Population Sector

Examine how a population recovers from a critical food deficit and then incorporate it into the population sector of the model.

Land Use Sector

Incorporating soil fertility into yield calculations would better represent reality which would increase confidence in the model. The reduction in soil fertility is sure to play a significant role in the future of food production in the Gambia and therefore should be incorporated into future versions of the model.

New land is allocated to crops based on its fixed percentage of total food energy. A mechanism built into the land use section to adjust the crops percentage of total food energy. This would allow for changes in the quantity of land allocated to each crop. It would be interesting to see if how a shift in cultivation would affect food production.

Water Resources Sector

Incorporate water resources data from Monographie Hydrologique Du Fleuve Gambie (Lamagat, et al., 1990) into the model to improve the water resources sector. It would be excellent to incorporate increased the functionality into the water resources sector with this additional data.

Following improvements in the water resources sector, salinity forecast system should be incorporated into the model. It would calculate the location of the saline front in the River Gambia which could be used in determining suitability of land along the river for irrigation, which would detail to the dam construction scenario. It is estimated that an increase in the sea level at a rate of 100 cm per century may result in the saline front migrating upstream at a rate of 370 meters per year (Republic of The Gambia, 2003). The consequences of the rise in sea level could be factored into the model by incorporating a salinity forecast system.

Other Model Recommendations

Adding an economic sector to the model would provide much added benefit especially in in terms of policy implementation. The primary driver behind any government policies is financial investment, as money directed at a policy begins to be reduced so will the effectiveness of that policy. Policies could be implemented within the model through changes in the allocation of government money.

Currently, the only way a policy can be implemented is by forcing a change to the structure of the model. Take Scenario 1, total fertility rate was decreased because family planning education was significantly increased. The addition of an economic sector would add more accuracy to the scenario by making education dependent on continued funding in order to be successful, just as it would be in the real world. The needs of the population would have to be balanced through the allocation of funds which would add another layer of complexity to the model.

References

Ahmad, S. & Simonovic, S. P., 2004. Spatial system dynamics: new approach for simulation of water resources systems. *simulation of water resources systems. J Comput Civ Eng, 18(4): 331–340.Journal of Computing in Civil Engineering,* 18(4), pp. 331-340.

Ahmad, S. & Simonovic, S. P., 2006. An intelligent decision support system for management of floods. *Water Resources Management,* 20(3), pp. 391-410.

Akhtar, M. K., 2011. *A system dynamics based integrated assessment modelling of global-regional climate change: A model for analyzing the behaviour of the social-energy-economy-climate system,* London, Ontario: The University of Western Ontario.

Allan, R. G., Pereira, L. S., Raes, D. & Smith, M., 1998. *FAO Irrigation and drainage paper 56 - Crop evapotranspiration: Guidelines for computing crop water requirements.* Rome: Food and Agriculture Organization of the United Nations.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M., 1998. *FAO Irrigation and drainage paper 56: Crop evapotranspiration - Guidelines for computing crop water requirements.* Rome: FAO.

AtKisson, A., 1999. *Believing in Cassandra: An Optimist Looks at a Pessimist's World.* White River Junction, Vermont: Chelsea Green Publishing.

Barlas, Y., 1989. Multiple tests for validation of system dynamics type of simulation models. *European Journal of Operational Research,* Volume 42, pp. 59-87.

Barlas, Y., 1996. Formal aspects of model validity and validation in system dynamics. *System Dynamics Review,* 12(3), pp. 183-210.

Beall, A., Fiedler, F., Boll, j. & Cosens, B., 2011. Sustainable Water Resource Management and Participatory System Dynamics. Case Study: Developing the Palouse Basin Participatory Model. *Sustainability,* Issue 3, pp. 720-742.

Behrensmeyer, A. K., 2006. Climate change and human evolution. *Science,* Volume 311, pp. 476-478.

Biswas, A., 1976. *Systems approach to water management.* London: McGraw Hill.

Bowden, M. & Glennie, J., 1986. Integrated water resource management on the central plains: the need for irrigation. *New Zeland Agricultural Science,* 20(1), pp. 18-22.

Brouwer, C. & Heibloem, M., 1986. *Irrigation Water Management: Training Mannual no. 3,* Rome: FAO.

Bulled, N. L. & Sosis, R., 2012. Examining the Relationship between Life Expectancy, Reproduction, and Educational Attainment. *Human Nature,* 21(3), pp. 269-289.

Camara , A., Viegas , M. & Amaro , A., 1986. Interfacing system dynamics and multiobjective programming for regional water resources planning. *The Annals of Regional Science,* 20(2), pp. 104-113.

Cham, M. et al., 2007. *Gambia National Adaptation Programme of Action (NAPA) on CLimate Change,* Banjul: Republic of The Gambia.

Christensen, J. et al., 2007. Regional Climate Projections. In: S. Solomon, et al. eds. *Climate Change 2007: The Physical Science Basis.* Cambridge, New York: Cambridge University Press, pp. 866-871.

Crawford, N. & Linsley, R., 1966. *Digital simulation in hydrology: Stanford Watershed Model IV,* Stanford: Civil Engineering Department, Stanford University.

Dastane , N. G., 1978. *Effective rainfall in irrigated agriculture.* Rome: FAO.

Davies, E. G., 2007. *Modelling Feedback in the Society-Biosphere-Climate System,* London, Ontario: The University of Western Ontario.

Davies, E. G. & Simonovic, S. P., 2008. *An Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic System: Model Description and Model Use Guide,* London, Ontario, Canada: Facility for Intelligent Decision Support.

Davies, E. G. & Simonovic, S. P., 2009. *Energy Sector for the Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic Model,* London, Ontario: The University of Western Ontario.

Davies, E. G. & Simonovic, S. P., 2010. ANEMI: A new model for integrated assessment of global change. *Interdisciplinary Environmental Review,* 11(2/3), pp. 127-161.

Davies, E. G. & Simonovic, S. P., 2011. Global water resources modeling with an integrated model of the social-economic-environmental system. *Advances in Water Resources,* 36(6), pp. 684-700.

Doorenbos, J. & Kassam, A., 1979. *FAO Irrigation and Drainage Paper No. 33: Yield response to water.* Rome: FAO.

Doorenbos, J. & Pruitt, W., 1975. *Irrigation and Drainage Paper 24: Guidelines for predicting crop water requirements.* Rome: FAO.

FAO, 1997. *Irrigation potential in Africa: A basin approach.* [Online]
Available at: http://www.fao.org/docrep/w4347e/w4347e00.htm
[Accessed 3 June 2013].

FAO, 2005. *Aquastat.* [Online]
Available at: http://www.fao.org/nr/water/aquastat/main/index.stm
[Accessed 8 June 2013].

FAO, 2005. *AQUASTAT.* [Online]
Available at: http://www.fao.org/nr/aquastat
[Accessed 3 July 2013].

FAO, 2011. *The State of the World's Land and Water Resources for Food and Agriculture (SOWLAW) - Managing systems at risk.* Rome, London: Food and Agriculture Organization of the United Nations, Earthscan.

FAO, 2013. *FAOSTAT*. [Online]
Available at: http://faostat.fao.org/
[Accessed 2 July 2013].

Fatajo, F. S., 2010. *National Issues Report on Key Sector of Agriculture (Adaptation) in the Gambia,* Banjul: UNDP.

Food and Agriculture Organization of the United Nations, n.d. *AQUASTAT*. [Online]
Available at: http://www.fao.org/nr/aquastat
[Accessed 3 July 2013].

Forrester, J. W., 1961. *Industrial Dynamics.* Cambridge: Pegasus Communications.

Forrester, J. W., 1968. *Principles of systems.* Portland: Productivity.

Forrester, J. W., 1969. *Urban Dynamics.* Cambridge: Pegasus Communications.

Forrester, J. W., 1972. *World Dynamics.* Cambridge: Pegasus Communications.

Forrester, J. W., 1987. Lessons from system dynamics modelling. *System Dynamics Review,* 3(2), pp. 136-149.

Forster, H., 1983. *Evaluation of the National Forest Inventory of The Gambia, Technical Report no. 10,* Banjul: Gambia-German Forestry Project.

Frenken, K., 2005. *FAO Water Reports 29 - Irrigation in Africa in figures - AQUASTAT Survey - 2005,* Rome: Food and Agriculture Organization of the United Nations.

Grigg, N., 1977. *Management of water resources: a systems approach.* Fort Collins: Colorado State University.

Grigg, N., 1977. *Management of water resources: a systems approach.* Ft. Collins: Colorado State University.

Hamilton, H., 1969. *Systems simulation for regional analysis: an application to river-basin planning.* Cambridge: MIT.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.

IPCC, 2013. *What is a GCM?.* [Online]
Available at: http://www.ipcc-data.org/guidelines/pages/gcm_guide.html
[Accessed 28 June 2013].

Kaboosi, K. & Kaveh, F., 2010. Sensitivity analysis of Doorenbos and Kassam (1979) crop water production function. *African Journal of Agricultural Research,* 5(17), pp. 2399-2417.

Kirkwood, C. W., 2013. *System Dynamics Methods: A Quick Introduction.* [Online]
Available at: http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/SDIntro.htm
[Accessed 19 June 2013].

Kuyu, R. et al., 2006. Agriculture Health in The Gambia: Agriculture Practices and Developments. *Ann Agric Environ Med,* Volume 13, pp. 1-12.

Lamagat, J., Alvergel, J., Bouchez, J. & Descroix, L., 1990. *Monographie Hydrologique Du Fleuve Gambie,* Dakar: Institut Francais De Recherche Scientifique Pour Le Development En Cooperation Organisation Pour La Mise En Valeur Du Fleuve Gambie.

Lesack, L. F., Hecky, R. E. & Melack, J. M., 1984. Transport of Carbon, Nitrogen, Phosphorus, and Major Solutes in the Gambia River, West Africa. *American Society of Limnology and Oceanography,* 29(4), pp. 816-830.

McSweeney, C., New, M. & Lizcana, G., 2008. *UNDP Climate Change Country Profiles: Documentation.* [Online]
Available at:
http://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Climate%20Change/UNDPCCCP_documentation.pdf
[Accessed 1 July 2013].

McSweeney, C., New, M. & Lizcano, G., 2012. *UNDP Climate Change Country Profiles - Documentation.* [Online]
Available at: http://country-profiles.geog.ox.ac.uk/
[Accessed 2 July 2013].

McSweeney, C., New, M. & Lizcano, G., 2012. *UNDP Climate Change Country Profiles - The Gambia.* [Online]
Available at: http://country-profiles.geog.ox.ac.uk/
[Accessed 2 July 2013].

McSweeney, C., New, M., Lizcano, G. & Lu, X., 2010. The UNDP Climate Change Country Profiles Improving the Accessibility of Observed and Projected Climate Information for Studies of Climate Change in Developing Countries. *Bulletin of the American Meteorological Society,* 10(2), pp. 157-166.

McSweeney, C., New, M., Lizcano, G. & Lu, X., 2010. The UNDP Climate Change Country Profiles Improving the Accessibility of Observed and Projected Climate Information for Studies of Climate Change in Developing Countries. *Bulletin of the American Meteorological Society,* Volume 91, pp. 157-166.

McSweeny, C., New, M. & Lizcano, G., 2008. *UNDP Climate Change Country Profiles: The Gambia.* [Online]
Available at: http://country-profiles.geog.ox.ac.uk/
[Accessed 1 July 2013].

Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. I. W., 1972. *The Limits to Growth.* New York: Universe Books.

Meadows, D. L. et al., 1974. *Dynamics of Growth in a Finite World.* Cambrigde, Massachusetts: Wright-Allen Press, In.

Meybeck, M., Lô , H., Cauwet, G. & Gac, J., 1987. Geochemistry of the sahelian Gambia river during the 1983 high-water stage. *Mitteilungen Geologisches Paläontologisches Institüt Universiteit Hamburg,* Volume 64, pp. 461-473.

Musser, K., 2010. *Gambia River Drainage Basin.* [Online]
Available at: https://commons.wikimedia.org/wiki/File:Gambiarivermap.png
[Accessed 6 July 2013].

Nakicenovic, N., 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.

Nakicenovic, N. & Swart, R. eds., 2000. *IPCC Special Report on Emissions Scenarios.* s.l.:Cambridge University Presss.

National Climate Committee, 2003. *First National COmmunication of The Republic of The Gambia to the United Nations Framework Convention on Climate Change,* Banjul: Republic of The Gambia.

Njie, M., 2009. *IWRM Roadmap for The Gambia,* Banjul: Republic of The Gambia.

Njie, M., 2010. *National Water Security in the First Half of the Twenty-First Century,* Banjul: Deparment of Water Resources.

Radzicki, M. J. & Taylor, R. A., 2008. *Origin of System Dynamics: Jay W. Forrester and the History of System Dynamics.* [Online]
Available at: http://www.systemdynamics.org/DL-IntroSysDyn/start.htm
[Accessed 3 July 2013].

Raes, D. et al., 2006. Simulation of yield decline as a result of water stress with a robust soil water balance model. *Agricultural Water Management,* 81(3), p. 335–357.

Republic of The Gambia, 2000. *National Action Programme To Combat Desertification (NAP),* Banjul: United Nations Convention to Combat Desertification .

Republic of The Gambia, 2003. *First National Communication of The Republic of The Gambia to the United Nations Framework Convention on Climate Change,* Banjul: Republic of The Gambia.

Republic of The Gambia, 2006. *Poverty Reduction Strategy: 2007-2011,* Banjul: Department of State for Finance and Economic Affairs.

Republic of The Gambia, 2008. *Climate Change, Adaptation & Mitigation Strategy Paper 2007-2011,* Banjul: Republic of The Gambia.

Risley, J., Guertin, D. & Fogel, M., 1993. Salinity-Intrusion Forecasting System for Gambia River Estuary. *Journal of Water Resources Planning and Management,* 119(3), pp. 339-352.

Roach, J., 2007. *Integrated surface water groundwater modeling in the Upper Rio Grande in support of scenario analysis,* Tucson, Arizona: The University of Arizona.

Sabri, M. M., Dosso, H., Basalirwa, M. & Kuatsinu, E. K., 2005. *Farmer Managed Rice Irrigation Project,* Abidjan: African Development Fund.

Sillah, B. M. S., 2009. *And Economic Analysis for the Impacts of Climate Change on Cash and Food Crop Production in The Gambia,* Riyadh: King Saud University .

Simonovic, S., 2009. *Managing Water Resources: Methods and Tools for a Systems Approach.* Paris: UNESCO Publishing.

Steduto, P., Hsiao, T. C., Fereres, E. & Raes, D., 2012. *FAO Irrigation and drainage paper 66 - Crop yield responce to water.* Rome: Food and Agriculture Organization of the United Nations.

Steduto, P., Hsiao, T. C., Fereres, E. & Raes, D., 2012. *FAO Irrigation and drainage paper 66: Crop yield responce to water.* Rome: FAO.

Sterman, J., 2000. *Business dynamics: Systems thinking and modelling for a complex world.* Boston: McGraw-Hill.

Tans, P. & Keeling, R., 2013. *Recent Monthly CO2 at Mauna Loa.* [Online]
Available at: http://www.esrl.noaa.gov/gmd/ccgg/trends/
[Accessed 18 July 2013].

The World Bank, 2012. *World Development Indicators.* [Online]
Available at: http://data.worldbank.org/data-catalog/world-development-indicators
[Accessed 2 July 2013].

Tidwell, V. C. & van den Brink, C., 2008. Cooperative modeling: linking science, communication, and ground water planning. *Ground Water*, 46(2), pp. 174-182.

Turner, G. M., 2008. A comparison of The Limits to Growth with 30 years of reality. *Global Environmental Change,* 18(3), pp. 397-411.

Turral, H., Burke, J. & Faures, J., 2011. *FAO Water Reports no 36: Climate change, water and food security,* Rome: FAO.

UNDP, 2013. *Country Profile: Human Development Indicators.* [Online]
Available at: http://hdrstats.undp.org/en/countries/profiles/GMB.html
[Accessed 26 June 2013].

UNDP, 2013. *The Rise of the South: Human Progress in a Diverse World,* New York: United Nations Development Programme.

UNEP, 1998. *Technical Publication 8a: Sourcebook of Alternative Technologies for Freshwater Augmentation in Africa*, Rome: UNEP.

United Nations, 2003. *The Population Policy Data Bank.* [Online]
Available at: www.un.org/esa/population/publications/abortion/doc/gambia.doc
[Accessed 22 06 2013].

United Nations, 2013. *World Population Prospecs: The 2012 Revision, Key Findings and Advance Tables,* New York: UN.

van Ittersum, M. K. et al., 2013. Yield gap analysis with local to global relevance—A review. *Field Crops Research,* Volume 143, pp. 4-17.

van Wart, J. et al., 2013. Estimating crop yield at regional to national scales. *Field Crop Research,* Volume 143, pp. 34-43.

Ventana Systems, 2010. *Vensim DDS Software (online).* [Online]
Available at: http://vensim.com/vensim-software/
[Accessed 16 July 2013].

Washington, R., 2006. African climate change: Taking the shorter route. *Bulletin of the American Meteorological Society,* Volume 87, pp. 1355-1366.

Winz, I., Brierley, G. & Trowsdale, S., 2009. The Use of System Dynamic Simulation in Water Resources Management. *Water Resource Management,* 23(7), pp. 1301-1323.

Wolstenholme , E., 1990. *System enquiry: a system dynamics approach.* Chichester: Wiley.

Appendices

Appendix A: Data Sources

Table 4: Climate projection data used in the climate sector

Data Type	Data Period	Additional Info	Data Source
Precipitation and Temperature Projections	2000-2100	Ensemble monthly time series data for precipitation and temperature is composed of the ensemble minimum, mean, and maximum from 15 model projections (McSweeny, et al., 2008) under three SRES emission scenarios (A2, A1B, and B1) are used in t for the Gambia (McSweeney, et al., 2008).	United Nations Development Program Climate Change Country Profile for The Gambia (McSweeny, et al., 2008)

Table 5: Population data used for model construction and calibration

Data Type	Data Period	Additional Info	Data Source
Total Population	1960-2011		World Population

(Capita)			Prospects (United Nations, 2013)
Age distribution (Capita)	1960-2011	Data is divided into the following age groups: 0-4, 5-9, 10-14, 15-19, 20-24, 25-29, 30-34, 35-39, 40-44, 45-49, 50-54, 55-59, 60-64, 65+	World Population Prospects (United Nations, 2013)
Total Fertility Rate (Births per woman)	1960-2011	For the Gambia and Brazil	World Population Prospects (United Nations, 2013)
Age Specific Fertility Rate (Births	Gambia: 1973, 1986-1990, 1993, 1995-2000, 2000-2005 Brazil: 1969-1970, 1982-1986, 1992-1996, 2005, 2006	Data for the Gambia and Brazil, divided into the following age groups:: 15-19, 20-24, 25-29, 30-34, 35-39, 40-44,	World Population Prospects (United Nations, 2013)
Life Expectancy (Years)	1960-2011	Life expectancy for: total population, female and male	World Population Prospects (United Nations, 2013)
Birth Rate (Births per 1,000 people)	1960-2011		World Population Prospects (United Nations, 2013)
Death Rate (Deaths per 1,000 people)	1960-2011		World Population Prospects (United Nations, 2013)

Mortality Tables for Developing Countries	1961-2010		World Population Prospects (United Nations, 2013)

Table 6: Data used for model construction and calibration for the land use sector

Data Type	Data Period	Additional Info	Data Source
Area Harvested (Hectare)	1960-2009	Area harvested for: Groundnut, Maize. Millet, Sorghum, Rice, Vegetables, Pulses, Cassava, and Fruit	FAOSTAT (FAO, 2013)
Meadows and Pastures (Hectares)	1960-2009		FAOSTAT (FAO, 2013)
Forest Area (Hectare)	1960-2009		FAOSTAT (FAO, 2013)

Table 7: Data used for model construction and calibration for the food production sector

Data Type	Data Period	Additional Info	Data Source
Yields (Hectare)	1960-2009	For: Groundnut, Maize. Millet, Sorghum, Rice, Vegetables, Pulses, Cassava, and Fruit	FAOSTAT (FAO, 2013)
Production (Tons)	1960-2009	For: Groundnut, Maize. Millet,	FAOSTAT (FAO, 2013)

		Sorghum, Rice, Vegetables, Pulses, Cassava, and Fruit	
Food (Tons)	1960-2009	For: Groundnut, Maize. Millet, Sorghum, Rice, Vegetables, Pulses, Cassava, and Fruit	FAOSTAT (FAO, 2013)
Food Energy (Kcal)	1960-2009	For: Groundnut, Maize. Millet, Sorghum, Rice, Vegetables, Pulses, Cassava, and Fruit	FAOSTAT (FAO, 2013)

Table 8: Data used for model construction and calibration for the water resources sector

Data Type	**Period**	**Additional Info**	**Data Source**
River Flow (m^3/s)	1976-1979		(Lesack, et al., 1984) (Njie, 2010)
Aquifer Capacity (0.1)	N/A	Estimation	(Njie, 2009) .
Surface Water Withdrawals	2005	Estimation	AQUASTAT (FAO, 2005)
Groundwater Withdrawals	2005	Estimation	AQUASTAT (FAO, 2005)

Curriculum Vitae

Name:	Jordan Atherton
Post-secondary Education and Degrees:	University of Western Ontario London, Ontario, Canada 2003-2008 B.E.Sc
Related Work Experience	Teaching Assistant The University of Western Ontario 2010-2012