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Essays in Applied Public Economics Using Computable General Equilibrium Models

by

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To my parents, who have motivated my curiosity

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Declaration

I declare that the thesis is my own work and has not been submitted for a degree at another university.

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Abstract

This thesis analyses two issues in public economics: (1) water allocation in Israel; and (2) malaria prevention in Ghana. In both cases a computable general equilibrium modelling approach has been applied for policy analysis.

Part I: In Israel, parliamentary investigative committees and water researchers have concluded that for decades, the administrative water allocation mechanism has mismanaged water allocation. Over subsidising of the agricultural sector, and underfunding of desalination plants, had led to a severe hydrological deficit. Critics argue that a water market allocation could solve these issues. However, the administrative allocation is crucial because it protects social value, which is not represented in a market mechanism. Part I of the thesis compares these two alternative allocation mechanisms using a general equilibrium model, for the case of Israel. The model concludes that from 1995 to 2006, the upper-bound water misallocation in Israel was relatively small, on the average of 5.5% of the potable water supply. The lower-bound value of agricultural amenities is imputed at approximately 2.3 times agricultural economic output. At the margin, introducing a water market in Israel is not recommended, *i.e.*, net-social welfare would fall.

Part II: Research that links between malaria and economic growth have, so far, used econometric approaches. These provide results that are too broad, and not particularly useful for policy analysis. We, therefore, develop a multi-region multi-household dynamic computable general equilibrium (DCGE) model, which is calibrated to Ghana as a case study. Households are disaggregated by five epidemiological malaria regions, urban-rural divide, and income level quintiles. The model links with malaria through regional demographic effects, and labour effectiveness indices. Hypothetical interventions simulate reducing malaria prevalence by 50%, for children under-five years with varying degrees of coverage. We find that even under this limited intervention, malaria prevention clearly adds to economic growth and reduces income inequality. Our approach is particularly useful for policy makers to compare alternative intervention strategies using cost-benefit methods, which are not commonly used in health policy.

Abbreviations

< 5 - Under five years old

CBS - Central Bureau of Statistics in Israel

CES - Constant Elasticity of Substitution

CET - Constant Elasticity of Transformation

CGE - Computable General Equilibrium

DCGE - Dynamic Computable General Equilibrium

GDHS - Ghana Demographic and Health Surveys

GHS - Ghana Health Service

GSK - GlaxoSmithKline

GSS - Ghana Statistical Services

IBT - Increasing Block Tariff

IFPRI - International Food Policy Research Institute

MCM - Million Cubic Meters

MVW - Marginal Value of Water

NIS - New Israeli Shekels

ROW - Rest of the World

SAM - Social Accounting Matrix

SOE - Small Open Economy

TFR - Total Fertility Rate

WHO - World Health Organization

Chapter 1

Introduction

This PhD thesis examines two separate themes within applied public economics. Part I discusses *water allocation* and compares the benefits of an administrative water allocation mechanism in Israel, to a market mechanism. Part II deals with the issue of *malaria prevention* and assesses the economic impact of malaria prevention on the economy in Ghana. In both, computable general equilibrium (CGE) modelling is used to analyse and discuss the implications of alternative policies.

Policy analysis is a process by which researchers analyse the various components relating to a specific issue, define appropriate goals, propose alternative policies, and examine their interactions and results. Models are used when it is infeasible to experiment on real economies, for example because of size limitations, the issue at hand, or the time frame. There are, however, several modelling techniques to choose from, and as Box and Draper (1987) famously wrote: "*...all models are wrong, but some are useful.*" This thesis employs applied CGE modelling, which is a useful simulation laboratory for quantitatively assessing the effects of external shocks and/or policies on the economy.

As discussed by Dervis et al. (1982); Shoven and Whalley (1992); Mas-Colell et al. (1995); Lofgren et al. (2002) and many others, in its core, general equilibrium models view the many markets of goods and inputs as an interrelated system, whereby values at equilibrium for all variables are simultaneously determined. Consumers maximize utility subject to their budget constraint, forming the demand-side of the model, while producers maximize profits, forming the production-side of the economy. In equilibrium, prices adjust so that equilibrium must hold, and demand equals supply. In cases with constant returns to scale (CRS), zero profit conditions are satisfied for each industry.

Furthermore, general equilibrium is based on the Arrow-Debreu theorem that provides a proof of a given equilibria (Arrow and Debreu, 1954). This fixed point theorem is essential for policy issues because before attempting to compute the equilibrium of the model, and compare it to counter-factual scenarios, it is necessary to first believe that equilibrium exists.

Applied CGE modelling is now a standard tool of empirical analysis. It is predominantly used for analysing policy issues, such as income distribution, trade policy, environment, structural adjustments to external shocks, growth and structural changes, government tax (subsidy) policy, etc.

The two themes discussed in this thesis focus on environmental issues and external shocks to labour resources. To analyse such themes, other modelling approaches, such as partial equilibrium, may in principle be sufficient. However, partial equilibrium only examines the direct effect of a limited component while keeping all other effects fixed. If we believe that the endogenous inter-linkages between the various markets is an important element in the analysis, and that the indirect effects are sizeable, then general equilibrium methods are needed. Furthermore, alternative policy scenarios cannot be similarly assessed using partial equilibrium techniques.

CGE models most often simulate comparative static results, an approach used in the water allocation model in Part I of this thesis. In the last decade, it has, however, become increasingly popular to incorporate dynamic elements using either a *forward* *looking* approach, or a *recursive* (myopic) approach. The latter is used in the malaria prevention model in Part II of the thesis.

Finally, a number of additional features can be added to CGE models, *e.g.*, varying "closure rule" assumptions, imperfect competition, imbalances, and various structural and institutional rigidities. These are all approaches that I have worked with during the PhD studies and in the development of my research. For example, the water allocation model uses a re-calibration approach to impute the value of the agricultural amenity, while the malaria prevention model started-off as a forward-looking "toy" model, and due to computational constraints, was later converted into a recursive model.

Water allocation (Part I)

Part I of the thesis, discusses water allocation and uses Israel as a case study. It is motivated both by my personal experiences as a child in Israel, and my academic interest in the allocation of limited resources. In the mid '70s through the '90s, I grew up in a small village approximately 20 kilometres south of Tel-Aviv. As a hobby, my parents have cultivated more than 70 different types of fruit trees, a vegetable patch, and small vineyard. Hundreds of acres of citrus fruits were grown around my house, and I have many fond memories of the agricultural landscape surrounding me.

Today, my "jungle" playground has, however, nearly dried-up, and is gradually being replaced by lucrative housing projects. My childhood village is steadily being absorbed by the nearest city, claiming it as one of its many neighbourhoods. With urbanization has come modern infrastructure, such as street lamps, a modern sewer system, and the city water supply. However, until 2001, water supply came from the village's own water well, and water prices were under agricultural tariffs, which were substantially lower than city water tariffs. (See Table 3.2 in Chapter 3.)

Water in semi-arid Israel, as well as in Palestine, Middle Eastern countries, and

Mediterranean countries, is a limited resource. How to allocate it efficiently, how to decide who owns the resource, and how to protect it, are all very important questions.[1] In 1959, a Water Law was enacted to control and protect Israel's water resources, and an administrative body called the *Water Authority* was empowered to allocate water. The main tool of the Water Authority is to classify water users according to different characteristics, *e.g.*, households, industrial, or agricultural users, and then assign to them different water quotas, water tariffs, and increasing block tariff structures. In order to enforce the administrative allocation, water resale is prohibited, and this further disconnects market forces from the pricing and allocation of water.

Similar to many households that were living in rural areas, but were not agrarian, my parents and our neighbours benefited from household water consumption at agricultural prices. However, the largest of such irregularities probably originated from the communally organized *kibbutzim* and *moshavim* that used a sizeable portion of agricultural water for non-farming activities and/or businesses, *e.g.*, a recreational swimming pool, or a "black" water market. With the gradual urbanization of the country, these irregularities were reduced, and tighter regulatory control of the water resource was enabled. However, it could be argued that this came at the cost of the rural environment.

The depletion of the water reserves in Israel has seriously damaged water quality. Excess pumping from water reserves over many years has caused a hydrological deficit of the most severe proportions. Every few years, when annual rainfall is very low, the Israeli Government announces a "Water Crisis." Critics (e.g., Plaut, 2000) argue that this illustrates why an administrative mechanism cannot accurately account for the true environmental value of water, and why it often misallocates water compared to a market mechanism. An administrative mechanism is politicized, subjective, and

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[1] This thesis has no intention of entering the complex political and social conflicts within the Middle East. Water ownership and allocation between Israel, Palestine, Jordan, Lebanon, and Syria, who share many of the same water resources, is an important and interesting topic in its own right.

slow to respond to weather conditions and population needs. Furthermore, the over-subsidization of agricultural water has driven farmers to increasingly grow low-revenue water-intensive crops. In some sense, it could be argued that a portion of the water resources in Israel are "exported", as embodied by farm exports.

Using a traditional CGE approach, to evaluate these arguments, would naturally favour a water market because it allows water inputs to flow to those users valuing them the most. In this thesis, however, I recognize that an administrative mechanism also promotes social goals that are not valued economically, such as green areas, food security, rural environment, and population dispersion. The main contribution in this part of the thesis is to compare two alternative allocation mechanisms in a context of erroneous policy choices. A *type I error* would be to introduce a water market, but then lose social welfare in the form of reduced agricultural amenities. A *type II error* would be *not* to introduce a water market, and therefore to inefficiently allocate water by an administrative mechanism.

Weighing the outcomes of these two errors, I find that at the margin, introducing a water market in Israel is not recommended, *i.e.*, net-social welfare would fall. In addition, infra-marginal social losses could be even larger, if other forms of amenities were to be included, *e.g.*, the loss to historical heritage, and especially the irreversible destruction of nature.

Part I of the thesis thus relates to two areas of research. It has relevance for natural resource management that aims to improve the efficient use of a scarce resource, and it has implications for political and social policy. Chapter 2 of the thesis is aimed as a future journal paper. It presents the issue, summarizes the main results, and discusses their policy implications. Chapter 3 of the thesis contextualises water policy in Israel, and documents the model developed in the previous chapter.

Malaria prevention (Part II)

Part II of the thesis focuses on malaria prevention in Ghana. This work is partially funded by GlaxoSmithKline (GSK), and is a result of a joint research effort with RAND Europe. It is motivated in spirit by the health targets of the Millennium Development Goals, mainly Goal 4, which is to reduce child mortality, and Goal 6, which is to combat HIV/AIDS, malaria and other diseases (WHO, 2005). More specifically, the aim is to assess the economic and distributional impact of malaria prevention in an endemic country.

A variety of agencies, who work either cooperatively or individually, are involved in combating malaria. These include governments of malaria-endemic countries, donor countries, international bodies, international firms, and private individuals.[2] GSK is one of the largest international pharmaceutical firms, and is directly involved in developing anti-malarial drugs and vaccines.[3]

In 2010, the economics department of GSK Vaccines decided to fund an academic research project on malaria, with the intention that it will be published in a peer reviewed journal. RAND Europe was contracted to carry out the research, and I was invited to join the team. Consequently, I took a lead role in the research: I designed and programmed the dynamic computable general equilibrium (DCGE) model (from scratch), and we shared equal burden on other aspects of the project. Due to my level of contribution, we agreed that I am the first and corresponding author on the future journal paper.

So far, research on the link between malaria and economic growth has used econometric methods. These give, however, results which are too broad and not particularly useful for policy analysis. Furthermore, critics argue that they over-state the benefits

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[2] International bodies include the World Bank, WHO, and the GAVI Alliance. A well-known individual donor is the Bill and Melinda Gates Foundation.

[3] A new malaria vaccine candidate is being developed by GSK. Results were recently published and suggest an efficacy of 55% (Agnandji et al., 2011). Malerone is a brand name anti-malarial drug, which was also developed by GSK.

of malaria reduction because they do no include general equilibrium effects, especially those of diminishing returns to effective units of labour (e.g., Acemoglu and Johnson, 2007).

Our research fills this gap, and provides a more detailed estimate of the impact of malaria at various levels, *e.g.*, household, regional, and/or age level. This is important for policy makers who must operate within a limited budget, and require information to design malaria intervention policies. On the same note, pharmaceutical firms, who are negotiating with government and donors on the provision of drugs and vaccines, have an interest in understanding market demands and communicate opinions. This approach is useful for cost-benefit methods, which are not commonly used in health policy. Finally, it has the potential to be similarly used to assess other diseases, *e.g.*, TB, HIV/AIDS, and obesity.

In the research, we simulate the impact of reducing malaria morbidity and mortality on the Ghanaian economy utilising a micro-based approach. A multi-sector, multi-agent, recursive DCGE model is developed and linked to (1) regional demographics with cohort-component projections for fertility, mortality, migration, and urbanization; and (2) labour effectiveness indices for production and productivity of parents with sick children, or adults affected by malaria during childhood. The model is calibrated to Ghana, with households disaggregated by five epidemiological malaria regions, urban-rural divide, and five income level quintiles. Hypothetical intervention scenarios simulate reducing malaria prevalence by 50% for children under-five years and with varying degrees of coverage.

The project is still on-going, and we are currently working on additional counterfactual scenarios that represent other possible health provision strategies. The final results submitted to a journal, may be slightly different from those presented here. In general, however, we find that malaria prevention clearly adds to economic growth and reduces income inequality, even under a limited intervention where only the under-five year old population is treated. In this case study of Ghana, the benefits from an intervention, per child covered, vary across regions, and generally contributes more to the high prevalence regions.

Chapter 4 of the thesis is a joint effort with Pricillia Hunt and Stijn Hoorens, and is aimed as a future journal paper. It describes the methodology by which we link malaria and economic growth, discusses policy issues, and summarizes the results of three hypothetical health intervention policies. Chapter 5 of the thesis is a detailed explanation of the DCGE model that I developed.

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Part I Water allocation

Chapter 2

Which is preferable for Israel, a market or an administrative water allocation mechanism?

2.1 Introduction

Most arid and semi-arid regions use an administrative water allocation mechanism, whereby the state monopolizes the water resource, and erects a regulatory body to administer it. The main tools used are quotas, price discrimination, and increasing block tariffs that are set and upheld by prohibiting the resale of water.[1]

Critics of this mechanism argue that allocation is subjective, politicized, and leads to inefficiencies (Dinar et al., 1997; Holden and Thobani, 1996). Much of the criticism centres on the agricultural sectors that have access to subsidized water. Farmers appear to have historical, senior rights, and are shielded by a strong lobby. Therefore, even when inefficiencies are detected, the political system finds it difficult to change antiquated allotments. The result is inefficient use of water, whereby farmers grow

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[1] For discussion on various countries, see review by OECD (2010), and by Diakité et al. (2009), Ruijs (2008), Roseta-Palma and Monteiro (2008) and Hajispyrou et al. (2002).

low-value and surplus crops, while non-agricultural water users struggle to develop expensive new supplies (Colby, 1990; Plaut, 2000). In addition, a 'black' water market may form, which further indicates that water is misallocated (Lichtman, 2009).[2]

These arguments are partly justified, but as discussed by Just et al. (1997), the goal behind an administrative allocation is to promote social objectives, such as water and food security, or equitable consumption across income groups or climate specific regions. Administrative mechanisms are also used to correct market-failures in situations of public goods, where an amenity provides non-marketed services, *e.g.*, agricultural landscape, tourism, and historical heritage. The multi-functionality of agricultural activities may produce benefits over and above the market value of agricultural production (Brunstad et al., 1999, 2005).

This chapter explores both positive and negative impacts of an administrative water allocation using Israel as a case study. The following questions are addressed: (1) Can the level of administrative misallocation be measured? (2) Who are the main inefficient water users, and how can allocation be improved? (3) What value do the amenities need to have in order to rationalize the current administrative allocation as efficient? (4) Which is preferable, a market or an administrative mechanism?

To answer these questions, an applied general equilibrium model is developed and calibrated to Israel from 1995 to 2006. In the initial case, a regulator decides on a framework in which price discrimination, quotas, and increasing block tariffs are set, and water trade is prohibited. Water users decide on the amount of water to buy within this framework.

Subsequently, in the counter-factual experiments, water trade is enabled within a *secondary* water market and prices adjust until markets clear. In the extension, the model accounts for the non-economic value of amenities, whereby the agricultural sectors internalize the benefit of producing amenities demanded by the households.

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[2] Chapter 3.1 gives a more detailed contextualised discussion of water in Israel.

If we consider the market allocation to be primarily efficient, the quantity of water traded would indicate the level of administrative misallocation. For example, a large secondary water market would indicate that the administrative mechanism is inefficient, and that a market mechanism would put water to better use. If however the social value provided by the administrative mechanism is also included, it is then possible that the benefits from a water market could be smaller than the loss incurred to social value, *i.e.*, a net-social welfare loss.

Thus, two alternative allocation mechanisms can be compared in a context of erroneous policy choices. A *type I error* would be to replace the current administrative mechanism with a market mechanism, given that the current administrative mechanism is true (the null hypothesis H_0). In this case, the loss to social welfare, in the form of agricultural amenities, is greater than the gain in efficiency from a water market. A *type II error* would be *not* to replace the administrative mechanism with a market mechanism, given that the market mechanism is the correct policy. In this case, the efficiency lost from not introducing a water market is larger than the social value preserved in the form of agricultural amenities.

At the parametrization stage of the model, the approach is to calibrate the model with (plausible) conservative parameters that would favour a market mechanism. On the one hand, the calibration would lead to the largest plausible administrative water misallocation, so that the potential size of a secondary water market is therefore a conservative *upper* bounds. This raises the *type II error*. On the other hand, the value of the agricultural amenity is aimed at being an underestimate *lower* bounds, which lowers the *type I error*.

Nevertheless, the results find that the potential size of a secondary water market (*i.e.*, the administrative misallocation) is rather small, and when the model is extended to impute agricultural amenities, the amenity value is large. In other words, it is less likely that Israel is wrongly maintaining its current administrative allocation.

The potential social loss from introducing a market mechanism might be significantly higher than the added benefits of efficient water use.

Furthermore, in the current analysis, only agricultural amenities are imputed. Therefore, had additional amenities been considered (*e.g.*, those stemming from tourism, historical heritage, irreversible destruction to nature) the infra-marginal losses from introducing a water market could be higher still.

The chapter makes the following contributions. First, it adds a new perspective to the discussion of water allocation efficiency in Israel. Contrary to most literature on Israel, the paper supports the continued use of an administrative water allocation mechanism. Second, it suggests a simple method, which can be used to evaluate and improve water allocation decisions also in other countries. Finally, the paper imputes the value of agricultural amenities in Israel, adding to the discussion by Fleischer and Tsur (2009) and Kan et al. (2009) on the economic value of agricultural amenities. Thus, the paper relates to two areas of research. It has relevance for natural resource management that aims to improve the efficient use of a scarce resource, and it has implications for political and social policy.

The chapter is structured as follows: Section 2.2 discusses how inefficient water allocation arises from an administrative mechanism and introduces a simplified theoretical model to estimate it. Section 2.3 expands to a more realistic multi-sector applied general equilibrium model for the Israeli economy. Section 2.4 discusses the empirical results. Section 2.5 extends the model to impute the value of the agricultural amenities and discusses the policy implications of the results. Finally, Section 2.6 concludes.

2.2 The water model

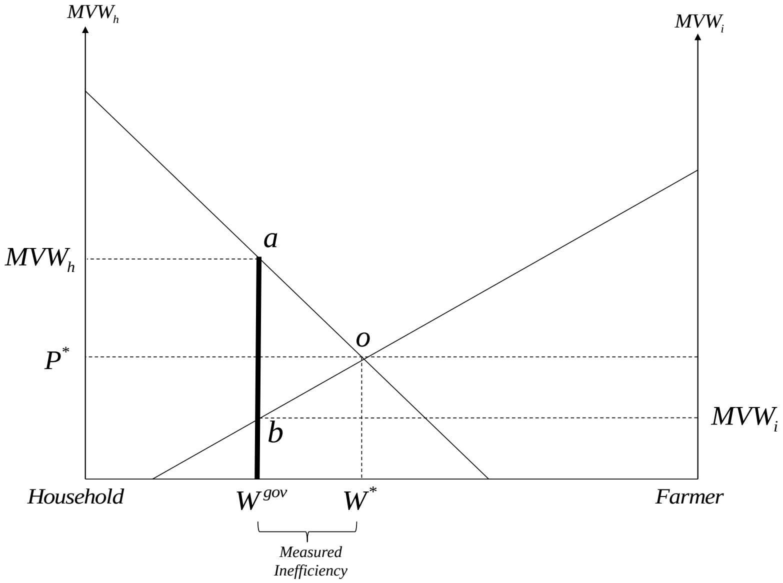
Applied general equilibrium models have been developed to analyse different issues within water management (see Dixon, 1990; Berck et al., 1991; Seung et al., 2000; Diao et al., 2008). Diao and Roe (2003) have discussed administrative water allocation in Morocco, and found that reducing protectionist agricultural policy without correcting for distortions in irrigated agriculture pricing would lead to increased inefficient water use. Creating a water market, however, could compensate for the decline in agricultural profits and raise efficiency. Gómez et al. (2004) have demonstrated that having a water market in the Balearic Islands, rather than an administrative mechanism, would lead to economic gains that in turn would allow for delays in investment in desalination plants. Becker (1995) focused on the Israeli agricultural sector. He used a linear programming model to analyse the effects of introducing a market mechanism on the shadow water prices for the various water basins, and reported the economic gains from a water market.

The common theme in the above papers, is that a market mechanism leads to economic gains. However, none of them include the social consequences of introducing a water market. In this chapter, social gains adds an additional dimension to the evaluation of the administrative mechanism.

The usual benefits of a market mechanism are illustrated in Figure 2.1. Assume a closed economy with only two water users. The total water resource is quantity $\bar{W}$, and a social planner allocates W^{gov} to the household, and $\bar{W} - W^{gov}$ to the farmer. Furthermore, water trade is prohibited. However, this allocation is clearly not optimal, because the marginal values of water are not equalized, $MVW_h > MVW_i$.

When water trade is enabled, the household benefits from buying additional units of water, while the farmer benefits from selling some of his water rights. The discrepancy between the initial administrative allocation and the market allocation is the horizontal distance $|W^{gov} - W^{*}|$, measured in cubic meters of water. In this paper,

Figure 2.1: Water quotas with two agents



Note: Total water $\bar{W}$ is allocated by the government. Household is allocated water quantity W^{gov}, while farmers are allocated $\bar{W} - W^{gov}$. Area *aob* is the dead weight loss from inefficient water allocation. The potential secondary water market is the volume $|W^{gov} - W^*|$, a proxy for inefficiency.

the quantity traded within this secondary water market is used as a proxy to indicate the level of inefficient allocation.[3]

2.2.1 A simplified trade model with water inputs

To describe the model that is used in this paper, consider a simplified closed economy. Firm $i \in N$ produces a single final good $Y_i \in y$, using a differentiable constant returns to scale production function $f_i\left(L_i, W_i\right)$ that uses labor and water inputs, respectively. Output prices and wages are $p_i, p_L \in p$, respectively.

A representative household $h \in H$ has a rational and locally non-satiated preference relation, with a continuous utility function $U\left(y\right)$. It consumes final goods Y_i, and water $W_h \in y$, and is endowed with a fixed supply of labor $\bar{L}$ and water $\bar{W}$.

The government, which is not explicitly modeled, holds the property rights of water, and assigns a different increasing block tariff (IBT) for each type of water

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[3] See further discussion in Chapter 3.3.

user, *i.e.*, firms and households pay $p_{W,i}, p_{W,h} \in p$, respectively. However, unlike in the paper by Diao and Roe (2003), water users are *not* bound by the water quota allotted to them. They can, in general, obtain as much water as they desire by paying increasingly higher prices, within the IBT framework.

Following Mathiesen (1985) and Rutherford (1995, 1999), I set up an Arrow–Debreu equilibrium as a mixed complementarity problem (MCP). A complementarity constraint enforces that two variables are complementary to each other, *i.e.*, that the following conditions hold for scalar variables x and y: $x \cdot y = 0,\ x \geq 0,\ y \geq 0$. This condition is compactly expressed as $0 \leq x \perp y \geq 0$.[4]

Given the above, $\forall i$, the firm's profit maximization problem is to choose labor and water demands, L_i and W_i, so as

$$\underset{L_i, W_i \geq 0}{\text{Max}}\, \pi_i\left(L_i, W_i\right) = p_i f_i\left(L_i, W_i\right) - p_L L_i - p_{W,i} W_i \tag{2.1}$$

The disposable income a household is $M = p_L \bar{L} + p_{W,h} \bar{W}_h + \sum_i^N p_{W,i} \bar{W}_i$, which includes income from wages, and water charge fees that are collected by the water authority and transferred to the household. $\bar{W}_i$ and $\bar{W}_h$ denote the administrative water allocation.[5]

The household's utility maximization problem is to choose consumption of goods and water, Y_i and W_h, so as to

$$\underset{Y_i, W_h \geq 0}{\text{Max}}\, U\left(Y_i, \cdots, Y_N, W_h\right) \qquad \text{s.t. } M \geq \sum_i^N p_i Y_i + p_{W,h} W_h \tag{2.2}$$

Focusing on water, the first order conditions must be satisfied so that the marginal

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[4] Intuitively, a complementarity constraint is a way to model a constraint that is combinatorial in nature since, for example, the complementary conditions imply that either x or y must be 0 (both may be 0 as well).

[5] Note that in the initial administrative allocation, $W_h = \bar{W}_h$, and could be netted out from both the household's income equation and utility maximization problem. However, they are intentionally there for clarity because when water trade is enabled, it is possible that $W_h \neq \bar{W}_h$.

value of water (MVW) equals the real water price.

$$MVW_i = \frac{\partial f_i(\cdot)}{\partial W_i} \leq \frac{p_{W,i}}{p_i} \quad \perp \quad W_i \geq 0, \qquad \forall i \tag{2.3}$$

$$MVW_h = \frac{\partial U(\cdot)}{\partial W_h} \leq \frac{p_{W,h}}{p_U} \quad \perp \quad W_h \geq 0 \tag{2.4}$$

There are three types of weak inequality conditions that must be satisfied in this general equilibrium model: (i) zero profit, (ii) market clearance, and (iii) income balance, each associated with three non-negative variables, *i.e.*, $y^* \geq 0$, $p^* \geq 0$ and $M^* \geq 0$, respectively.

I define the unit cost function as $c_i = C_i(p_L, p_{W,i}, Y_i = 1)$, and the unit expenditure function of the household as $e = E(p_i, p_{W,h}, U = 1)$. Finally, using Shephard's lemma, the demands for inputs by the producers, and demand for final goods and water by the household are summarised by the following weak inequalities, $\forall i$:

Zero profit conditions:

$$0 \leq c_i - p_i \quad \perp \quad Y_i \geq 0 \tag{2.5}$$

$$0 \leq e - p_U \quad \perp \quad U \geq 0 \tag{2.6}$$

Market clearing conditions:

$$0 \leq Y_i - \frac{\partial e}{\partial p_i} \cdot U \quad \perp \quad p_i \geq 0 \tag{2.7}$$

$$0 \leq \bar{W}_h - \frac{\partial e}{\partial p_{W,h}} \cdot U \quad \perp \quad p_{W,h} \geq 0 \tag{2.8}$$

$$0 \leq U - \frac{M}{p_U} \quad \perp \quad p_U \geq 0 \tag{2.9}$$

$$0 \leq \bar{L} - \sum_{i=1}^{N} \frac{\partial c_i}{\partial p_L} \cdot Y_i \quad \perp \quad p_L \geq 0 \tag{2.10}$$

$$0 \leq \bar{W}_i - \frac{\partial c_i}{\partial p_{W,i}} \cdot Y_i \quad \perp \quad p_{W,i} \geq 0 \tag{2.11}$$

Income balance:

$$M = p_L \bar{L} + p_{W,h} \bar{W}_h + \sum_{i=1}^{N} p_{W,i} \bar{W}_i \quad \perp \quad M \geq 0 \tag{2.12}$$

where price vector p^* and activity levels y^* constitute a *competitive equilibrium.*

2.2.2 Secondary water market

As described in Figure 2.1 and Equations (2.3) and (2.4), assume that at the initial administrative allocation with restricted water trade, $\frac{p_{W,i}}{p_i} = MVW_i < MVW_h = \frac{p_{W,h}}{p_U}$, *i.e.*, the household has a higher marginal value of water than firm i. When water trade is allowed, the household would prefer to buy water from firm i (and the firm prefers to sell), up to a point where $MVW_i = MVW_h$.

More generally, water users can be *buyers* or *sellers*, and having $M = N + H$ water users leads to M^2 trade configurations,[6] with ψ_{mn} being the *relative* marginal value. If user $m \in M$ is a buyer, and user $n \in M$ is a seller, a possible trade channel is when $\frac{MVW_m}{MVW_n} = \psi_{mn} > 1$; otherwise, it cannot be a possible trade channel. This is summarise by

$$\frac{MVW_m}{MVW_n} = \begin{cases} \psi_{mn} > 1 & \text{possible trade channel} \\ \\ \psi_{mn} \leq 1 & \text{not possible} \end{cases} \tag{2.13}$$

These conditions, therefore, limit the number of configurations to only $T = \frac{M(M-1)}{2}$ possible trade channels, with $t \in T$ being one specific channel. (Section 2.3.4 discusses how the marginal values of water are estimated, and Table 2.3 provides a concrete example for Israel.)

Thus, when water trade is enabled, the units of water, γ_t, that are transferred between seller n and buyer m are measured by

$$0 \leq \gamma_t \perp p_{W,n,t} - (1 - \epsilon)\, p_{W,m,t} \geq 0, \qquad \forall t \tag{2.14}$$

with $p_{W,n,t}$ and $p_{W,m,t}$ being the water market prices for the seller and buyer, respectively. For computational purposes, $\epsilon \to 0$ is a small number to *'help'* the solver with slack activities, thus avoiding the problem of infinite solutions, *i.e.,* a degenerate

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[6] N firms and H households.

model.[7]

There are various combinations (scenarios) of activating and deactivating water trade channels, *e.g.*, activating each channel separately, or all together. Therefore, each of the $t \in T$ channels has a binary action (designed by the scenario); active or not-active, $\{\mathcal{A}, \mathcal{NA}\} \in Action$. There are $\{t_{\mathcal{A}}, t_{\mathcal{NA}}\} \in T$ channels, $\{i_{\mathcal{A}}, i_{\mathcal{NA}}\} \in N$ firms, and $\{h_{\mathcal{A}}, h_{\mathcal{NA}}\} \in H$ households, that are active or not-active, respectively.[8]

Finally, for a set of actions, the market clearing conditions (2.8) and (2.11) are replaced with

$$0 \leq \bar{W}_{\mathcal{A}} - \frac{\partial e_{\mathcal{A}}}{\partial p_{W,h_{\mathcal{A}}}} \cdot U_{\mathcal{A}} + \sum_{i_{\mathcal{A}}} \frac{\partial c_{i_{\mathcal{A}}}}{\partial p_{w,i_{\mathcal{A}}}} \cdot Y_{i_{\mathcal{A}}} \quad \perp \quad p_W = p_{W,h_{\mathcal{A}}} = p_{W,i_{\mathcal{A}}} \geq 0 \quad (2.15)$$

$$0 \leq \bar{W}_{i_{\mathcal{NA}}} - \frac{\partial c_{i_{\mathcal{NA}}}}{\partial p_{W,i_{\mathcal{NA}}}} \cdot Y_{i_{\mathcal{NA}}} \quad \perp \quad p_{W,i_{\mathcal{NA}}} \geq 0 \quad (2.16)$$

$$0 \leq \bar{W}_{h_{\mathcal{NA}}} - \frac{\partial e_{\mathcal{NA}}}{\partial p_{W,h_{\mathcal{NA}}}} \cdot U_{\mathcal{NA}} \quad \perp \quad p_{W,h_{\mathcal{NA}}} \geq 0 \quad (2.17)$$

Equation (2.15) states that the supply of traded water, $\bar{W}_{\mathcal{A}}$, will equal the demand for traded water, provided that water prices equalize within the secondary water market. Equations (2.16) and (2.17) reflect cases in which some water users are prohibited from trade, and have user-specific water prices and quotas.[9]

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[7] To insures that when multiple t channels are opened (active), only *net transfers* of water is considered. For example, a case of infinite solutions is when a first user sells to the second, the second sells to the third, but the first also sells to the third. By adding ϵ, the solution is limited to one (possible) case where, for example, the first sells to the second and to the third, while deactivating the second selling to the third.

[8] In other words, a water user will *not* trade because it is either his own choice or it is *blocked*.

[9] Here, there is only *one* representative household. Equation (2.17) is a case where the household is blocked from trading, and therefore $\frac{\partial e_{\mathcal{A}}}{\partial p_{W,h_{\mathcal{A}}}} \cdot U_{\mathcal{A}} = 0$ in Equation (2.15). Extending the analysis to multiple-households is a simple matter, *e.g.*, updating Equations (2.2) and (2.12), but requires further assumptions regarding water ownership in the applied model. Adding the government explicitly, would probably be required.

2.3 The applied general equilibrium model and the data

In order to adequately represent the actual empirical Israeli economy, the general equilibrium model that was discussed in the previous section is extended. The following will describe the main features of the applied model and of the data used. The full analytical model is discussed in more detail in Section 3.4.[10]

Table 2.1 presents key water figures for 2006. Roughly 68% of the total supply of water in Israel is potable water, of which there are four main users. Approximately 39% of potable water is consumed by the agricultural sector, 6% by the manufacturing sector, 16% by the service sector, and 39% by private households.[11]

The use of non-potable water, *i.e.*, salinized, contaminated, sewage effluents, flood, brackish water, etc., has increased in the past two decades, due to growing pressures on the supply of water, and improvements in technology and infrastructure. Approximately 95% of it is used by the agricultural sector, and the rest by the manufacturing sector.

The applied small open economy is aggregated into three main production sectors: agricultural, manufacturing, and services, and one representative household. The government is not explicitly modeled, but its actions are manifested through the initial water allocation, i.e., quota and increasing block tariff (IBT) assignments to water users.

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[10] The model is programmed and simulated in GAMS using Rutherford (1999)'s MPSGE.

[11] Water consumption by private households and service sectors is regarded as residential water consumption. Yearly data is reported by the *Israeli Water and Sewage Authority* by eleven subgroups. Approximately 55% of total potable water is consumed by residential users, of which 71% are private homes, and the rest are service sector, *i.e.,* commercial and public office buildings, swimming pools, gardens, etc.

Table 2.1: Key water figures in Israel (2006)

	Potable Water				Non-Potable Water		
User	**Mil. Cubic Meters**[a]	**% of Total**	**Expenditure (mil. NIS)**[b]	**Marginal Value Water**[c]	**Mil. Cubic Meters**[a]	**% of Total**	**Expenditure (mil. NIS)**[b]
Agriculture	519	39	768	1.48	589	95	474
Manufacturing	84	6	209	2.49	30	5	24
Services	213	16	833	5.15			
Household	524	39	1,889	4.85			
Total	**1,341**	**100%**			**619**	**100%**	
% Total Water	**68%**				**32%**		

Source: **a** The Water and Sewage Authority, Israel. **b** Own Calculation: water quantity times relevant price band. c From the Water Authority 2006 price plan, with assumptions discussed in Section 2.3.4.

2.3.1 Production

Each of the three production sectors uses the following five inputs: labor, capital, intermediate goods, potable water, and non-potable water.[12] The production function is setup as a four-level nested constant elasticity of substitution (CES) structure, which simplifies the calibration procedure and captures the different substitution elasticities for pairs of inputs. Some of the main assumptions are the following:

First, the model is calibrated for a short-to-medium time horizon, which affects the assumptions that are made on factor mobility. Within a time frame of three to four years, land inputs are relatively rigid because of soil type, location, infrastructure, and legislative constraints (Hertel, 2002). Here, because capital includes land, capital is also highly rigid, and is assigned as a sector specific input. This is especially true for the agricultural sector.

Second, in order to capture the user specific characteristics of water, sector specific output-supply-price elasticities and water-demand-price elasticities are used to calibrate for the unknown substitution elasticities. These are summarized in Table 2.2, which are the mid-values from empirical papers. The agricultural sector has

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[12] Service sectors have *zero* expenditure on non-potable water.

Table 2.2: Output-supply-price and demand-price elasticities

	Output Supply Elasticity[a]	**Water Demand Elasticity**[a]	**Potable/Non-Potable Substitution**[b]
Agricultural	0.8	-0.7	1.1
Manufacturing	3.0	-0.7	1.1
Services	3.0	-0.1	
Household		-0.1	

Source: [a] Approximate mid-values reported in various papers. [b] Israel Water Authority

Note: The above values, together with the cost share from the social accounting matrix, calibrate the input substitution elasticities for households and sectors. (See Section 3.4.)

a relatively inelastic supply price elasticity of 0.8, partly due to high land rigidity. Non-agricultural sectors have an elastic supply price elasticity of 3.0. Furthermore, both the agricultural and manufacturing sector have a water demand price elasticity of -0.7, while the residential water demand price elasticity is -0.1, i.e., service sectors and households.[13] As in many applied models, intermediate inputs are assumed to enter in fixed proportions (Leontief technology). Finally, the substitution elasticity between potable and non-potable water is assumed to be 1.1.[14]

Third, labor inputs freely migrate between the various sectors, and have a global wage level, p_L. Finally, in the benchmark, water inputs are allotted to users and are non-tradable, and water prices, $p_{W,i}$, are sector specific. As discussed in Section 2.2.2, when water-trade is allowed, water is reassigned as a global input, and trade occurs until the market clears. Water prices change sufficiently to drive water marginal values to equalize between users.

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[13] Sections 3.5 and 3.6 provide a detailed description of the empirical literature and assumptions behind these values, and explain the calibration method from the known elasticities and cost share to the unknown substitution elasticities within the production and utility functions.

[14] Water Authority assumes a substitution ranging from 1 to 1.2 between potable and non-potable water for agricultural use, depending on the water quality of non-potable water.

2.3.2 Household

The small open economy has one representative household that is endowed with labor, capital, and water resources, $\bar{L}$, $\bar{K}$, $\bar{W}$, respectively. Tax revenues are transferred to the household, including positive (negative) transfers of income to cover balance of payments, *bop*. Income is

$$M = P_{W,h}\bar{W}_h + \sum_{i=1}^{n}\Big(P_L\bar{L}_i + P_{K,i}\bar{K}_i + P_{W,p,i}\bar{W}_{p,i} + P_{W,np,i}\bar{W}_{np,i} + \tau_i + bop_i\Big) \tag{2.18}$$

and utility is derived by consuming potable water and final goods, using a two-level nest CES-Cobb Douglas function. Table 2.2 reports that the residential water demand price elasticity is -0.1, which I use to calibrate the unknown substitution elasticity between the demand for water and a bundle of final consumption goods.

2.3.3 General assumptions in the model

Two assumptions are made in the model. First, in order to properly compare the welfare effects between the benchmark and the counter-factual scenarios, and because this is a static model, the balance of payments (BOP) is fixed to the year specific levels. Otherwise, it would not make sense to allow for policy experiments to increase the trade deficit and thus increase welfare, at the expense of foreign borrowing. Such a situation would be misleading because in a fully dynamic model, borrowing will have to be paid back at some point.[15]

Second, having increasing block water tariffs usually means that higher block tariff users subsidize lower block tariff users. Here, however, the model is simplified by aggregating many different users to only four main groups, each having one water price. Disaggregating users into further subgroups is possible, but would require a more detailed social accounting matrix. In this model it is therefore assumed that all

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[15] Practically, to fix the BOP to its benchmark level, household is endowed with a *fixed* amount of bop_i for each type of good $i \in N$.

users within a group have the same size and preferences, or that they have already traded water internally between themselves.

2.3.4 Data and marginal value of water

The data used in the model is obtained from the *Use-Supply* tables published by the Israeli Central Bureau of Statistics (CBS) for 1995, 2000, 2004, 2005 and 2006. (Similar data for 2007 is not yet available.) The data include sector outputs and inputs, household consumption and trade balance, as well as levels of taxes and subsidies. From these, social accounting matrices (SAM) are constructed and used to calibrate the model (Round, 2003). Labour inputs are obtained from the Compensation of Employees by Industry tables from the Israeli CBS.

The Water Authority assigns increasing block tariff (IBT), whereby consumers pay progressively higher water prices for each increasing quantity of water consumed.[16] Each main user, *i.e.*, agricultural, manufacturing, services, and households, has a different IBT structure.[17]

CBS does not report the water sector separately from the electricity sector, and does not distinguish between potable and non-potable water. Therefore, the expenditure on water has to be estimated by other means, rather than directly from the Use-Supply tables. Residential water expenditure, *i.e.*, household and service sectors, are estimated by summing the total water quantity times the relevant tariff band for each type of residential user.[18] Agricultural water expenditure is obtained by multiplying the quantity of total potable water supply by tariff block A. This method is similarly used to estimate the expenditure on potable water for manufacturing, and expenditure on non-potable water, which each have one main water price band.

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[16] But not necessarily higher, *e.g.*, manufacturing has a lower price for water use above the 100% quota.

[17] Data obtained from the Water Authority and summarized in Section 3.7.2 of Chapter 3.

[18] Detailed data on eleven residential sub-groups is reported by the Water Authority, *Residential Water Consumption* (an annual publication in Hebrew).

Water users can obtain as much, or as little, water as they are willing to pay-for. This means that their marginal value of water (MVW) is equal, or somewhere below the next tariff block, of the last unit of water. Table 2.1 summarizes the total monetary expenditure on water, and the estimated marginal value for 2006. Recall that conservative values are preferred, and that this would increase water trade, *e.g.*, by lowering the MVW for farmers and increasing it for households. The following are the underlying assumptions for the marginal value of water:

Agricultural water quotas were revised in 1989 and the following tariff blocks were introduced. Tariff A is charged up-to 50% of the quota, tariff B between 50-80%, and tariff C between 80%-100%. There are two further bands above 100% with lower prices.[19] Since 1989, extensive cuts in potable water quotas have been made, and most of agricultural users pay tariff A, which is thus assigned as their marginal value for water.[20]

Manufacturing sectors have one main tariff up to 100% of the quota, and this is assigned as the marginal value of water.[21]

Different service sectors are assigned different tariffs. For example, hospitals and *mikves*[22] fall under tariff A. Hotels fall under tariff B, while the rest of the service sectors (*e.g.,* commerce, education, sport, public) fall under tariff C. Public gardens are charged tariff D. In the model, tariff C is used as the marginal value of water for service sectors, because it captures 62% of the water used. Public gardens consume around 25% of water in the service sector, but they do not account for GDP.

Finally, the household price scheme for 2006 includes four tariff blocks. Tariff B captures around 61% of the total consumed water by households, and is therefore

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[19] The two further blocks are: (1) up-to 10% above the quota, and (2) above 10% above the quota. See Section 3.7.2 of Chapter 3 for further detail.

[20] From a discussion with the Water Authority. Agricultural water consumption is not published, as it is done with residential consumption. Furthermore, the secondary water market would be smaller if tariff B would have been chosen. When in doubt, the larger, more conservative, secondary water market is preferred.

[21] There is also a lower water price above 100% of the quota. See Table 3.2 for further details.

[22] Jewish ritual bath.

Table 2.3: Water trade channels: relative MVW for 2006

		Buyer $m \in M$			
		Agricultural	Manufacturing	Services	Household
Seller $n \in M$	Agricultural	1	**1.684**	**3.484**	**3.283**
	Manufacturing	0.594	1	**2.069**	**1.949**
	Service	0.287	0.483	1	0.942
	Household	0.305	0.513	**1.061**	1

Note: These are the ratio of seller/buyer water marginal value. Divide values from the fifth column in Table 2.1 and numbers in bold are the possible water trade channels.

chosen as their estimated marginal value of water.[23]

Table 2.3 is an applied example of the discussion in Section 2.2.2. It shows that having four main water users in Israel leads to sixteen water trade configurations. In order to obtain the *relative* marginal value of water (MVW) for a buyer/seller ψ_{mn}, as in Equation (2.13), divide the marginal values of water for each pair of users reported in Table 2.1. Values greater than one indicate which water trade channels are possible, and who would be the sellers and buyers. The six possible channels are marked in bold in Table 2.3. The service sector, for example, values water by approximately 3.484 times that of the agricultural sector, and therefore, would buy from the agricultural sector (not sell).

2.4 Measuring the efficiency of an administrative water allocation

In this section of the applied model, water is initially allotted administratively to each of the four users, and water trade is forbidden. Then, in the counter-factual experiments, trade is allowed and water inputs are re-shuffled until all users have the same marginal value of water.

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[23] In 1997, band B captured 70% of the total household water. Source: Israeli Water Authority, *Residential Water Consumption* (in Hebrew). In 2010, the price bands were changed. However, since the model's data covers until 2006, the effects of this new price band is left for future research.

Compared to a market allocation, a certain degree of administrative misallocation is expected. The question is, therefore, how large is the potential secondary water market likely to be? A large misallocation could indicate a poor administrative mechanism. It would suggest that a market mechanism may be superior, and that the government is committing a *type II error* by maintaining the current administrative allocation and *not* introducing a water market.

If, however, the misallocation is rather small, it is unclear which mechanism is better. Section 2.5, therefore, extends the model and includes the non-marketed social value. Together, this section and the next contribute to a better assessment of the most preferable mechanism for Israel.

2.4.1 Results for 2006

The main results, which are: the size of the secondary potable water market, the welfare gains, and their effect on the nominal water price, are reported in Table 2.4.

The most important outcome is the all-channel-trade scenario, in which the secondary potable water market is estimated at 80.8 million cubic meters (MCM). This is approximately 6.0% of the total potable water consumption in Israel in 2006. The agricultural sector sells 22.5 MCM of potable water to the manufacturing sector, 17.9 MCM to the service sector, and 40.3 MCM to households.

Because the Water Authority practices price discrimination, the secondary water market clears when nominal water prices rise (or fall) sufficiently to allow the marginal value of water to equalize for all users (reported in the right hand side of Table 2.4). In the all-trade scenario, the agricultural water price rises by 22.6%, and falls for manufacturing, services, and households by 27.2%, 64.8%, and 62.7%, respectively. This means that in 2006, the market clearing nominal water price (shadow price) would have been NIS/MC 1.81.

Being a general equilibrium model, water trade also affects other variables in

Table 2.4: Model results (2006, % change)

			% of	**Welfare**	**% Change in water prices**				
		Water*	**total**	**gains**	**Potable water**				**Non-potable**
	Channel (seller to buyer)	**MCM**	**potable**	**NIS mill.**	**Agri**	**Indus**	**Serv**	**House**	**water**
1.	Agriculture to Manufacturing	32.7	2.4	21.5	8.0	-35.9			1.1
2.	Agriculture to Services	20.7	1.5	24.9	5.0		-69.8		1.2
3.	Agriculture to Household	44.5	3.3	51.0	11.5			-66.0	2.6
4.	Manufacturing to Services	9.5	0.7	5.7		17.5	-43.2		0.3
5.	Manufacturing to Household	15.5	1.2	8.2		31.9		-32.3	0.6
6.	Household to Services	0.7	0.1	0.1			-4.1	1.8	0.0
	All Channel Trade	**80.8**	**6.0**	**86.3**	**22.6**	**-27.2**	**-64.8**	**-62.7**	**4.4**
	(of which)								
	Manufacturing buys	22.5	1.7						
	Services buys	17.9	1.3						
	Household buys	40.3	3.0						
	Shadow Water Price (All Channel)				**NIS/CM 1.81**				

*Total potable consumed, in 2006, was 1340.5 Million Cubic Meters (MCM).

Note: Model's results for 2006 data. The second column is the quantity of water traded within each channel of the secondary water market. The third column is the percent of water traded of the total potable water supply in that year. The fourth column are the welfare gains in New Israeli Shekels (NIS) Million. The right hand section is percent change of nominal water price from the initial allocation.

the economy such as production levels, sector specific return to capital, wage level and welfare. Table 2.5 reports the most important of them. These changes might seem small, but are a result of potable water inputs being only 2% of total input cost in the agricultural sector, and less than 0.1% for manufacturing and service sectors. Household expenditure on potable water is only 0.2% of disposable income.[24] Therefore, the household utility level (welfare) rises by only 0.01%. This is, however, equivalent to a 2.3% increase in economic value relative to the size of the water sector, and approximately 86.3 Million New Israeli Shekels (NIS) in 2006 prices (see fourth column in Table 2.4). The intuition behind these results is that by allowing for water trade, water inputs are put to better use, and the production possibility frontier of

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[24] CBS Israel reports that household water consumption is approximately 1% of disposable income. This, however, includes all elements of water such as sewage cost, recycling, etc. In this model, these additional costs are attributed to capital inputs rather than water, because they are not directly related to water trade.

Table 2.5: Other key results (2006, % change)

	Agriculture			Manufacturing		
Channel	**Prod.**	**Price**	**Return on Capital**	**Prod.**	**Price**	**Return on Capital**
3. Agr sell to Hh	-0.2	0.4	0.13	-0.024	0.14	0.13
All Trade	**-0.4**	**0.7**	**0.13**	**-0.04**	**0.15**	**0.14**

	Services			Other Variables		
	Prod.	**Price**	**Return on Capital**	**Wage**	**Water Sector GDP**	**Price Non-Potable**
3. Agr sell to Hh	-0.01	0.13	0.13	0.13	1.4	2.6
All Trade	**0.02**	**0.10**	**0.13**	**0.27**	**2.3**	**4.4**

Note: Model output for 2006 - continued from Table 2.4. Values are percent change from the initial allocation.

the economy moves outwards.

To better understand the mechanism within this general equilibrium model, it is useful to focus, for example, on channel 3 in Table 2.4 and Table 2.5, where the agricultural sector sells *only* to households. In this channel, which has the largest impact on water trade, the size of the water transfer is around 44.5 MCM. Relative to the initial administrative prices, market water prices rise by 11.5% for the agricultural sector, and fall by 66% for households (see Table 2.4 channel 3).

As Table 2.5 reports, agricultural output falls by 0.2%, which raises the agricultural price by 0.4% and raises agricultural return on capital by 0.13%. As mentioned earlier, capital is a sector specific input, and will not have a direct effect on the rest of the economy. However, when water inputs are transferred to households, this raises demand for labour within the agricultural sector, and leads to a wage increase across the whole economy. Indirectly, this raises the cost of production in the other two sectors, even though they are not involved in the water market. Production levels, therefore, fall in the manufacturing and service sectors, and output prices rise.

Table 2.6: Values used for sensitivity analysis, 2006

	Output Supply Elast.			**Water Demand Elast.**		
Sector	**Min**	**Model**	**Max**	**Min**	**Model**	**Max**
Agriculture	0.4	**0.8**	1.2	-0.1	**-0.7**	-2
Manufacturing	1	**3**	5	-0.1	**-0.7**	-2
Services	1	**3**	5	-0.01	**-0.1**	-1
Household				-0.01	**-0.1**	-1

Note: Max. and min. range for supply-price and demand-price elasticities. Bold numbers are the benchmark values.

2.4.2 Sensitivity analysis

Sensitivity analysis was performed on each sector using minimum and maximum parameters for the various output supply elasticities, and water demand elasticities (summarized in Table 2.6). These parameters are well above and below the accepted values that are reported and used in other studies. The results suggest that the model is well-behaved, and that the main results are robust.

Output supply price elasticity has a negligible effect on the size of the water market because, as previously mentioned, water accounts for a very small fraction of the input cost in production. Furthermore, capital is a sector specific input, which dampens the effect of parameter changes. Experimenting also with capital as a fully tradable input does not change the size of the secondary water market by any measure worth reporting.

A larger effect on the secondary water market comes from changing the water demand elasticities. Using unlikely, extreme, values for both agriculture and manufacturing sectors, the potential secondary water market reaches a range of 3.6% to 7.8% of the total potable water supplied. Yet, the outcomes are not significantly different from the main result of 6%. Changing the water demand elasticities for residential users, *i.e.*, service sectors and households, by an unlikely order of magnitude of 10, changes the range from 4% to 18% of total potable water. Again, these are unlikely elasticities, but do not change the overall message described previously.

Finally, stretching the water demand elasticities so that the agricultural and manufacturing sector are -1, and the service sector and households are -0.4, would increase the secondary water market to 198 MCM, which is 14.8% of total potable water supply.

The model is also tested with different marginal values of water. Because the agricultural sector is the main seller of water, raising its water marginal value to the next price block, decreases the water market to 4.8% of total potable supply, and the nominal water shadow price rises to 2.05 NIS/CM. This outcome is not surprising, since the seller will sell less when his marginal value of water rises.[25]

Increasing the marginal value of water for the buyers, such as households and the service sector, either separately or jointly, will also not change the overall result but rather reallocate water differently between them. This is because at the top tariff blocks, both users have the same prices. Furthermore, the marginal value chosen for residential water users are already on the high-side, because the water price paid at the 'city gates' are lower than the actual price paid by final users. Thus, reducing their marginal value of water would have only reduced the secondary water markets.

In conclusion, besides confirming the validity of the model, the sensitivity analysis provides another important message. It shows that even when the deep parameters are somewhat imprecise, the size of the secondary water market is in the vicinity of 6% of the total potable water supplied (80 MCM in 2006). This is a rather small misallocation, and its significance will be discussed shortly. Furthermore, the results are mostly sensitive to the choice of the marginal values of water, which are harder to estimate. In this model, however, the idea was to capture the largest size of inefficiency possible, under plausible assumptions. Thus, increasing the marginal value of water for the agricultural sector (the seller) or lowering it for residential use (the buyer) would only reduce the misallocation.

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[25] Since manufacturing has one price block, no sensitivity test was conducted on its marginal value of water.

Table 2.7: Secondary water markets for 1995-2006

	Potable Water (Million Cubic Meters, MCM)			**Non-Potable (MCM)**	
Year	**Total**	**2nd Water Market**	**% of Total**	**Total**	**Nominal Price Change (%)**
1995	1574.7	**79.2**	**5.0**	406.5	3.5
2000	1481.4	**98.2**	**6.6**	442.3	4.6
2004	1359.0	**84.3**	**6.2**	595.3	5.0
2005	1344.1	**79.8**	**5.9**	617.3	4.1
2006	1340.5	**80.8**	**6.0**	618.5	4.4

	Nominal Change in Potable Water Price (%)				**Shadow Water**
Year	**Agriculture**	**Manufacturing**	**Services**	**Households**	**Price (NIS/CM)**
1995	13.4	-20.0	-76.1	-74.3	0.88
2000	20.8	-29.4	-73.6	-71.6	1.13
2004	22.5	-29.4	-66.4	-64.2	1.61
2005	21.2	-28.4	-63.8	-61.5	1.77
2006	22.6	-27.2	-64.8	-62.7	1.81

Note: Top section of Table 2.7, columns three and four, show the (potential) quantity of a secondary potable water market since 1995. Bottom section shows the percent change to potable water price from the initial allocation, and sixth column is the shadow price of potable water in nominal New Israeli Shekels (NIS) per cubic meter.

2.4.3 Comparing results for 1995 through 2006

The applied model has also been calibrated for 1995 through 2006, for the years that CBS Israel had available data. Marginal values for water are re-assigned according to the relevant water prices chosen by the Water Authority at each year.[26] Using the year specific SAM, and the water demand-price elasticities and output-supply-price elasticities as reported in Table 2.2, the substitution elasticities are re-calibrated as discussed in Section 2.3.1. New water trade channels are set as in Section 2.3.4, *i.e.*, each year has its own values for Table 2.3.

The main results are summarized in the top section of Table 2.7, and conclude that the potential secondary potable-water market, for those years, would have been consistently around 5% to 6% of the total supplied potable water. The bottom section

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[26] The Water Authority updated water prices according to a water index or due to administrative reform. The water index is based on the changes to the consumer price index, electricity prices and average wage levels. (For further discussion, see Section 3.7.2.)

Table 2.8: Potable water expenditure as % of total cost (net of tax)

	Agriculture	**Manufacturing**	**Services**	**Households**
1995	5.7	0.08	0.14	0.3
2000	2.5	0.031	0.12	0.2
2004	2.3	0.034	0.11	0.2
2005	2.2	0.034	0.11	0.2
2006	2.0	0.031	0.11	0.2

Note: from the social accounting matrix.

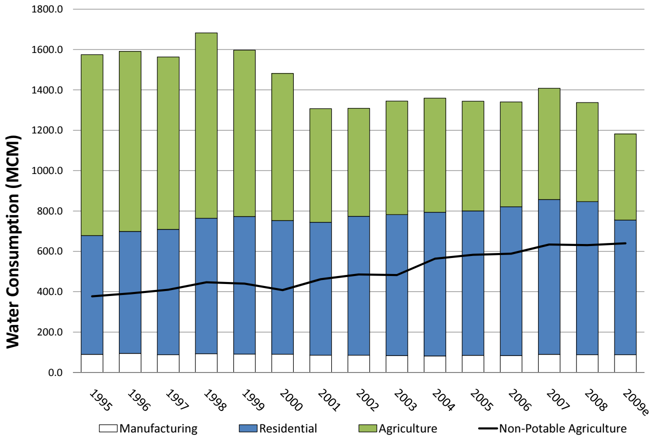
of Table 2.7 reports the changes to water price, relative to the initial administrative allocation, and the shadow water price.

At first, two results seem counter-intuitive. First, for 1995, the model estimates that the potential secondary potable water market would have been the smallest, compared to the other years in the data (5.0% of total potable water). This is an indication of a high efficient allocation. Curiously, in that year, the supplied potable water was also the largest, 1575 MCM. Since the agricultural sector was portrayed as inefficient, "water guzzler" in Israel, one would think that when the supply of potable water is large, there is more room for waste. The question is then, why was 1995 the most efficient year?

The reason is that in 1995, the infrastructure of non-potable water was at its infancy, and the agricultural sector was unable to substitute with lower quality water. Table 2.8 reports that the expenditure on potable water as a percent of total input cost, was twice as high in 1995 as compared to later years. Therefore, potable water was an essential input in those years.

The second counter-intuitive result is that the most inefficient allocation (at 6.6% of total potable water) was measured in the year 2000, in the midst of a water crisis in Israel. During the dry winters of 1998/9 through 2001/2, the Water Authority had cumulatively reduced agricultural potable water by approximately 40%, which were never returned in later years. Thus, by eliminating quotas, one should expect a more

Figure 2.2: Potable water consumption by main users (MCM)



Source: The Water Authority, Israel.

Note: During the drought between winters 1998/9 through 2001/2, agricultural water quantities were reduced by 40%. This coincided with a rise in agricultural consumption of non-potable water. Water consumption by manufacturing sectors and residential users (per-capita) were fairly consistent. Roughly with population growth, residential water consumption rises by 2.3% per year (on average).

efficient allocation.

However, by 2000, new infrastructure and technologies that improved non-potable quality, enabled the agricultural sector to substitute potable water consumption with non-potable water, as illustrated in Figure 2.2. This meant that the expenditure on potable water dropped from 5.7% to a 2.5% of total cost on inputs (see Table 2.8), releasing excess potable water.

Furthermore, between 1995 and 2000, the Water Authority had reformed the water pricing scheme, disfavouring the manufacturing sector. While residential nominal water prices (households and the service sector) rose by approximately 16.5%, and for the agricultural sector by 20.7%, the manufacturing sector had an increase of 45.7% in nominal water price.[27] The model captures the fact that the manufacturing sector would have liked to purchase more water from the agricultural sector, thus enlarging the potential secondary water market. Overall, these examples demonstrate

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[27] Source: Water Authority water price data. This type of pricing change was due to an administrative reform, rather than a change to the water price index. See Table 3.2 in Section 3.7.2.

how water authorities could use this kind of model to improve allocation efficiency.

2.4.4 Policy implications

The policy implications of the model, as described so far, are the following: First, water authorities across the world can use this method to estimate the level of allocation efficiency both within the current price-quota framework and for future proposed reforms. For example, the major reforms in Israel, between 1998 and 2001, though meant to deal with the serious water shortage of the time, were actually damaging and led to even more inefficient allocation. Furthermore, the latest pricing reforms in 2010, were not sufficiently evaluated.

Second, recalling that the results are meant as conservative, upper-bound, estimates of the secondary water market, I find that the administrative misallocation between 1995 to 2006 is on the average of 85 MCM; Israel incurs an economic loss of around NIS 86 Million (in 2006 prices). Therefore, the likelihood of committing a *type II error* (*i.e.,* of *not* introducing a water market when it should have been implemented) is rather low.

Finally, up until now, only the economic costs of an administrative mechanism were considered. By imputing some of the social value generated by the social planner, the next section infers the lost social value generated when a market mechanism is implemented. It therefore would indicate the likelihood of committing a *type I error* (*i.e.,* introducing a market mechanism when the current administrative would have been preferable).

2.5 Inferring the value of agricultural amenities

Typically, incomplete markets, or as in our case, no markets at all, are characterized by distortions and welfare losses. However, when amenities are involved, it is possible to rationalize this distortion as a corrective measure for sectors that create positive amenities, but are not valued economically. For example, in addition to producing marketed goods, the agricultural sector also provides environmental amenities such as agricultural landscape, clean air, tourism, heritage preservation and other cultural elements that characterizes a country's self-narrative.[28] Furthermore, the agricultural sector may also produce public "bads" such as non-point pollution. This, however, is not analysed here because of the complexity of the issue and the additional assumptions it would require.

The positive effects of agricultural amenities have been studied by various authors, *e.g.*, Drake (1992); Bowker and Didychuk (1994); Bergstrom et al. (1985); Brunstad et al. (1999); Fleischer and Tsur (2003, 2009) and Kan et al. (2009), who use micro-level data to impute the value of agricultural amenities. This chapter, however, uses the general equilibrium model, developed in the previous sections, to impute the value of agriculture amenity under a multifunctional agricultural sector, more similar to Peterson et al. (2002); Vatn (2002); Brunstad et al. (2005).

It is assumed that in addition to privately traded commodities, the agricultural sector also provides amenities, which it is not rewarded for producing. A regulator, however, recognizes this distortion and uses administrative water allocation to correct for it. The imputed value, in this extension, characterizes the amenity value which would rationalize the administrative water allocation as being efficient. Therefore, assuming the amenity value would have been accounted for in the first place, even with the possibility of water trade, water users would choose not to trade.

Algorithm 2.1 summarizes the method by which the amenity value is imputed.

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[28] For example, in the case of Israel, the farming community is viewed as the forefathers of the Zionist Movement and the State of Israel. This gives them an intrinsic cultural value in the mind of the Israelis. A further example is a city, such as Nes Tziona. By maintaining a few orange groves and planting numerous orange trees around its parks and streets, this city is trying to preserve its heritage as being once a centre of orange production in Israel.

Algorithm 2.1 Imputing the amenity value

1. An arbitrary amenity value is chosen and taxed at 100% tax.
2. As in Section 2.4, compute size of water trade in a secondary water market.
3. Reduce tax on amenity to 0%, and re-compute size of the secondary water market.
4. Increase (decrease) amenity value and repeat (3) until the size of the secondary water market is null.

Using a fixed proportion transformation function,

$$Y_{agr} = \min \left\{ \frac{Y^{c}_{agr}}{a}, \frac{Y^{nc}_{agr}}{b} \right\} \tag{2.19}$$

the agricultural sector is now assumed to jointly produce two types of goods; a privately traded commodity Y^{c}_{agr}, *e.g.*, apples, and a non-commodity Y^{nc}_{agr}, *i.e.* an amenity such as landscape and heritage. Both goods are demanded by the representative household, but by initially setting a 100% tax rate on the non-commodity, and transferring the tax revenue directly to the households, the household pays for the commodity, but not for the non-commodity. In such a way, the household consume the amenity free of charge, *i.e.*, its price is zero. As long as the amenity tax rate is maintained at 100%, any arbitrary amenity value used in the data-set has no bearing on the water trade results, reported in the previous Section 2.4.

Next, the amenity tax rate is reduced to 0%, and the size of secondary water market is re-computed. The model iteratively increases (decreases) the amenity value until a value is found that leads to *zero* water trade, even when trade is possible.

Table 2.9 summarizes the imputed agricultural amenity value for the main channels, and for the all-trade channel scenario, for 2006. The conclusion is that it amounts to approximately NIS 87.3 billion. This is roughly 2.27 times the value of the agricultural economic output, and equivalent to 5.7% the total country's economic output.

Table 2.9: Agriculture amenity value (2006)

	Channel	Amenity Value^a	As % of Agriculture output^b	As % of total output^b	Amenity value lost from a water market^a	*Net-social* welfare lost from a water market^a
		(2006 Million NIS)			(2006 Million NIS)	
1.	Manufacturing buy	26,000	68	1.7	-28.7	-68.4
2.	Services buy	53,500	139	3.5	-61.8	-69.4
3.	Households buy	87,250	227	5.7	-165.6	-104.7
6.	**All Channel Trade**	**87,250**	**227**	**5.7**	**-321.5**	**-215.0**

*Source: ^{a} Model Result. ^{b} In 2006, agricultural economic output was NIS 38.5 billion, and total country output was NIS 1,542.1 billion. Source: Israel CBS and used in the SAM.

Note: The second column is the amenity value that rationalizes an efficient administrative allocation. The third and fourth columns are the size of the amenity value as a percent of the agricultural output and total output. The fifth column is the direct amenity value lost, and column six is the overall net-social welfare lost from introducing a water market with the imputed amenity value included in a re-calibrated SAM. The difference between them are the welfare benefits from a water market.

Similarly, it is equivalent to 69% of the total agricultural *social* output, *i.e.*, economic output plus amenity.[29]

With a lack of information, the amenity enters a Cobb-Douglas utility consumption bundle with other goods. Hanemann (1991), in a related paper, discussed cases where public goods are readily substitutable for public goods, and others where they are not. At an aggregate level, it seems less realistic that the former is true for Israel. Therefore, reducing the substitution elasticity with other goods would only increase the imputed amenity level (meaning that by using a Cobb-Douglas utility function, the value of the agricultural amenity is rather a conservative underestimate).

To gauge whether the value of the imputed agricultural amenity is plausible within an Israeli context, I compare with Kan et al. (2009), who impute the agricultural landscape amenity by using micro-level Israeli data. Using a positive mathematical programming (PMP) model based on Howitt (1995), they quantify the potential social benefits of changing intra-agricultural land allocation among crops in the northern

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[29] In 2006, agricultural economic output was NIS 38.5 billion. Total agricultural *social* output is therefore NIS 125.7 billion, of which 69% is the value of agricultural amenity.

region of Israel.

Similar to my approach, they use two stages. In the first stage, they calibrate the model separately for each region such that it reproduces the land allocation under optimal profit-maximization. In the second stage, they reformulate the objective function to incorporate both the profit function of farmers and the region specific amenity value. This is based on estimates by Fleischer and Tsur (2009) of the households 'willingness to pay' for preserving various types of *vegetative* agricultural landscapes.

Kan et al. (2009) assume that once farmers internalize the landscape amenity that they produce, they will shift away from a market-equilibrium allocation as long as they are at least fully compensated from a consequential profit loss. They conclude that in Israel, the agricultural landscape amenity value is roughly 33% of the total agricultural *social* output (while here I impute a figure of 69%).[30]

Comparing their results to mine, the order of magnitude is rather similar, though my results are twice as high. Our estimates are however not directly comparable for the following reasons. First, Kan et al. (2009) focus on a subset of the agricultural sector, *i.e.*, vegetative agriculture that accounts for approximately 64% of total agricultural output. They, therefore, only impute the agricultural *landscape* amenity. In my approach, the imputed value includes all aspects of the agricultural amenity (*e.g.*, including the value of culture and heritage) that Kan et al. (2009) cannot consider.

To impute the full agricultural amenity value, they would require estimates for each specific type of "willingness to pay", and not only those for preserving *vegetative* landscapes. Underlying my analysis is a strong assumption that households live in a free society, and that water allocation is a result of an open and public debate. The argument is that households agree to continue with the current allocation, rather than depose it completely, and this suggests that they have internalized the non-economic value of agricultural production and are "willing to pay" for it.

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[30] In Kan et al. (2009) Table 2, this is referred as *social* benefits to remind the reader that it includes both the production profits and the amenity value, and I therefore do the same.

A second reason for having a higher value is that Kan et al. (2009) analyse only the northern regions of Israel. Vegetative agriculture is predominately located in the wetter north of the country, and not in the arid south. In my paper, however, agriculture is analysed country-wide. Since both northern and southern farmers pay the same rates for water inputs, adding southern farming into the analysis would increase the agricultural amenity value, as a whole.

Finally, it would be possible to compare more closely my results with theirs by further disaggregating the agricultural sector into vegetative industry and others.

2.5.1 Policy implication and results

To quantify a situation where policy makers may erroneously introduce a water market, the following steps are implemented. The social accounting matrix (SAM) is re-calibrated to incorporate the value of the imputed amenity from Table 2.9, and the analysis in Section 2.4 is then re-done.

In this case, all water market results are identical to those presented in Section 2.4, *i.e.,* water quantities, water prices, and changes to production are the same. Recall that as long as the tax on the amenity is 100%, sectors of production do not internalize any benefits from producing an amenity, and its value, therefore, does not matter.

What *is* however different is the analysis of welfare. In this re-calibrated SAM, the household utility function also includes a demand for amenities. When a water market is introduced, agricultural production falls, which leads to a loss of NIS 321.5 million of amenity value. Yet, as previously discussed, a water market improves the use of water inputs and raises (economic) welfare by NIS 106.5 million. (This is similar to the result reported in Table 2.4.)[31] Overall, introducing a water market in a case where an agricultural amenity is considered could result in a *net-social* welfare

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[31] Without considering agricultural amenities, Table 2.4 reported that a water market raises (economic) welfare by NIS 86.3 million.

loss of NIS 215 million. (See Table 2.9.) The main policy implication of these results is therefore that the Israeli society is likely to lose out if a water market is introduced, *i.e.*, likelihood of committing a *type I error* is high.

There are further additional points supporting the current Israeli administrative allocation. First, if (as I find here) the average yearly misallocated water is approximately 85 MCM of water, this amounts to approximately half the yearly production of a desalination plant.[32] Einav (2009) reports that the investment cost is somewhere in the range of half to one billion NIS. If the saved welfare loss from the administrative mechanism is around NIS 215 million every three to four years, within less than a decate, a desalination plant would be a better sustainable alternative to a market mechanism.[33]

Second, assuming that the ratio of landscape amenity to agricultural output is 33% (rather than my 69%), as estimated by Kan et al. (2009), a *very rough* low-value amenity could be NIS 18.9 billion (compared to my figure of NIS 87.3 billion).[34] A re-calibrated SAM using this value would result in an insignificant rise to net-social welfare of NIS 15.9 million (not a fall). This however does not clearly support any single allocation mechanisms as being superior; rather, its magnitude is close to zero.

As opposed to statistical methods that use inference to assess the reliability of results, computable general equilibrium has no such equivalent. But recalling that the parameters in the model are intended to overestimate the benefits from a water market, and underestimate the value of the amenities, the value of NIS 15.9 million is very small. This suggests that maintaining the administrative mechanism is probably a safer approach.

Finally, this paper has only focused on agricultural amenities and does not include

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[32] Or in the vicinity of importing water from Turkey, which was discussed between the two countries.

[33] Recall that 3 to 4 years is the short-to-medium run time-frame of the model.

[34] Divide the 2006 agricultural economic production level of NIS 38,497 million by (1-0.33)=0.69 (*i.e.*, its proportion out of total *social* output as estimated by Kan et al. (2009),) and obtain NIS 57,458 million. This is therefore an amenity value of NIS 18,961 million.

amenities created by other sectors, *e.g.*, public and private gardens, world heritage sites, irreversible destruction to nature.[35] These are overlooked because the method implemented here cannot be used to compute them. Residential users have higher marginal value of water making them natural buyers of water. If it were possible to reward them for producing the amenity, as was done with the agricultural sector, they would have demanded even more water. In this case, Algorithm 2.1 has no bound. Therefore, the infra-marginal social-welfare loss from introducing a water market could be much higher than what has been found here. This further supports the current administrative mechanism.

2.6 Conclusions

In Israel, parliamentary investigative committees and researchers from the natural and social sciences have concluded that for decades, the administrative water allocation mechanism has mismanaged water allocation. Over subsidising of the agricultural sector, and underfunding of desalination plants, has led to a severe hydrological deficit. Critics argue that a water market allocation could solve these issues. Yet, the administrative allocation is crucial because it protects social value, which is both difficult to evaluate economically and is not represented in a market mechanism.

By developing an applied general equilibrium model, this chapter compares two water allocation mechanisms in Israel, in a context of two erroneous policy choices. Israel could make a *type I error* by introducing a water market, which would come at the expense of the environment and social value. Israel could also make a *type II error* if they continue with the current administrative mechanism, and therefore, lose

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[35] Recall from Section 2.3.4, that garden water consumption is around 25% of total residential. Furthermore, the amenity value of world heritage sites are unknown. For example, since 2000, the Jordan river has been dammed at the southern tip of the Sea of Galilee. The water trickling downstream is recycled water for touristic purposes. No water from the Jordan river is reaching the Dead Sea, which will eventually dry up. The irreversible environmental and historical implications are not measured here.

the efficient use of the scarce water inputs.

The model developed in this chapter simulates the introduction of a water market with and without agricultural amenities. On the basis of the results, it concludes that: (1) between 1995 to 2006, the upper-bound average of inefficient water use was around 85 million cubic meters of potable water, approximately 5.5% of the total potable water supply. This amounts to an economic loss of NIS 80 to 100 million (in 2006 prices); and (2) introducing a water market could lead to a lower-bound social loss of around NIS 320 million. Therefore, weighing these two losses suggest that a safer approach for Israel would be to continue with the administrative allocation mechanism.

However, as Diao and Roe (2003) discuss, having a water market may, in the long-run, make water similar to any other traded commodity. This could motivate agents to search for better technology that increase water supply (*e.g.*, private and government collection of runoff water, desalination of seawater, and recycling sewage water) for resale into the market for profit. My conclusions apply to the short-to-medium run water situation, and the long-run potential gains from a market mechanism are, therefore, not fully quantified. This would be an area for further research that could help policy makers, not only in Israel, but also in other countries suffering from water scarcity, to assess water allocations mechanisms in-conjunction with a green agenda.

Chapter 3

Water policy in Israel and the water model

In this chapter, the water allocation issues that were discussed in Chapter 2 are contextualized by providing an extended description of the Israeli water situation. Furthermore, the full analytical model that was used is presented. The chapter is structured as follows: Section 3.1 outlines the historical development of water management since the creation of the state of Israel in 1948. Section 3.2 focuses more specifically on the ongoing "water crisis" since the 1990s and the response by consecutive governments. Section 3.3 discusses the water market as an alternative allocation mechanism, and also illustrates the difficulty in changing allocation mechanisms. Section 3.4 presents the full analytical water model that was used as a basis for the analysis in Chapter 2. Finally, Section 3.5 through Section 3.7 present the calibration methods that were used and the data collection.

3.1 The history of water management in Israel

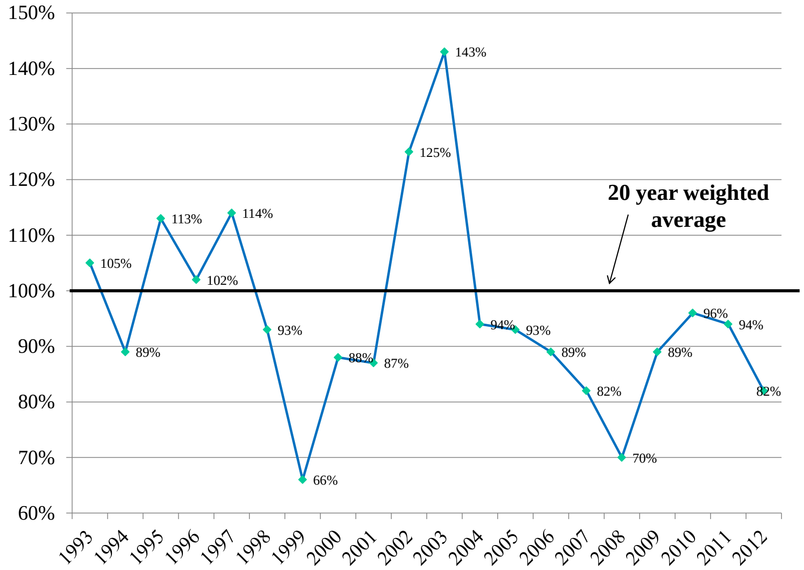
Menahem (1998), Becker and Lavee (2002) and others, have extensively discussed the historical development of Israeli water policy. They divide it into three periods: In the first period, 1948-67, water sources and institutional frameworks were developed. The government pro-actively used administrative water allocation for social and political goals, *e.g.*, to supplement money transfers, to promote settlement and food-security policies, and to subsidize the agricultural sector and various manufacturing industries.

A Water Law was enacted in 1959 to control and protect the Israeli water resource. It states that all sources of water are public property and that a person's land rights do not confer rights to any water sources running through or under his land. Every person is entitled to use water, as long as it does not cause the salination or depletion of the water resource. For egalitarian reasons, all users pay the same water price irrespective of the proximity to its source. Finally, the Water Law forbids the resale of water quotas, which disconnects market forces from the pricing and allocation of water.

In the second period, 1967-90, agricultural expansion was prioritized over water resource conservation, and water management responded reactively to seasonal rainfall variations. For example, during droughts, water quotas were sharply reduced, targeting first the agricultural sector, and returned to previous levels when rainfall was plentiful again.

Finally, in the third period, from 1990 to the present, a gradual paradigm shift has taken place from a reactive water management style, towards a more proactive approach that considers both water demand needs, and aims to preserve the natural resources. But changes have been slow, and over 40 years of excessive consumption above the natural rate of replenishment, has led to severe hydrological deficits, which permanently threatens water quality.

Figure 3.1: National weighted rainfall as percent of the 20 year average



Source: The Water Authority.

Note: Rainfall varies according to geographical location, i.e., the north of the country is generally wetter than the south. The figure shows the national weighted variability compared to a 20 year weighted average.

3.2 The recurrent water crisis in Israel

In every decade since the 1990s, Israel has experienced years of low rainfall, which has on several occasions forced the government to consider drastic measures (see Figure 3.1). Between the winters of 1995/6 to 1998/9, rainfall was below 1400 million cubic meters (MCM). Consumption was, however, significantly higher than supply, and by the end of that period, the Israeli government officially declared a "water crisis." Water quotas to farmers and to the manufacturing sector were reduced, and households were required to cut back water use to the bare essentials, *e.g.*, they were required to dry up gardens. (See water consumption in Figure 2.2 of Chapter 2.)

The situation, furthermore, prompted the formation of the Arlozoroff Committee in 1997. Its main objectives was to evaluate the overall water management in Israel, and to suggest policy reforms that would deal with the ongoing water crisis. The committee included various specialists, *e.g.*, economists, engineers, and policy makers.

Its role was advisory and it had no legal power.

Some of the main conclusions of the committee were that economic incentives should be used to divert potable water from the agricultural sector towards residential consumption. Farmers, who as a result, would suffer losses should initially be compensated. Agricultural water prices should be raised by 80% over a number of years, under the assumption that an 8% increase in price would result in a reduction of 4% to 5% of the quantity of agricultural water consumption. Finally, investment in desalination plants should begin immediately (Davidovich, 2008). These conclusions set the tone for future debates, even though they were never fully accepted nor implemented.

The prolonged draught that started in Winter 1995/6 continued, and peaked by Winter 2001/2. Increasing pressure on the Israeli Government to resolve the problem lead to the formation of the 2001 Parliamentary Inquiry Committee. Its aim was to investigate the causes of the ongoing water crisis, and suggest key reforms.

The main findings of the committee were presented in 2002 and some of its key recommendations were: to establish an independent professional Water Authority; to encourage and attract water professionals, such as water engineers, hydrologists, economists, and other water resource management professionals to enter the water sector; to reduce bureaucracy and enhance the development of reclamation plants. Finally, similar to the Arlozoroff Committee, it was recommended to invest in desalination plants so that by 2005, the natural resources would return to levels above the hydraulic "Red Line."[1] Thereafter, it was advised to continue increasing the water supply, through desalination or imports, so that sustainable water management would

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[1] The Sea of Galilee is the largest body of potable water storage in Israel. It supplys approximately 30% of the yearly potable water supply. Hydrologists had set a scale, to manage water supply according to three lines: (1) Upper Red Line (-208.8 meters below sea level): above this line, authorities open the dams and allow water to flow freely down the Jordan River; (2) Lower Red Line (-213): below this line, the ecological system of the Sea of Galilee is in danger, and (3) Black Line (-214.87): below it, water extraction is not allowed. (December 2001, was the lowest ever recorded level at -214.87).

be maintained (Drayzin, 2002; Magen, 2002).

In the period between Winter 2007/8 and Winter 2010/11, another cluster of low yearly rainfall lead the government to announce a water crisis once again. Water allotments to the agricultural sector and several manufacturing industries were reduced, and public awareness programs urged residential users to conserve water. Non-essential household water use was limited, and overuse penalized, *e.g.*, watering gardens was severely limited. Once again, the administrative framework of water pricing and quotas was re-considered, and in 2010 revised.

In 2008, a report from the State Comptroller Committee assessed the reasons for this new crisis, and the degree to which the recommendations from previous committees had been implemented. This report warned that the available water supply continued to be in deficit, and that many of the important recommendations from the 2002 Parliamentary Inquiry Committee had not actually been implemented, *e.g.*, the construction of desalination plants had been delayed by approximately five years because the plentiful rainfall of Winter 2002/3 had enabled policy makers to divert attention to more urgent budgetary needs (Davidovich, 2008; Tal, 2008).

In each of these periods, the public and political debate about water management is rekindled. Some of the debate has focused on issues of pride and blame, and other on the practical level of water management. Questions which often arise are: (1) Why is a country that prides itself as being modern, continuously struggles with water shortages? (2) Who is to blame for this situation? (3) Where should water cuts be made? and (4) What measures should be taken to amend the problem and halt the irreversible destruction to water resources?

In a critical discussion of Israel's administrative mechanism, Plaut (2000) argues that this mechanism is harmful, and produces waste and misallocation. Water supply and demand do not balance, and the administrative mechanism is unable to adjust water allocation efficiently and quickly. He adds that the current system motivates farmers to use all the yearly allotted water, in order to justify and preserve their water quotas for the next year, even if it means dumping it.[2] This type of behaviour resembles other settings, *e.g.*, government ministries and bodies, or sub-divisions within large firms that exhaust all resources before the budgetary-year ends. Lichtman (2009) investigates and reports illegal, shady, and inequitable water activities in Israel's farming sector, and estimates that a black water market operates at around 10 million cubic meters (MCM) yearly, *i.e.*, equivalent to a small desalination plant. This black market has been similarly reported by Globes Newpaper (1999); Rivlin (2010) and others.

3.3 A water market as an alternative to the administrative mechanism

One can argue that the on-going water crisis in Israel is a result of mismanagement. Alternative water allocation mechanisms have been discussed by several researchers in Israel and abroad. Dinar et al. (1997), Holden and Thobani (1996) and Livingston (1995) give a general review of the theoretical advantages and disadvantages of alternative mechanisms. Becker and Zeitouni (1998a), Fishelson (1994), Moore (1994) and Zeitouni et al. (1994) discuss alternative mechanisms within the Israeli context, and Bielsa and Duarte (2001), Calatrava and Garrido (2005), Garrido (2007), Pujol et al. (2006), and Simon and Anderson (1990) discuss this in other countries.

One popular alternative to an administrative mechanism is a water market, because use tradable permits would enable market forces to internalize the true value of the resource. Both sellers and buyers would gain from trade, regardless of whether the permits were auctioned or allocated free-of-charge (Becker, 1995; Holden and

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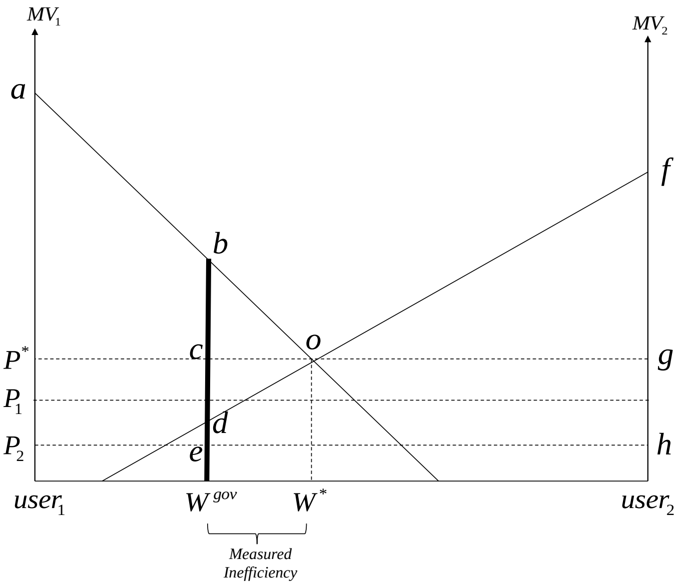
[2] There are cases where water users are grossly negligent and literally dump water. In other cases, farmers are sold water at prices far below its resource value, which they use to grow low value crops on desert fields, which critics bluntly call this dumping.

Thobani, 1996). As discussed and summarised in case studies by Bhatia et al. (1995); Holden and Thobani (1996); Dinar et al. (1997); Grafton et al. (2010), water markets are relatively new in some regions such as Chile, Australia, and the USA. In other regions, such as Spain and India, water markets have been functioning for many years.

There are four approaches to initialise a water market: (1) Random access (or lotteries); (2) Administrative rules based upon eligibility criteria; (3) Auctions; and (4) Historical allotments. Random access is more common in allocating permits among residents, while auctions are more common for allocating permits to non-residents. The most widely used method for initializing a *new* water market has been the historical approach, which is also known as the "first-come, first served" or "grandfathered" (Tietenberg, 2002).

Historical permits are widely used for several reasons: First, incumbent water users are not made worse-off, and are therefore less likely to oppose the adoption of a new mechanism. (This is further discussed below.) This, therefore, facilitates policy makers to navigate through the political process and implement change. Second, historical allotment recognizes the fact that previous water consumers have invested in resource extraction and infrastructure, and serves to protect those investments. Finally, empirical evidence suggests that using historical allocation leads to a smaller financial burden on water users. Permit expenditure, which is the auction revenue collected by the government, is typically higher than the extraction costs, which are the real production costs for water. Where an auction method could create opposition to change, historical allocation is more likely to be accepted (Lyon, 1982; Tietenberg, 2002).

Figure 3.2: Water quotas with two agents



Note: Total water $\bar{W}$ is allocated by the government. User 1 is allocated water quantity W^{gov}, while user 2 is allocated $\bar{W} - W^{gov}$. Area *bod* is the dead weight loss from inefficient water allocation. The potential secondary water market is the volume $|W^* - W^{gov}|$, a proxy for inefficiency.

An illustrative example

Figure 3.2 is used as an illustrative example, and is an extension of the discussion from Section 2.2 of Chapter 2.[3]

Assume a closed economy with only two water users. The total water resource is quantity $\bar{W}$, and the social planner allocates W^{gov} to user 1, and the rest $\bar{W} - W^{gov}$ to user 2. Furthermore, water trade is prohibited. However, this allocation is clearly not optimal, because the marginal values of water are not equalized between users. User 1 would benefit from buying some of user 2's water rights, while user 2 would also benefit from selling-off some of his water rights. Overall, the economy suffers a dead weight loss equal to area *bod*.

In addition, the social planner also sets water prices. When prices are set below the market price, two possibilities arise: At level P_1, user 1 has an excess demand for water, and user 2 has an excess supply. At level P_2, both users have excess demands.

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[3] Becker (1995) uses a similar example.

In Chapter 2, *misallocation* was defined as the absolute horizontal distance $|W^* - W^{gov}|$ measured in cubic meters of water. Allocation inefficiency rises when the discrepancy between the initial allocation and the market allocation rises. Focusing on price P_2, when a water authority aims to reduce the inefficiency, it should raise the water price from P_2 to P^*, and adjust water quotas to point W^*. Overall, the economy gains.

However, without compensation, some incumbent water users are made worse-off, which would motivate them to block this change, even if it improves overall welfare. For example, consumer surplus of user 1 is area $abeP_2$, and consumer surplus of user 2 is area $fdeh$. When price and quotas are readjusted to the optimal P^* and Y^*, the consumer surplus of user 1 changes to area aoP^*, which may (or may-not) be an improvement, depending on whether additional area boc is greater (or smaller) than the reduction in area P^*cep_2. On the other hand, the consumer surplus of user 2 is unambiguously reduced to area fog. Thus, efficiency is increased, but at the cost to some.

Furthermore, the process of adopting a new, more efficient, allocation mechanism may be too costly and unwarranted because the total non-recoverable value which was used to block the change may be greater than the economic gains of area bod. For example, user 2 will be willing to spend area $godeh$ to block the adoption of a new mechanism. Without compensation, she will loss this area anyway if a change occurs. Regarding user 1, this is ambiguous.

Finally, as Figure 3.2 shows, initialising a water market using historical allotments is more favourable for both incumbent users. If the government first allocates the allotments and then allows water trade, user 2 would sell the water quantity $|W^* - W^{gov}|$ to user 1 and in return receive the area coW^*W^{gov}. This area would be greater than the reduction in production profit of area $oW^*W^{gov}d$. Similarly, User 1 also benefits because his production profit from area boW^*W^{gov} is larger that the payment of coW^*W^{gov}.

The tension between various pressure groups (between those who want to maintain versus those who demand change) usually intensifies during severe water shortages and subsequent water quota cuts (Plaut, 2000; and as reported in the Israeli media). Policy makers are required to evaluate the current allocation mechanism, and if necessary, to implement policy reforms. When it is infeasible to experiment on real economies, models can be used to simulate various policy alternatives.

Chapter 2 has evaluated the benefits of a market mechanism versus the current administrative mechanism using Israel as a case study. In the following sections, the full analytical model, which was used as the basis for my analysis, is presented.

3.4 A full description of the applied water model

Following Section 2.2.1 in Chapter 2, the applied model is extended in the following way. The water model is a static general equilibrium model. For the specific Israeli case, production is aggregated into three main sectors: agricultural, manufacturing, and service sectors. Each of them uses labour, capital, potable and non-potable water, and intermediate goods as inputs in production. There is one representative household, which derives utility by consuming water and final goods. Finally, government is not explicitly modelled, but its actions are manifested through the initial water allocation. Tax revenue from production is directly transferred to the representative household.

Water is initially allotted to each of the four users, and water trade is not possible. Then, when trade is allowed, water inputs are re-shuffled until all users have the same marginal water value.

Following Mathiesen (1985); Rutherford (1995, 1999), I set-up an Arrow–Debreu equilibrium as a mixed complementarity problem (MCP). In a general equilibrium setting, three types of weak inequality conditions must be satisfied: (i) zero profit, (ii) market clearance, and (iii) income balance, each associated with three non-negative variables, *i.e.*, $y^* \geq 0$, $p^* \geq 0$ and $M^* \geq 0$, respectively.[4]

3.4.1 Production structure

Production has a four-level structure, which simplifies the calibration procedure and captures the different substitution elasticities for pairs of factor inputs. The inputs of production include an intermediate good, and four primary inputs, *i.e.*, capital, labour, potable-water and non-potable-water. The following are the main assumptions that were made for the production functions.

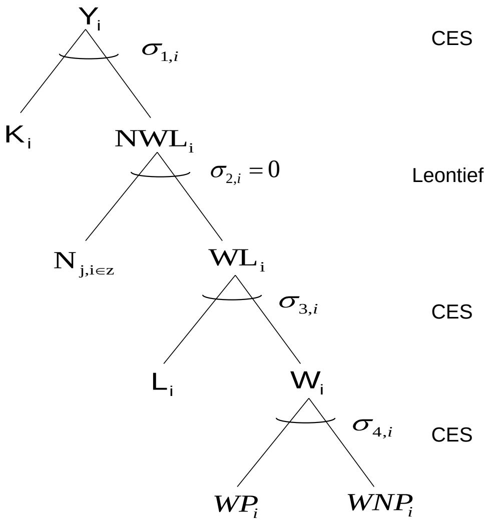
First, the time frame of the general equilibrium model affects the assumptions that we have on factor mobility, and the interpretation of the results. Hertel (2002), who has written extensively on this issues, regards three to four years as the medium-run, which he believes is a sufficient amount of time for adjustment to take place. In the short-run, however, agricultural production has limited buffer stock, which makes it especially vulnerable to supply shocks and leads to wide fluctuations in commodity prices. In the long-run, the importance of stock diminishes and production has time to adjust.

Furthermore, land supply rigidity depends on many factors, such as the availability of suitable land, the potential to convert land from one type of crop to another, or to another sector, *e.g.*, agriculture to manufacturing. Furthermore, the existence of legislative or policy constraints can impede the transfer of land and make it immobile. Therefore, a lower land supply elasticity reflects higher immobility. For example, in the centre of Israel, former farmlands are standing idle and ex-farmers are waiting for authorization to convert land into lucrative housing developments or office space. This

---

[4] Recall that a complementarity constraint enforces that two variables are complementary to each other; i.e., that the following conditions hold for scalar variables x and y: $x \cdot y = 0, \quad x \geq 0, \quad y \geq 0$. This condition is compactly expressed as $0 \leq x \perp y \geq 0$. Intuitively, a complementarity constraint is a way to model a constraint that is combinatorial in nature since, for example, either x or y must be 0 (or both may be 0 as well).

Figure 3.3: The production function



Note: Production is a four level nested function. The lowest level combines potable and non-potable water into an aggregate water. The third level combines the aggregated water and labor inputs. In the second level, intermediate goods are combined with the water-labor aggregate. Finally, in the top level, capital is aggregated with the intermediate goods-water-labor aggregate.

stands in contract to manufacturing and service sectors, which have lower barriers. Thus, for the reasons outlined above, and because land is incorporated into capital inputs, I assign capital as a sector-specific input.

As Figure 3.3 illustrates, capital is placed in the top level of the production function because it makes the derivation of the calibration function for rigid inputs, easier to solve. The output supply elasticities, which are found in empirical papers, are used to calibrate for the substitution elasticity between factor inputs. (The calibration method is discussed in further detail in Section 3.5.)

The second assumption for the production function relates to the water inputs. In the initial allocation, potable-water inputs are allotted to users and are non-tradable. They are, therefore, sector-specific with $p_{W,i}$ as their water prices. However, when water trade is allowed, potable-water is reassigned as a global input. Trade continues until the market clears, and water prices change sufficiently to drive water marginal values to equalize between users. Non-potable water, however, is assumed to be fully mobile.

In the production function, an aggregate water bundle is composed of potable and non-potable in the third level. This allows me to calibrate substitution elasticities using water demand elasticities, which are readily available in empirical papers. Finally, it is assumed that labour inputs freely migrate between the various sectors, and have a global wage level, p_L.

Figure 3.3 illustrates production Y_i for $i \in z$ final goods, and with j as i's alias. The four-level nested constant elasticity of substitution (CES) structure has the following form. In the lowest level, potable water, $W_{p,i}$, and non-potable water, $W_{np,i}$, are combined to form a water aggregator W_i. In the third level, water W_i and labor L_i inputs are combined to form an aggregator WL_i. In the second level, intermediate inputs $IN_{j,i \in z}$ are combined with the aggregator WL_i to form the aggregator NWL_i. Finally in the top level, capital K_i is combined with NWL_i to form the output Y_i.

Beginning with the **top level**, the implicit function theorem equates profit maximization with cost minimization, which takes the form:

$$\begin{aligned} \min_{K_i, NWL_i} \quad & \quad p_{K,i} K_i + p_{NWL,i} NWL_i \\ \text{s.t.} \quad Y_i = & \quad A_{1,i} \left[\alpha_i K_i^{\rho_{1,i}} + (1-\alpha_i) \, NWL_i^{\rho_{1,i}} \right]^{\frac{1}{\rho_{1,i}}} \end{aligned}$$

$\sigma_{1,i}$ is the substitution elasticity within the CES production function. $p_{K,i}$ is the return on capital, $p_{NWL,i}$ is the price index for the aggregator. α_i defines the CES share parameters, and ρ_i is the CES exponent. Note that it is related to the substitution elasticity via $\sigma_i = \frac{1}{1-\rho_i}$ where $\sigma_i \geq 0$. Finally, $A_{i,1}$ is the level of technology.

Solving the minimization problem, and for simplification, reassigning the share parameters to incorporate the substitution elasticity using the relationship, $a_{K,i} =$

$(\alpha_i)^{\sigma_{1,i}}$ and $a_{NWL,i} = (1-\alpha_i)^{\sigma_{1,i}}$, yields the following input demand equations:

$$0 \leq p_{K,i} \quad \perp \quad K_i \geq \frac{a_{K,i}}{A_{1,i}^{1-\sigma_{1,i}}} \left[\frac{(1-\tau_i)\, p_{Y,i}^{cons}}{p_{K,i}} \right]^{\sigma_{1,i}} Y_i$$

$$0 \leq p_{NWL,i} \quad \perp \quad NWL_i \geq \frac{a_{NWL,i}}{A_{1,i}^{1-\sigma_{1,i}}} \left[\frac{(1-\tau_i)\, p_{Y,i}^{cons}}{p_{NWL,i}} \right]^{\sigma_{1,i}} Y_i$$

with zero profit conditions denoting $p_{Y,i}$ and $p_{Y,i}^{cons}$ as the producer and consumer price indexes for sector i, respectively.

$$\begin{aligned} p_{Y,i}^{cons} &\leq \frac{1}{A_i\,(1-\tau_i)} \left[\alpha_{K,i} p_{K,i}^{1-\sigma_{1,i}} + \alpha_{NWL,i} p_{NWL,i}^{1-\sigma_{1,i}} \right]^{\frac{1}{1-\sigma_{1,i}}} \perp Y_i \geq 0 \\ p_{Y,i} &= (1-\tau_i)\, p_{Y,i}^{cons} \end{aligned}$$

At the **second level**, we assume the aggregate NWL_i has a fixed proportions share of intermediate goods IN_{ji}, and a water-labor sub-aggregate WL_i. The following is the optimization problem:

$$\begin{aligned} \min_{WL_i, N_{ji}} \quad & p_{WL,i} WL_i + \sum_{j=1}^{z} p_{Y,ij} IN_{ji} \\ \text{s.t.} \quad NWL_i = \quad & \min \left[\frac{WL_i}{a_{WL,i}},\ \frac{IN_{ji}}{a_{IN,ji}},\ \ldots\ ,\ \frac{IN_{zi}}{a_{IN,zi}} \right] \end{aligned}$$

Solving this minimization problem yields the following demand equations and price index

$$0 \leq p_{WL,i} \quad \perp \quad WL_i \geq a_{WL,i} NWL_i$$

$$0 \leq p_{Y,i} \quad \perp \quad IN_{ji} \geq a_{IN,ji} NWL_i$$

with price index

$$p_{NWL,i} \leq a_{NWL,i} p_{WL,i} + \sum_{j=1}^{n} a_{IN,ji} p_{Y,i} \quad \perp \quad NWL_i \geq 0$$

At the **third level**, a water aggregator W_i and labor L_i inputs are aggregated into WL_i, where $\sigma_{3,i}$ is the substitution elasticity. The optimization problem is to

$$\begin{aligned} \min_{W_i, L_i} \quad & p_{W,i} W_i + p_L L_i \\ \text{s.t.} \quad WL_i = \quad & A_{3,i} \left[\alpha_{WL,i} W_i^{\rho_{3,i}} + \left(1 - \alpha_{WL,i}\right) L_i^{\rho_{3,i}} \right]^{\frac{1}{\rho_{3,i}}} \end{aligned}$$

and the solution yields the following equations:

$$\begin{aligned} 0 \leq p_{W,i} \quad \perp \quad W_i \geq \frac{a_{W,i}}{A_{3,i}^{1-\sigma_{3,i}}} \left[\frac{p_{WL,i}}{p_{W,i}} \right]^{\sigma_{3,i}} WL_i \\ 0 \leq p_L \quad \perp \quad L_i \geq \frac{a_{L,i}}{A_{3,i}^{1-\sigma_{3,i}}} \left[\frac{p_{WL,i}}{p_L} \right]^{\sigma_{3,i}} WL_i \end{aligned}$$

with price index

$$p_{WL,i} \leq \frac{1}{A_{3,i}} \left[\alpha_{W,i} p_{W,i}^{1-\sigma_{3,i}} + \alpha_{L,i} p_L^{1-\sigma_{3,i}} \right]^{\frac{1}{1-\sigma_{3,i}}} \perp WL_i \geq 0$$

Note that labor can migrate freely between all production sectors, and therefore has an economy-wide wage rate.

At the **fourth level**, potable water, $W_{p,i}$ and non-potable water $W_{p,i}$ inputs are aggregated into W_i, where $\sigma_{4,i}$ is the substitution elasticity. The optimization problem is:

$$\begin{aligned} \min_{W_{p,i}, W_{np,i}} \quad & p_{W,,p,i} W_{p,i} + p_{W,np,i} W_{np,i} \\ \text{s.t.} \quad W_i = \quad & A_{4,i} \left[\alpha_{W,p,i} W_i^{\rho_{4,i}} + \left(1 - \alpha_{W,p,i}\right) L_i^{\rho_{4,i}} \right]^{\frac{1}{\rho_{4,i}}} \end{aligned}$$

and the solution yields the following equations:

$$
\begin{aligned}
0 \le p_{W,p,i} \quad \perp \quad W_{p,i} &\ge \frac{a_{W,p,i}}{A_{4,i}^{1-\sigma_{4,i}}} \left[\frac{p_{W,i}}{p_{W,p,i}}\right]^{\sigma_{4,i}} W_i \\
0 \le p_{W,np} \quad \perp \quad W_{np,i} &\ge \frac{a_{W,np,i}}{A_{4,i}^{1-\sigma_{4,i}}} \left[\frac{p_{W,i}}{p_{W,np}}\right]^{\sigma_{3,i}} W_i
\end{aligned}
$$

$$
p_{W,i} \le \frac{1}{A_{4,i}} \left[\alpha_{W,p,i} p_{W,p,i}^{1-\sigma_{4,i}} + \alpha_{W,np,i} p_{W,np,i}^{1-\sigma_{4,i}}\right]^{\frac{1}{1-\sigma_{4,i}}} \perp W_i \ge 0
$$

Note that non-potable water can migrate freely between all production sectors, and therefore has an economy-wide price. At the margin, this increases the size of the secondary water market for potable water.

3.4.2 Household utility structure

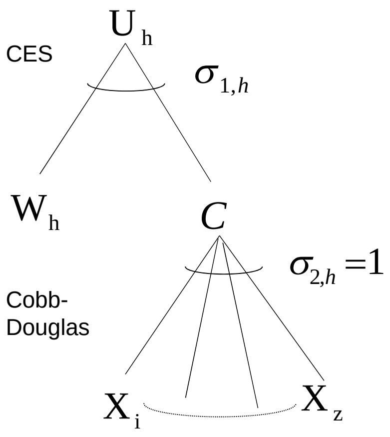
The small open economy has one representative household, $h \in H$, that is endowed with labor, capital, and water resources. It receives tax revenue, and transfers positive (negative) value of income to cover balance of payments. Thus, the disposable household income is:

$$
M = P_{W,h} W_h + \sum_{i=1}^{z} \left(P_L L_i + P_{K,i} K_i + P_{W,p,i} W_{p,i} + P_{W,np,i} W_{np,i} + p_{Y,i}^{cons} \tau_i + bop_i \right)
$$

Extending this model for multiple households is a simple matter, but would then require assumptions regarding water ownership. In such a case, the above income equation would need to be revised. However, it would seem better to add a government agent that owns the water endowments.

Figure 3.4 illustrates the household utility function, as a two level maximization problem. The lowest level combines all final goods into an aggregator, while the top level combines water inputs with the aggregator.

Figure 3.4: Household utility



Note: Utility is a two level nested function. The lowest level combines all final goods into an aggregate. In the top level, water input is combined with the final goods aggregate.

The **top level** maximization problem is of the following form:

$$\begin{aligned} \max_{W_h, C} \quad U = & \quad H\left[\beta W_h^{\rho_{1,h}} + (1-\beta)\, C^{\rho_{1,h}}\right]^{\frac{1}{\rho_{1,h}}} \\ \text{s.t.} \quad M \geq & \quad p_{W,h} W_h + p_C C \end{aligned}$$

W_h is household water consumption, with $p_{W,h}$ its consumer water price. C is an aggregated quantity of final goods consumed, with p_C its consumer price index. H is a shift parameter, and $\sigma_{1,h} = \frac{1}{1-\rho_{1,h}}$ is the substitution elasticity.

I re-parametrize $b_W = \beta^{\sigma_{1,h}}$ and $b_C = (1-\beta)^{\sigma_{1,h}}$, and solve the maximization problem. This yields the following demands and unit utility cost:

$$0 \leq p_{W,h} \quad \perp \quad W_h \geq b_W \left[\frac{P^U}{p_{W,h}}\right]^{\sigma_{1,h}} M$$

$$0 \leq p_C \quad \perp \quad C \geq b_C \left[\frac{P^U}{p_C}\right]^{\sigma_{1,h}} M$$

$$P^U \leq \left[\beta_W \left(p_{W,h}\right)^{1-\sigma_{1,h}} + \beta_C \left(p_C\right)^{1-\sigma_{1,h}}\right]^{\frac{1}{1-\sigma_{1,h}}} \perp U \geq 0$$

In the **second-level**, the aggregated goods consumed is assumed to have a Cobb-Douglas structure with the following maximization problem,

$$\begin{aligned} \max_{X_i} C &= \Phi \cdot \Pi_{i=1}^{z} \left\{X_i^{\gamma_i}\right\} \\ \text{s.t. } I &\geq \sum_{i=1}^{z} p_{Y,i}^{cons} X_i \end{aligned} \tag{3.1}$$

and note that $\sum_{i=1}^{z} \gamma_i = 1$, $I = M - p_{W,h} W_h$ and Φ is a shift parameter.

Solving the maximization problem yields the demand for each final good, X_i,

$$0 \leq p_{Y,i}^{cons} \quad \perp \quad X_i \geq \frac{\gamma_i I}{p_{Y,i}^{cons}}$$

and $p_{Y,i}^{cons}$ as its consumer unit price

$$p_C \leq \Phi \cdot \Pi_{i=1}^{z} \left\{\left(p_{Y,i}^{cons}\right)^{\gamma_i}\right\} \perp C \geq 0$$

3.4.3 Balance of payments and market clearing conditions

Economies are dynamic and can run trade imbalances at any period by buying or selling assets. However, since this is a static model, I fix the balance of payments (BOP) in all counter-factual scenarios to the initial value. Otherwise, it would be difficult to interpret welfare effects. For example, if a policy experiment leads to an increase in the trade deficit, welfare will increase due to foreign borrowing. This is misleading because at some point, borrowing will have to be paid back. Thus, household is assigned an endogenous endowment bop_i, which fixes the trade surplus (deficit) for each good to its initial value.

As previously mentioned, it is assumed that in the short-to-medium run, capital

K_i, is a rigid input, with a sector specific return on capital. Labour, L_i, and non-potable water, $W_{np,i}$, are fully flexible across all sectors with a uniform wage rate and non-potable water price. The market clearing conditions for these three primary inputs are:

$$\begin{aligned}
L^s &= \sum_{i=1}^{z} L_i \\
W_{np}^d &= \sum_{i=1}^{z} W_{np,i} \\
K_i^s &= K_i^d
\end{aligned}$$

All goods in the economy are fully consumed, either as household final goods, as intermediate inputs for production, or as net exports, defined by:

$$Y_i = X_i + N_{ji} + NX_i$$

The market clearing condition for potable-water is discussed in the next section.

3.4.4 Secondary potable water market

Being the main feature of this paper, the following section is added for completeness, even though it follows relatively closely with Section 2.2.2. It furthermore expands on some aspects of water trade, which were not mentioned previously.

Having $i \in N$ firms (with j alias for i) and $h \in H$ households water users, let $M = N + H$ be the total number of water users. As discussed in Section 2.2.2 of Chapter 2, and depicted in Figure 3.2, each user is allocated a different *potable water* quota with a different water price. As long as water trade is *prohibited*, the market clearing condition for potable water is

$$\begin{aligned} W_i^s &= W_i^d \\ W_h^s &= W_h^d \\ p_{W,i} \neq p_{W,j} &\neq p_{W,h} \end{aligned} \tag{3.2}$$

and because water users choose the amount of water to consume, the water price of the last unit is also the marginal water value. Each user has, therefore, a different marginal value of water (MVW) such that

$$MVW_i \neq MVW_j \neq MVW_h$$

When a secondary water market is *enabled*, water inputs are transferred to those users valuing them most. The market clears once a uniform *real* water price is reached. Water users can be *buyers* or *sellers*, and having M water users leads to M^2 trade configurations, with ψ_{mn} being the *relative* marginal value. If user $m \in M$ is a buyer, and user $n \in M$ is a seller, a possible trade channel is when $\frac{MVW_m}{MVW_n} = \psi_{mn} > 1$; otherwise, it cannot be a possible trade channel. This is summarised by

$$\frac{MVW_m}{MVW_n} = \begin{cases} \psi_{mn} > 1 & \text{possible trade channel} \\ \\ \psi_{mn} \leq 1 & \text{not possible} \end{cases}$$

These conditions, therefore, limit the number of configurations to only $T = \frac{M(M-1)}{2}$ possible trade channels, with $t \in T$ being a specific channel. (Table 2.3 had provided a concrete example of this.) Thus, when water trade is enabled, the units of water, γ_t, that are transferred between seller n and buyer m are obtained by

$$0 \leq \gamma_t \perp p_{W,n,t} - (1 - \epsilon)\, p_{W,m,t} \geq 0, \qquad \forall t \tag{3.3}$$

with $p_{W,n,t}$ and $p_{W,m,t}$ being the water market prices for the seller and buyer, respectively. For computational purposes, $\epsilon \to 0$ is a small number to *“help”* the solver with slack activities, thus avoiding the problem of infinite solutions (a degenerate model). This insures that when multiple t channels are opened (active), only *net transfers* of water is considered. For example, a case of infinite solutions is when a first user sells to the second, the second sells to the third, but the first also sells to the third. By adding ϵ, the solutions is limited to one (possible) case where, for example, the first sells to the second and to the third, while deactivating the second selling to the third.

There are various combinations (scenarios) of activating and deactivating water trade channels, *e.g.*, activating each channel separately, or all together. Therefore, each of the $t \in T$ channels has a binary action (designed by the scenario); active or not-active, $\{\mathcal{A}, \mathcal{NA}\} \in Action$. There are $\{t_{\mathcal{A}}, t_{\mathcal{NA}}\} \in T$ active/non-active channels, $\{i_{\mathcal{A}}, i_{\mathcal{NA}}\} \in N$ active/non-active firms, and $\{h_{\mathcal{A}}, h_{\mathcal{NA}}\} \in H$ active/non-active households, respectively. In other words, a water user will *not* trade because: it is either a choice, or it is *blocked*.

Thus, when Equation (3.3) is enabled, $\forall t_{\mathcal{A}}$, water units, $\gamma_{t_{\mathcal{A}}} > 0$, are exchanged between users up to the point where sellers and buyers have equalised water prices, $p_{W,n,t} = (1-\epsilon)\, p_{W,m,t}$. If, however, the unit water price of a seller is higher than the unit price of a buyer, $p_{W,n,t_{\mathcal{A}}} > (1-\epsilon)\, p_{W,m,t_{\mathcal{A}}}$ (a strict inequality), the activity goes slack, $\gamma_{t_{\mathcal{A}}} = 0$, *i.e.*, there is no trade.

Enabling water trade for various water trade channels and actions, $\forall i$ and $\forall h$, the market clearance condition of Equation (3.2) is updated by the following:

$$\begin{gathered}
W^s_{h_{\mathcal{A}}} + \textstyle\sum_{i_{\mathcal{A}}} W^s_{i_{\mathcal{A}}} = W^d_{h_{\mathcal{A}}} + \textstyle\sum_{i_{\mathcal{A}}} W^d_{i_{\mathcal{A}}} \\
p_{W,i_{\mathcal{A}}} = p_{W,j_{\mathcal{A}}} = p_{W,h_{\mathcal{A}}} \\
W^s_{i_{\mathcal{NA}}} = W^d_{i_{\mathcal{NA}}} \\
W^s_{h_{\mathcal{NA}}} = W^d_{h_{\mathcal{NA}}} \\
p_{W,i_{\mathcal{NA}}} \neq p_{W,j_{\mathcal{NA}}} \neq p_{W,h_{\mathcal{NA}}}
\end{gathered} \tag{3.4}$$

3.4.5 Agricultural amenity

This section extends on the basic water market model, and imputes the value of the agricultural amenity. To do so, the representative agricultural producer, $agr \in z$, is now assumed to jointly produce two types of goods; a privately traded commodity, Y^c_{agr}, *e.g.*, apples, and a non-commodity, Y^{nc}_{agr}, *i.e.* an amenity good such as landscape and heritage. To clarify notation, note that when the amenity is added, the agricultural output and consumer price, previously defined as $Y_{agr}, p^{cons}_{Y,agr}$, are split into two variables: $Y^c_{agr}, p^c_{Y,agr}$ and $Y^{nc}_{agr}, p^{nc}_{Y,agr}$. For all other goods, nothing changes.

The household utility function is re-defined to include the demand for both goods, *i.e.*, agricultural commodity and non-commodity. However, by initially setting the non-commodity tax rate to $\tau^{nc} = 100\%$, and transferring the tax revenue directly to the households, the household pays for the commodity, but not for the non-commodity. Therefore, the household consumes any level of amenity available, *i.e.*, its price is zero. As long as the tax rate on the amenity is maintained at 100%, any arbitrary amenity value used in the benchmark data-set, and has no bearing on the water trade results. (Still, it does affect the level of utility.)

The level of amenity is imputed by reducing the tax rate to $\tau^{nc} = 0$, which allows agricultural firms to internalize the amenity they produce. The model, then, searches for an imputed amenity level that would lead to *zero* water trade, even when trade is possible. (See Section 2.5 of Chapter 2 for further discussion.)

Changes to production

Assuming a fixed proportion transformation function, the new profit-maximization problem of the agricultural sector, which now includes both a commodity good and a non-commodity, is:

$$\begin{aligned}\underset{Y_{agr},Y^{c}_{agr},Y^{nc}_{agr}}{\text{maximize}}\ \pi_{agr} &= (1-\tau_{agr})\,p^{c}_{Y,agr}Y^{c}_{agr} + (1-\tau^{nc})\,p^{nc}_{agr}Y^{nc}_{agr} - p_{Y,agr}Y_{agr} \\ \text{s.t. } Y_{agr} &\geq \min\left\{\frac{Y^{c}_{agr}}{a}, \frac{Y^{nc}_{agr}}{b}\right\}\end{aligned}$$

with τ_{agr} and $p_{Y,agr}$ defined previously, as the agricultural production tax rate and the producer price, respectively. τ^{nc} is the tax rate on the non-commodity.

Solving the maximization problem, we obtain the following supply functions for commodity and non-commodity goods:

$$\begin{aligned}0 \leq p^{c}_{agr} &\quad \perp \quad Y^{c}_{agr} \geq aY_{agr} \\ 0 \leq p^{nc}_{agr} &\quad \perp \quad Y^{nc}_{agr} \geq bY_{agr}\end{aligned}$$

The zero profit conditions leads to the unit cost of production.

$$p_{Y,agr} \leq a \cdot (1-\tau_{agr})\,p^{c}_{agr} + b \cdot (1-\tau^{nc})\,p^{nc}_{agr} \perp Y_{agr} \geq 0$$

Changes to household utility

The non-commodity (the amenity) enters a Cobb-Douglas utility function with other commodity goods in Equation 3.1, *i.e.*, the amenity is added to the bundle of consumption goods as $amenity \in z$. The significance is that the substitution elasticity between the non-commodity and commodity goods is, therefore, assume to be 1.[5] This seems to be a rather high substitution elasticity parameter, which reduces the amenity value in the solution, and makes it a conservative estimate.

The relevant empirical research relating to amenities is extremely limited because

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[5] This is a well-known property of a Cobb-Douglas function.

being a non-commodity, an amenity has no market price. If, however, better information was available, it would then be possible to calibrate the substitution elasticity between the amenity and other goods. For example, by using a similar approach as applied to other inputs in this paper, such as water in the utility function, and input factors in the production function. What is required, therefore, is the demand price elasticity of the agricultural amenity.

3.5 Calibrating substitution elasticities in production

Well-documented water demand elasticities and output supply elasticities are collected from previous studies, and are used to capture the specific characteristics of the water sector. This section explains how these parameters are integrated into the model, and are used to calibrate the substitution elasticity between input factors in the production function.

Many empirical studies have estimated the supply price elasticity for the agricultural sector at around 0.8. (See Askari and Cummings (1977), Peterson (1988), Rao (1989) for a good review of the findings.) For manufacturing and service sectors, a great deal of literature focuses on supply price elasticities of single sectors, *e.g.*, transport, housing, energy, but to my knowledge, there are no aggregate level estimate. Generally, however, supply price elasticities are elastic.[6]

The left-hand side of Table 3.1 summarises the sector-specific elasticities that are used in this paper, which are mid-values from the literature review. The table shows that the agricultural sector has a relatively inelastic supply price elasticity of $\eta_{agr} = 0.8$, which is partly due to the rigidity of land (as discussed previously). Since the non-agricultural sectors are generally elastic, I use a supply price elasticity of $\eta_{i \neq agr} = 3$ for both manufacturing and service.

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[6] For example, literature that report for single sectors are Blackley (1999); Green et al. (2005); Malpezzi and Maclennan (2001) that find elastic values for the housing market, as high as 20. Dahl

Table 3.1: Calibrating the substitution elasticities, SAM 2006

	Exogenous							Endogenous		
	Output Supply Elasticity[a]	**Water Demand Elasticity**[a]	**Potable/ Non-Potable Elasticity**[b]	**SAM Cost Shares(2006, %)**[c]				**Calibrated Substitution Elasticity**		
	η_i	$\epsilon_{W,i}$	$\sigma_{4,i}$	$\theta_{K,i}$	$\theta_{W,1,i}$	$\theta_{W,2,i}$	$\theta_{W,3,i}$	$\sigma_{1,i}$	$\sigma_{2,i}$	$\sigma_{3,i}$
Agriculture	0.8	-0.7	1.1	46.5	3.3	6.2	19.0	0.70	0	0.84
Manufact.	3.0	-0.7	1.1	56.0	0.03	0.1	0.4	3.81	0	0.7
Services	3.0	-0.1		19.0	0.1	0.1	0.3	0.70	0	0.1
		$\epsilon_{W,h}$			$\theta_{W,h}$			$\sigma_{1,h}$		
Household		-0.1			0.21			0.1		

Source: [a] Approximate mid-values reported in various papers. [b] Israel Water Authority. [c] Cost shares are from the Social accounting Matrix. Source: Central Bureau of Statistics Israel and own calculation.

Note: Calibrating substitution elasticities is done by combining the supply and demand elasticities with the cost shares.

These exogenous parameters (left section of Table 3.1) are combined with the cost shares from the social accounting matrix (middle section), to provide the calibrated substitution elasticities, $\sigma_{\text{level},i}$, (right section of the table) as follows:

Consider the four level production structure, which was discussed in Section 3.4.1 and Figure 3.3. In the top-level, a perfectly elastic aggregator NWL_i is combined with the immobile capital input. The substitution elasticity $\sigma_{1,i}$ is calibrated by

$$\sigma_{1,i} = \frac{\eta_i \theta_{K,i}}{1 - \theta_{K,i}} \tag{3.5}$$

which assumes that one of the inputs is immobile (see Rutherford, 2002, p.20). $\theta_{K,i}$ is the benchmark value cost share of capital, which is immobile, is obtained from the social accounting matrix (SAM). η_i is the supply price elasticity obtained from empirical studies.

In the second-level, it is common practice to aggregate intermediate inputs and sub-aggregates in fixed-proportions, $\sigma_{2,i} = 0$.

Finally, in the third-level, water and labour inputs are combined, and their sub-

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and Duggan (1996) reports a supply price elasticity of 1.27 in the U.S. energy market.

stitution elasticity $\sigma_{3,i}$ is calibrated by

$$\sigma_{3,i} = \frac{\epsilon_{W,i} + \sigma_{2,i}\theta_{W,3,i} - (\sigma_{2,i} - \sigma_{1,i})\,\theta_{W,2,i} - \sigma_{1,i}\theta_{W,1,i}}{(\theta_{W,3,i} - 1)} \tag{3.6}$$

with $\sigma_{1,i}$ and $\sigma_{2,i}$ being the elasticities from the upper levels. $\theta_{W,1,i}$, $\theta_{W,2,i}$, $\theta_{W,3,i}$ are the water cost-shares relative to each nest, for the various sectors i, which are obtained from the SAM. (Section 3.5.1 explicitly shows how Equation (3.6) is obtained.)

$\epsilon_{W,i}$ is the water demand price elasticity reported in many empirical studies, and summarised in Table 3.1. For the agricultural sector in various countries, Bernardo et al. (1987), Booker and Young (1994), Moore and Hedges (1963), Nieswiadomy (1985), Scheierling et al. (2004) find values for $\epsilon_{W,i}$ ranging from -0.14 to -1. For the Israeli agriculture sector, -0.7 is an accepted figure by researchers. For example, Eckstein (2001) estimates the agricultural demand price elasticities in Israel to be between -0.5 to -0.8, while Becker and Lavee (2002) state that it is close to -1.

For the manufacturing sector, Williams and Suh (1986) and Wang and Lall (2002) estimate the water demand price elasticities to be between -0.7 to -1, while I use -0.7. For service sector, which are mainly office buildings within residential areas, I use surveys for residential water demand price elasticities. Fishelson (1994) estimates the residential water demand in Israel at -0.1, which is used in this paper. Hansen (1996), Arbués et al. (2003), Dalhuisen et al. (2003) and others report that residential water demand price elasticities are low, ranging between -0.1 and -0.3.[7] (A similar parameter is used for the households who are also residential water consumers.)

Finally, recall that the substitution elasticity between potable and non-potable water, in the fourth-level, is assumed to be 1.1, which is based on research by the Water Authority in Israel.

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[7] Sensitivity analysis was reported Section 2.4.2.

3.5.1 Calibrating third-level substitution elasticity

The following explains how to obtain $\sigma_{3,i}$ in Equation (3.6), which is based on Rutherford (2002). I use a three-level nested production function similar to Section 3.4.1, but apply it to a general CES case rather than the Leontief structure in the second-level. Furthermore, the fourth-level is aggregated into the third.[8]

If we construct the cost function from a calibrated benchmark in which input prices and total cost are unity, we can scale the benchmark values of the sub-aggregate cost as unity and express the demand for water as

$$W = [p_W]^{-\sigma_3} p_{WL}^{\sigma_3 - \sigma_2} p_{NWL}^{\sigma_2 - \sigma_1} [p_Y]^{\sigma_1} \bar{W}$$

The derivative of the the demand for water with respect to the input price of water, at the initial allocation point where all prices are unity is

$$\frac{\partial W}{\partial p_W} \mid_{p=1} = \left[-\sigma_3 + (\sigma_3 - \sigma_2) \frac{\partial p_{WL}}{\partial p_W} + (\sigma_2 - \sigma_1) \frac{\partial p_{NWL}}{\partial p_W} + \sigma_1 \frac{\partial p_Y}{\partial p_W} \right] \bar{W} \qquad (3.7)$$

By Shephard's Lemma, the derivative of the unit cost function with respect to input prices, leads to the share of inputs at the benchmark calibration, as follows

$$\frac{\partial p_{WL}}{\partial p_W} = \frac{p_W \bar{W}}{p_W \bar{W} + p_L \bar{L}} = \theta_{W,3}$$

$$\frac{\partial p_{NWL}}{\partial p_W} = \frac{p_W \bar{W}}{p_W \bar{W} + p_L \bar{L} + p_N \bar{N}} = \theta_{W,2}$$

$$\frac{\partial p_Y}{\partial p_W} = \frac{p_W \bar{W}}{p_W \bar{W} + p_L \bar{L} + p_N \bar{N} + p_K \bar{K}} = \frac{p_W \bar{W}}{p_Y \bar{Y}} = \theta_{W,1}$$

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[8] It is well-known that a Leontief function is a special case of a CES function, that assumes a substitution elasticity of zero. Furthermore, their is no need to calibrate the fourth-level elasticity because it is already known.

where an over-bar, $\bar{\square}$, indicates values at the benchmark.

Combining the above with Equation (3.7), obtain

$$\frac{\partial W}{\partial p_W} \mid_{p=1} = \left[-\sigma_3 + (\sigma_3 - \sigma_2)\,\theta_{W,3} + (\sigma_2 - \sigma_1)\,\theta_{W,2} + \sigma_1 \theta_{W,1}\right] \bar{W}$$

Define the elasticity of demand as $\epsilon_W \mid_{p=1} = \frac{\partial W}{\partial p_W} \frac{p_W}{W}$, and therefore

$$\epsilon_W \mid_{p=1} = \left[-\sigma_3 + (\sigma_3 - \sigma_2)\,\theta_{W,3} + (\sigma_2 - \sigma_1)\,\theta_{W,2} + \sigma_1 \theta_{W,1}\right]$$

Finally, solving for for σ_3 yields

$$\sigma_3 = \frac{\epsilon_W + \sigma_2 \theta_{W,3} - (\sigma_2 - \sigma_1)\,\theta_{W,2} - \sigma_1 \theta_{W,1}}{(\theta_{W,3} - 1)} \qquad \blacksquare$$

3.6 Calibrating substitution elasticity in household utility

Section 3.4.2 describes the household's utility structure as a two level CES-Coub Douglas function. Using water demand price elasticities, $\epsilon_{w,h}$, I calibrate the first-level substitution elasticity, $\sigma_{1,h}$, between water and the consumption bundle using the following equation:

$$\sigma_{1,h} = \frac{\epsilon_{w,h}}{\theta_{w,h} - 1} \tag{3.8}$$

The cost share of water, $\theta_{w,h}$, is obtained from the SAM. Household water demand price elasticity, $\epsilon_{w,h}$, is estimated at –0.1, as I did for service sectors. Interestingly, because the water cost share is nearly zero, the substitution elasticity equals minus the demand elasticity of water (see right-hand side of Table 3.1). Finally, in the second-level, final goods are aggregated using a Cobb-Douglas function with $\sigma_{2,h} = 1$, which is standard practice in many applied general equilibrium models.

Calibration method

Similar to Section 3.5.1, the household substitution elasticity is calibrated using water demand price elasticities. At the calibrated benchmark, in which input prices and total expenditure are unity, we can scale the benchmark values of the sub-aggregate expenditure as unity and express the demand for household water as

$$W_h = \bar{W}_h p_{W,h}^{-\sigma_{1,h}} p_U^{\sigma_{1,h}}$$

where p_U is defined as the expenditure function for a unit utility.

Differentiate the above with respect to household water expenditure, and obtain

$$\frac{\partial W_h}{\partial p_{W,h}} = \bar{W}_h \left[-\sigma_{1,h} p_{W,h}^{-\sigma_{1,h}-1} + \sigma_{1,h} p_U^{\sigma_{1,h}-1} \frac{\partial p_U}{\partial p_{W,h}} \right] \tag{3.9}$$

Again by Shephard's Lemma, the derivative of the unit expenditure function with respect to input prices will lead to the share of inputs at the benchmark calibration.

$$\frac{\partial p_U}{\partial p_{W,h}} = \frac{p_{W,h}\bar{W}_h}{p_{W,h}\bar{W}_h + p_C\bar{C}} = \theta_{W,h}$$

Recalling that all prices are unity at benchmark, rearrange 3.9 as:

$$\frac{\partial W_h}{\partial p_{W,h}}|_{p=1} = \bar{W}_h \left[-\sigma_{1,h} + \sigma_{1,h}\theta_{W,h} \right]$$

Finally, defining the own-price elasticity of household water demand as $\epsilon_{W,h}$, and solving for $\sigma_{1,h}$, obtain

$$\sigma_{1,h} = \frac{\epsilon_{W,h}}{\theta_{W,h} - 1} \qquad \blacksquare$$

3.7 Data collection and building the SAM

This section briefly summarizes the data collection process and assumptions made in the calibration of the model.

3.7.1 Social accounting matrix

Careful attention was placed on the construction of the social accounting matrices (SAM), which are based on *Use* and *Supply* tables published by the Israeli Central Bureau of Statistics (CBS). Note that the Use and Supply tables for years 2000, 2004, 2005, 2006 were reported in purchaser prices so that aggregates matched. However, data for 1995 were not directly comparable, because Use data was reported in current output prices, while Supply data was reported in purchaser's prices. As a result, aggregates did not match, and additional assumptions had to be made in order to balance the SAM. Double checking the weights of inputs in production with later years, I assume the 1995 SAM to be sufficiently accurate to be used for comparison with the other years.

Water expenditure for each sector is estimated via other means, and not directly through the Use-Supply tables. This is because CBS does not report water separately from the electricity sector for two reason. First, due to national security reasons, CBS does not reveal sources and dependents. Second, electricity consumption is the largest input into water production, and it is natural for CBS to aggregate them together. As Plaut (2000) reports, electricity is approximately 28% of Mekorot's input costs, which amounts to approximately 6% of Israel's total electricity consumption.[9]

The Water Authority publishes potable and non-potable water consumption for agricultural and manufacturing use, and residential use, *i.e.*, services and household.

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[9] This high energy requirement is due to having water pumped from the Sea of Galilee, an elevation of about 210 meters below sea level into the National Water Carrier, which has an elevation of 152 meter above sea level. From there, gravity continues to transport the water towards the centre of Israel.

Residential use is reported for eleven sub-groups: housing, education, sport, public gardens, public buildings, health, hotels, commerce and trade, security and transport, construction, and service. Data for 2000, 2004, 2005, 2006 is available, while data for 1995 was estimated using the proportions of consumption from the available data of 1996.

Thus, water expenditure in households and service sector is the sum water quantity times the relevant tariff band, as reported by the Water Authority. Agricultural water expenditure is obtained by multiplying the quantity of total potable water supply by the first price block. Likewise for manufacturing, the quantity of water is multiplied by the main water tariff block. Finally, Labour inputs obtained from the Compensation of Employees by Industry tables, were provided by CBS.

3.7.2 Water consumption by user and water prices

Water price data was received from the Water Authority from January 1996 to December 2009. Prices update according to changes in the water-index, which is based on changes to the consumer price index, electricity prices, and average wage levels, or as an administrative decision with governmental approval. In order to obtain a yearly water price, I average prices (if they were changed more than once during the year). Water prices are calculated by the cost of extraction, and by additional costs which are supposed to capture distribution and environmental sustainability.

The Water Authority uses a complex increasing block tariff (IBT) for each type of consumer. As Table 3.2 illustrates, the agricultural sector pays a different price from the residential users, with a different IBT structure. Within residential users, different price are also charged. The Water Authority has changed its pricing structure in 2010, aiming to simplify this structure (See Water Authority (2010)).

Table 3.2: Water price by user (yearly average)

Year[a]	**Quantity**	**1996**	**2000**	**2004**	**2005**	**2006**	**2009**
Household	First 8 CM	2.32	2.69	3.19	3.31	3.52	4.17
	Next 7 CM	3.42	3.99	4.49	4.61	4.85	5.75
	Any additional CM	4.97	5.78	6.28	6.40	6.69	7.93
Hospitals and *mikve*		3.68	4.28	2.26	2.38	3.43	2.77
Hotels		1.27	1.69	2.19	2.30	2.48	4.23
Public Buildings, Stores, Business, etc.		3.68	4.28	4.78	4.90	5.15	6.04
Public Gardens		4.97	5.78	6.28	6.40	6.69	7.68
Manufacturing (Potable)	In allocation limits	1.10	1.60	2.28	2.48	2.49	3.19
Excess	Up to 10% over allocation	0.36	0.36	0.36	0.36	0.36	0.36
Excess	Above 10% over allocation	0.96	0.96	0.96	0.96	0.96	0.96
Agriculture (Potable)	Quantity A	0.78	0.94	1.31	1.46	1.48	1.63
	Quantity B	0.89	1.08	1.54	1.69	1.70	1.87
	Quantity C	1.11	1.38	1.98	2.13	2.15	2.36
Excess	Up to 10% over allocation	0.36	0.36	0.36	0.36	0.36	0.36
Excess	Above 10% over allocation	0.96	0.96	0.96	0.96	0.96	0.96
Recycled (Shafdan)		0.52	0.62	0.79	0.79	0.80	0.86
Effluents		0.38	0.45	0.51	0.51	0.52	0.64

Source: Israeli Water Authority

[a] In 2010, the price bands were changed. However, since the data of the model covers until 2006, I do not investigate the effects of this new price band.

3.8 Conclusion

Chapter 2 uses a CGE model to compare two alternative water allocation mechanisms, with Israel as a case study. The outcome of the study is that the current administrative allocation in Israel is likely to be more socially beneficial than a market mechanism. The aim of Chapter 3 is to expand on and contextualize the Israeli water situation, and give a full description of the CGE model and the calibration methods that were used.

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Part II Malaria prevention

Chapter 4

Estimating the macro-economic impact of malaria: a case study of Ghana (with P. Hunt and S. Hoorens)

4.1 Introduction

The scale of malaria infection in Africa is widespread. In 2010 it was estimated that there were 216 million episodes of the disease, of which 81% were in the African region. Moreover, of the approximately 0.655 million deaths estimated, 91% were in Africa. Children are the most vulnerable, and approximately 86% of malaria deaths globally involve children under-five (< 5) years of age (WHO, 2011).

Besides the obvious toll on human life, this has considerable economic consequences for developing countries. Research on the correlation between malaria and economic growth find that it harms efforts to stimulate growth in low-income countries. This is specifically highlighted in the seminal work of Gallup and Sachs (2001), who estimate that malaria elimination in sub-Saharan Africa could increase per capita growth by as much as 2.6% a year. Other literature using cross-country regressions generally supports these findings (McCarthy et al., 2000; Sachs, 2003).

However, the nature and extent of the link between health and economic growth remains contended. Acemoglu and Johnson (2007), for example, criticise the above-mentioned types of cross-country regressions, because they neglect the general equilibrium effects of diminishing returns to effective units of labour. Low-income countries are disadvantaged in a number of ways and these studies might be capturing omitted variables rather than health, particularly when health improvements are accompanied by population increases.

This debate, however, is neither practical, nor useful to policy makers of malaria-burdened countries and donors. They require more detailed information to assist them in assessing the optimal health provision policy and investment, and for performing distributional analysis. Consequently, Mills et al. (2008) review literature on the economic value of malaria reduction, and call for further macroeconomic modelling to inform policy makers of the efficient provision of treatment.

This research responds to this call by applying a modelling approach - a dynamic computable general equilibrium modelling (DCGE), which has gained ground recently in health economics in application to HIV/AIDS, anti-microbial resistance, pandemic influenza and non-communicable disease (Kambou et al., 1992; Dixon et al., 2004; Smith et al., 2005, 2009; Thurlow, 2007; Rutten and Reed, 2009). However, it remains a new field within health economics, and specifically in application to malaria.

The aim of this chapter is to impute the economic value of malaria prevention on an endemic country. Its contribution is not only in linking health and economic growth, as is discussed mainly in the literature, but also as a useful approach for policy analysis.

There are various avenues by which malaria affects economic growth. Here, the focuses is on the link between malaria prevention and the labour resources, mainly because labour is a fundamental component to economic production and development.

Other potential connections are left out in order to maintain a clearer assessment of the impact. Furthermore, the analysis centres on the effect that malaria prevention would have on children < 5 years of age, who are the most vulnerable to the disease, but do not contribute to economic production in the short-run. This provides an interesting long-term perspective into malaria prevention, because it considers the future development of a country's labour resources.

Finally, because the preventative interventions are assumed to be administered "free of charge," the results show the benefits of various scenarios. This is particularly useful to policy makers, who wish to compare the costs of alternative interventions with their expected benefits. Such traditional cost-benefit analysis methods, however, are not common to health policy.

As a case study, the model is calibrated to data from Ghana, an African country with endemic malaria. The following questions are addressed: (1) What are the economic benefits of malaria prevention per covered child? (2) Does treatment lead to poverty reduction? (3) Would a different allocation of limited treatment resources lead to higher benefits per capita?

This chapter is structured as follows: Section 4.2 reviews malaria and its social and economic consequences in order to establish the context used to frame the economic model. Section 4.3 focuses on Ghana, as a case study, and describes the overall malaria condition, including the epidemiological heterogeneity across the country. Section 4.4 describes the multi-sector multi-agent DCGE model used for the Ghanaian economy. Section 4.5 explains the cohort-component demographics model; Section 4.6 describes the labour efficiency index model; with Section 4.7 highlighting some limitations. Finally, Section 4.8 reports results, and Section 4.9 concludes.

4.2 Malaria and its social and economic consequences

Malaria is caused by a family of macroparasites, transmitted by certain species of the anopheline mosquito. When infecting humans, the parasites invade red blood cells that causes them to rupture synchronously, thus producing symptoms of fever and chills, along with headaches, vomiting, and diarrhoea. Infection may also cause long-term anaemia, liver damage, neurological damage. and even death. Malaria reduces, therefore, economic production both in the short and long-run.

In order to reduce and eliminate malaria infection, countries employ a variety of preventative methods, such as insecticide treated nets (ITN), intermittent preventive treatment for pregnant women (IPTP), indoor residual spraying (IRS), reducing the breeding sites of mosquitoes, and administering various anti-malarial drugs, with varying degrees of success to prevent infection. At present, there are no vaccines for malaria, but candidate vaccines are currently under development (Agnandji et al., 2011; Garcia-Basteiro et al., 2012).

It is generally accepted that a mentally and physically healthier population is associated with a healthier economy (Schultz, 2010). The negative effects of poor health on productivity and economic development in most sub-Saharan African countries have been widely documented (McCarthy et al., 2000; Bhargava et al., 2001; Schultz, 2010), including the specific effects of malaria (Sachs and Malaney, 2002; Bleakley, 2003, 2010). Control of malaria is therefore expected to predominantly affect the economy through improvements to the quantity and quality of human capital, which is defined as the stock of skills, education, physical abilities, competencies and other productivity-enhancing characteristics embedded in labour (Acemoglu, 2009). In this paper, it represents the efficiency units of labour embedded in raw labour days.

There are further channels by which malaria may affect the economy, such as health care spending, tourism spending, foreign investment and migration (Sachs and Malaney, 2002). In order to keep a focused analysis, these are not considered here.

Therefore, the economic benefits observed in the model are lower bounds, and would only be larger if these other effects were included.

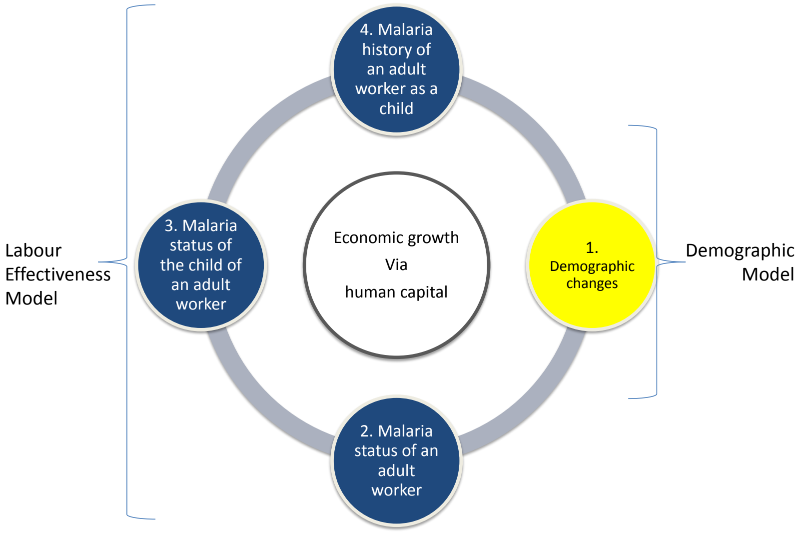
The workforce is a fundamental part of a the resources of a country, and the future demographic condition has an important influence on the potential economic growth. Regional variation in labour skill-supply, and the national and international demand for various skills sets, furthermore affect economic growth potentials.

Many studies use life expectancy as a proxy for health, and link the health status of a population with economic growth potential and the level of productivity of the country (Sachs and Malaney, 2002; Weil, 2010). A review of thirteen related studies finds that increases in life expectancy increases the long-run level of output (Bloom et al., 2004). Acemoglu and Johnson (2007) have, however, a critical opposing view to this, and find no evidence that the large increases in life expectancy raised income per capita.

The potential effects that malaria has on human capital are summarized in a typology of four factors (illustrated in Figure 4.1). First, demographic changes are a result of improved malaria control which reduces mortality rates, particularly those of children. This raises the life expectancy, and changes the population size and age structure. Second, when adult workers are healthier, they have less days off work (defined as absenteeism), which directly increases production. When workers are present at work, but less-ill (defined as presenteeism), productivity also improves. Third, when children of adult workers are healthier, parents (carers) will loose less days off work from caring for ill children. Finally, when the adult workers were healthier as children, they benefit later in life, by having missed less school days, and having less health complications. This improves their mental and physical capacity, and allows them to generate more production and productivity as adults (Barlow, 1967; Weil, 2010).

This typology is grouped into two health components: (1) a demographics com-

Figure 4.1: A typology of the effects that malaria has on economic growth



ponent for the size of the labour force; and (2) a labour effectiveness component that accounts for the impact of the three malaria health statuses on production and productivity. The following sections review the context behind this typology, collect data, and set the stage for developing the two health models that are linked with the DCGE model.

4.2.1 Demographic changes and mortality (first component)

There is a wealth of evidence for the direct link between preventative interventions with malaria morbidity and mortality (e.g., D'Alessandro et al., 1995; Nevill et al., 1996; Nyarango et al., 2006; Bhattarai et al., 2007). The future potential labour resources of a country (*i.e.*, working age population) is related to demographic conditions and to regional variations in malaria epidemiology. Other things being equal, an increase in the proportion of the working age population will increase the income per capita levels.

Changes to malaria prevalence affect the size, growth rate, and age structure of the population over time. In the short to medium term, a reduction in malaria may lead to an increase in the fertility rate due to pregnant women suffering less miscarriages, and an increased vitality of both men and women, which leads to higher levels of conception (Barlow, 1967). Additionally, the mortality rate falls overall, but proportionately more among children. This raises the population growth and shifts the age structure towards dependent children. In the long term, fertility rates are expected to fall because families do not need to compensate for the risks of high mortality with higher fertility rates. Therefore, the age structure gradually shifts towards a greater weight on the working-age adults (Weil, 2010). Section 4.5 discusses the population projection model that is used to estimate the link between malaria and the demography of Ghana.

4.2.2 Labour effectiveness (second component)

As previously mentioned, changes to malaria affect production and productivity through the absenteeism and presenteeism of adult workers. The following literature review collects the number of days lost and productivity lost, per year, due to malaria. These values are then used to develop a model for the labour effectiveness index in Section 4.6.

Malaria status of adult workers and their children

An example offered by Weil (2010) describes how "a person who is lying in bed suffering an acute bout of malaria is unable to supply any productive labour at all. ... People suffering disease can work fewer hours to those who are healthy, may work at a slower pace, and may be mentally less acute." Capturing these three elements - hours of work, pace of work effort, and mental acuteness, Table 4.1 summarizes the lost number of days from work or lower productivity across various countries of Africa. Generally, an adult is absent from work for one to four days per episode of malaria, and has lower output when at work equivalent to approximately two days.

Table 4.1: Adult worker lost production days and productivity due to malaria illness

Authors	**Country**	**Days lost per incident Absenteeism**	**Days lost from Presenteeism**	**Productivity loss from Presenteeism (indexed to 1)**
Cropper et al. (2000)	Ethiopia	18 (per year)		
Ettling and Shepard (1991)	Rwanda	3		
Ettling et al. (1994)	Malawi	2.7		
Guiguemdé et al. (1997)	Burkina Faso	4		
Leighton and Foster (1993)	Kenya	2-4	2	
Leighton and Foster (1993)	Nigeria	1-3	2	
Sauerborn et al. (1991)	Burkina Faso	3.5		
Sauerborn et al. (1995)	Burkina Faso	5	1	
Hong (2011)	US			0.89
Hanlon et al. (2012)	Ghana			0.75 (inc. mort)
Asante et al. (2005)*	Ghana	9.35 (per year)		
Gollin and Zimmermann (2008)	Not explicit			0.9
Murray and Lopez (1996)**	Not explicit			0.9
Ashraf et al. (2009)***	Not explicit			0.864
Average		**3 days**	**2 days**	**0.9**

*Males only; **Disability weight; *** Disability weight rescaled

Gollin and Zimmermann (2008) use an estimate for effective unit of labour of an individual with malaria as 0.9, where a malaria-free person as 1.0. Ashraf et al. (2009) develop disability weights and find that on a scale where perfect health is zero and death one, malaria episodes reduce the abilities of a person by 13.6%.[1] This means that a person with malaria is only 0.864 as effective as a healthy individual.

Improvements in health treatment may reduce the amount of time that healthy adult workers need to stay out of work to take care of sick children or other family members. Table 4.2 summarises that workers lose approximately one to two working days to care for someone with malaria.

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[1] For example, the disability weights are: blindness (0.600), severe iron deficiency anaemia (0.093), HIV (0.136), AIDS (0.505), tuberculosis seronegative for HIV (0.264), malaria episodes (0.136), and neurological sequelae of malaria (0.473) (Ashraf et al., 2009).

Table 4.2: Days lost due to caring for children with malaria

Authors	Country	Days lost to caring
Aikins (1995)	The Gambia	2.16 hours per day per child for 4 days
Cropper et al. (2000)	Ethiopia	11 (per year)
Ettling and Shepard (1991)	Rwanda	1
Ettling et al. (1994)	Malawi	1.2
Guiguemdé et al. (1997)	Burkina Faso	Assumed to be 1.2
Leighton and Foster (1993)	Kenya	2-4
Leighton and Foster (1993)	Nigeria	1-3
Sauerborn et al. (1991)	Burkina Faso	2.7
Sauerborn et al. (1995)	Burkina Faso	1/3 of adult illness time
Asante et al. (2005)*	Ghana	5.0 (per year)
Average		**1-2 days**

*Males only.

Malaria history of adults workers as children

Malaria can negatively affect the development of human capital by reducing educational outcomes and achievement. This in turn lowers productivity when children reach the working age. In particular, children with repeated bouts of malaria miss more schooling days, and therefore have lower performance (Weil, 2010; Baird et al., 2011).

Studies for Sri Lanka and Kenya find that due to malaria, children miss approximately five to six school days per episode, and 20-30 days overall. These repeated cases lowered school performance by approximately 15%. Students that were given preventative interventions for malaria performed 26% better compared to a control group (Leighton and Foster, 1993; Fernando et al., 2003a,b, 2006).

Malaria may also affect the quality of education that students receive, as teachers miss school days due to acquiring malaria or to care for family members, who have acquired malaria. Leighton and Foster (1993) find that primary teachers in Nigeria miss on average six days per year because of malaria, which reduces the number of days that students receive instruction from their regular teachers.

When children are carers, the amount of education they earn is reduced. The

Table 4.3: Impact of malaria as a child for labour productivity later in life

Authors	**Country**	**Efficiency units due to illness as a child, using wages as proxy**
Bleakley (2003)	US	0.85
Cutler et al. (2010)	India	0.83-0.97
Bleakley (2010)	US, Brazil, Colombia, Mexico	0.5
On Average		**0.75**

education of girls may be inordinately affected by malaria because when parents cannot stay home to care for sick children, they often turn to their daughters to care for their siblings. The girls therefore may miss more school days than boys, while tending to sick siblings (Fernando et al., 2006).

Malaria can also cause cognitive declines through negative effects on health, such as anaemia, malnutrition, or neurological injury, leading to learning disabilities or psychological difficulties (Holding and Snow, 2001; Chima et al., 2003). In Kenya, school children who are hospitalised with cerebral malaria are 4.5 times more likely to have learning difficulties (Holding et al., 1999). Malaria during pregnancy raises the risk of low birth weight babies, which in turn raises the risk of neurosensory, cognitive and behavioural development problems in children. Low birth weight babies are found to be two to four times more likely to fail grades in school (Taylor, 1984; McCormick et al., 1992; Sachs and Malaney, 2002).

Bleakley (2003, 2010) demonstrates that individuals with malaria as children earn 15 to 50% less in adulthood than those who were malaria-free. Cutler et al. (2010) also confirms this for India, but with less severity. These wage deviations partly indicate the differences in worker productivity, which were caused by malaria.

In summary, malaria has both direct and indirect effects on education, and on the potential of children to engage actively and productively in the labour force later in life. As reported in Table 4.3, the average reduction in productivity caused by malaria is estimated at 20-30%.

Table 4.4: Key statistics on malaria in Ghana, 2009

Annual number of cases of clinical malaria reported 2002-2009	3.1-3.8 million
All Ages	
Malaria as cause of admission (of total admissions)	32.9%
Malaria as case of death (of total deaths)	13.4%
<5 **years of age**	
Malaria as cause of admission (of total admissions)	58.1%
Malaria as cause of death (of total deaths)	20.2%

Source: Ghana Health Service (GHS, 2009; GSS, 2009).

4.3 Ghana case study

Ghana is a sub-Saharan African country with a population of 24 million. The country has recently experienced economic growth and development towards becoming a middle-income country. However, life expectancy of Ghanaian women and men was 59 and 58, respectively (Agyeman-Duah et al., 2006), compared to 81 and 75 in the EU, in 2005 (Eurostat, 2012).

Furthermore, malaria in Ghana is still endemic, and is a major public health concern.[2] It is the single largest cause of morbidity and a significant cause of mortality. 30-40% of deaths in < 5 year old Ghanian children are attributed to malaria. Whilst there are public health programmes to deliver malaria prevention and manage cases, malaria prevalence[3] has changed little since the early 2000s.

A number of attempts have been made to address the malaria problem in the country. For example, household ownership of an insecticide treated net (ITN) has risen from 3% in 2003 to 33% in 2008 (GSS, 2009). However, as reported by Ghana Demographic and Health Survey (see Table 4.4), more than three million cases of clinical malaria are reported to public health facilities each year. In 2009, it was the top single cause of hospital admission for children aged < 5 (58.1%), and their

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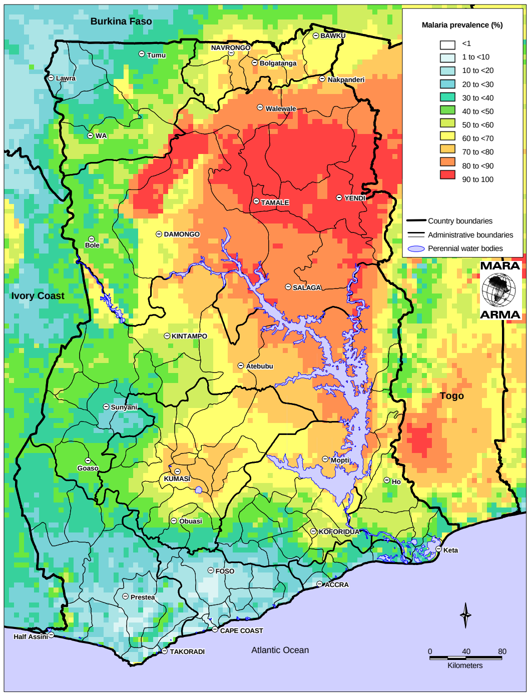
[2] Endemic areas are defined as areas with significant annual transmission, be it seasonal or perennial (Snow et al., 1999).

[3] Prevalence is defined as the number of malaria cases per population. This could be stratified by age group, region, etc.

Figure 4.2: Malaria prevalence in Ghana

Ghana: Malaria Prevalence Model



This map is a product of the MARA/ARMA collaboration (http://www.mara.org.za). March 2002, Medical Research Council, PO Box 17120, Congella, 4013, Durban, South Africa
CORE FUNDERS of MARA/ARMA: International Development Research Centre, Canada (IDRC); The Wellcome Trust UK; South African Medical Research Council (MRC);
Swiss Tropical Institute, Multilateral Initiative on Malaria (MIM) / Special Programme for Research & Training in Tropical Diseases (TDR), Roll Back Malaria (RBM).
Malaria Prevalence Model: I. Kleinschmidt et al. 2001. An empirical malaria distribution map for West Africa. Tropical Medicine and International Health 6: 779-786.
Topographical data: African Data Sampler, WRI, http://www.igc.org/wri/sdis/maps/ads/ads_id

Source: Source: http://www.mara.org.za/pdfmaps/GhaPrevModel.PDF
This map is a product of the MARA/ARMA collaboration (http://www.mara.org.za).

main cause of death (20.2%). This suggests that there is a great deal of room for improvement in terms of malaria prevention and case management - particularly for children.

The entire Ghanaian population is at risk of malaria, but there are variations across the zones by prevalence, annual duration of transmission, and the type of malaria parasite. (See Figure 4.2 for prevalence by zone.) To consider the geographical epidemiological variation within the economy, and to link between health and the labour force, we divide Ghana into five malaria epidemiological zones: (1) the tropical rainforest; (2) Accra; (3) the coastal savannah and mangrove swamps; (4) the northern savannah and (5) the southern savannah. These zones reflect four different ecological zones in Ghana and one metropolitan Accra.

Figure 4.3: Mapping administrative districts to ecological zones

Administrative District	Ecological Zone
Western Central Ashanti	Forest
Greater Accra	Accra
Volta (50% of pop.) Eastern	Coastal
Northern Upper East Upper West	North Savannah
Volta (50% of pop.) Brong Afaso	South Savannah

Note: Social Accounting Matrix from Breisinger et al. (2009, 2011).

Broadly speaking, Ghana has ten administrative regions, which were mapped onto the five epidemiological zones as summarized in Figure 4.3. The Coastal zone covers the Eastern and Volta regions; the Forest zone includes the Ashanti, Western, and Central regions; the Southern Savannah includes Brong Afaso and part of Volta; and the Northern Savannah includes the Upper West, Upper East, and Northern regions.

The reasons for this demarcation are the following: First, the zones are used to capture some of the heterogeneity in malaria endemicity (see Figure 4.2). Data on malaria prevalence across regions and age groups of Ghana (2002), is available from the Mapping Malaria in Africa/Atlas du Risque de la Malaria en Afrique (MARA/ARMA). High prevalence rates of malaria are concentrated in the Northern district (North Savannah) and in Ashanti (Forest), where Malaria prevalence ranges from 23 to 63% for < 1 years old across the zones, as reported in Table 4.5. For the > 15 population, prevalence ranges from 23.5 to 54%.

Second, the Social Accounting Matrix (SAM) used in this paper is based on previous studies by the International Food Policy Research Institute (IFPRI) (Breisinger

Table 4.5: Malaria prevalence (%) by region and age groups of Ghana, 2002

Agro-ecological zones	**Administrative region**					**Age groups**
		0	**1 to 4**	**5 to 9**	**10 to 14**	**15 plus**
Forest	Ashanti region	63.12	n/a	65.65	62.62	23.53
	Western region	n/a	n/a	n/a	n/a	n/a
	Central region	n/a	n/a	n/a	n/a	n/a
Southern Savannah	Brong Ahafo	n/a	n/a	n/a	n/a	n/a
	Volta region*	34.99	n/a	n/a	n/a	n/a
Coastal	Eastern region	46.76	n/a	n/a	n/a	n/a
Northern Savannah	Upper East region	56.28	83.8	79.79	77.38	54.14
	Upper West region	n/a	n/a	n/a	n/a	n/a
	Northern region	n/a	n/a	n/a	n/a	n/a
Accra	Greater Accra	23.25	n/a	30.05	n/a	24.9

Note: Prevalence is defined as the total number of cases in the population at a given moment as a percentage of the total population. * Half of Volta is in the Coastal region. n/a is not available.
Source: MARALite.

et al., 2009, 2011). Their focus has been to capture economic activity variation at the sub-national level due to agricultural production patterns and technologies. IFPRI had referred to zones as (agri-) ecological zones, while we overlay them on (malaria) epidemiological zones.

Social accounting matrix

Our economic dataset is based on a highly disaggregated social accounting matrix (SAM) for Ghana, which contains the revenues and expenditures for commodities and agents. The SAM is developed by Breisinger et al. (2009, 2011) and represents the Ghanaian economy in 2007.[4] It is constructed from a wide range of data: Using 2005/2006 Ghana Living Standards Survey (GSS, 2008), the SAM includes 90 households that are differentiated by the ten Ghanaian administrative regions, urban-rural characteristics, income and consumption. With data from the Ministry of Food and Agriculture (MOFA) and Industrial Census (GSS), 142 activities and 70 commodities

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[4] The SAM was generously provided by the International Food Policy Research Institute (IFPRI).

were estimated. It also includes accounts for the government, investment and savings, and the rest of the world.

For our particular study, the SAM was re-aggregated and stratified by the five malaria epidemiological zones, urban-rural location, and five income level quintiles. The exception is Greater Accra which is assumed to be fully urban.[5] Therefore, the re-aggregated SAM, and the DCGE model, characterise nine epidemiological urban-rural regions, which have overall 45 heterogeneous representative households.[6]

Finally, production sectors are not the main focus of this research, and will not directly effect economic growth. Therefore, the large number of activities and commodities in the original SAM were aggregated into four main ecological agricultural sectors, an industry sector, and a services sector.

4.4 A dynamic general equilibrium model for Ghana

To explore the effects of malaria on the labour force, we developed a dynamic, multi-sector, multi-agent, computable general equilibrium (DCGE) model, which integrates two health components: (1) a demographics model; and (2) a model for the labour effectiveness index.

The DCGE model does not attempt to make precise predictions about the future development of the Ghanaian economy. Its purpose, however, is to measure how additional malaria health prevention would affect the economy-wide growth and poverty reduction, compared to a baseline scenario of no additional intervention. The model is also different from traditional DCGE models, which usually focus on the national level. Here, the focus is on the regional heterogeneity in health between many households.

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[5] We follow the original SAM, and therefore Greater Accra is fully urban.

[6] To be completely explicit, there are four epidemiological zones with an urban rural divide, and therefore, eight regions. Greater Accra is fully urban. This leads to nine regions, each having five income level quintiles, and therefore, to 45 separate households.

Table 4.6: Coverage of the preventative malaria intervention in the baseline and three alternative scenarios

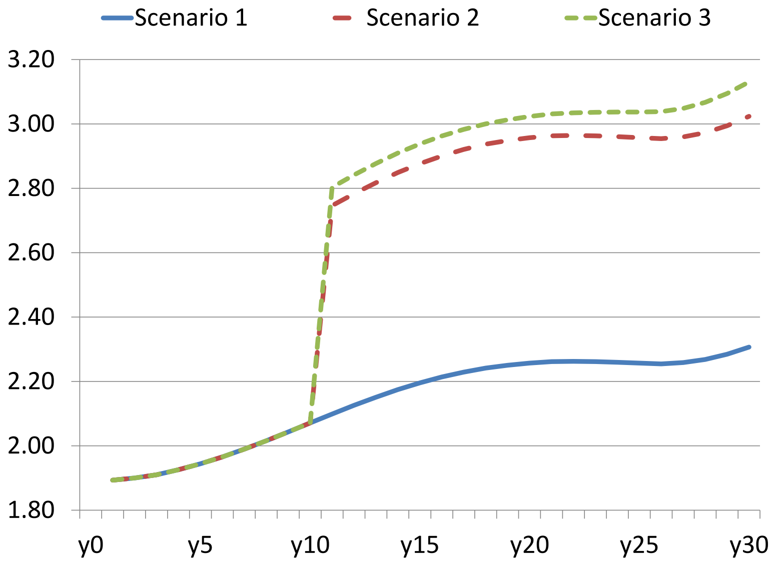
Scenario	**Description**
Baseline:	Coverage is 0%
Scenario 1:	Coverage rises to 65% nationally in year 1 onwards for under-fives
Scenario 2:	Scenario 1 coverage from year 1 until year 10, then increases to 85% nationally
Scenario 3:	Scenario 1 coverage from year 1 until year 10, then increase to 100% for two high malaria prevalence zones

In the baseline scenario, the model projects economic growth for a case where there is *no* additional malaria intervention above the current situation. In the three counterfactual scenarios, we simulate cases where additional malaria treatments are given "free of charge," *e.g.*, by administering additional insecticide treated nets or other prophylaxis. Each scenario assumes that the *efficacy* of the intervention is 50%, but differ by the level of *coverage* and targeting of zones. Furthermore, the intervention is given only to children < 5, and then taken away as their cohort moves to ages > 5. Finally, the model begins at year 0, and malaria intervention at year 1, which thereafter continues throughout the simulated period.

As summarized in Table 4.6, Scenario 1 assumes that a malaria intervention is rolled-out nationally, covering 65% of the < 5 population. This scenario is considered feasible in the short-run. In Scenarios 2 and 3, we assume that the hard-to-reach population can gain access to the intervention, in the medium to long-run. Therefore, in Scenario 2, coverage increases after 10 years to 85% nationally. In Scenario 3, coverage rises to 100%, for the two high prevalence zones, while remains at 65% for the rest of the zones. Figure 4.4 reports the number of children covered for each of the simulated scenarios.

The next section gives a summary of the DCGE model that is developed for this research. Chapter 5 provides a full analytical description of the model, its assumptions, and the parameters that it uses.

Figure 4.4: Number of under five year covered (millions)



Source: Authors' own calculations

4.4.1 A description of the model

We follow Mathiesen (1985) and Rutherford (1995, 1999) and set up an Arrow–Debreu equilibrium as a mixed complementarity problem (MCP). Three types of weak inequality conditions are satisfied simultaneously: (1) zero profit, (2) market clearance, and (3) income balance, each associated with a non-negative variable.

We design a multi-sector, multi-agent, recursive dynamic CGE model,[7] and use the social accounting matrix (SAM) by Breisinger et al. (2009, 2011) to calibrate the model for Ghana. As mentioned previously, the SAM is re-aggregated so that it characterises five epidemiological malaria zones, two urban-location (urban, rural), and five income levels. This leads to 45 representative households, $h \in H$.

Each household is endowed with capital, land, and three occupational categories of labour, L_{lh}. We define the set of labour skill-types by

$$\{\text{self-employed, skilled, unskilled}\} \in l$$

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[7] Coded in GAMS using Rutherford (1995, 1999)'s MPSGE. This allows handling of CGE models in a consistent and compact format with mixed complementarity.

Households accumulate capital (depreciated capital plus investment), transfer (receive) funds from the government and the rest of the world, and also pay tax to the government, thus forming the disposable income of households.

Households are assumed to be rational, with a locally non-satiated preference relation,[8] and a continuous, multi-level, extended linear expenditure system (ELES) utility function (Howe, 1975). In the first-level, a representative household maximizes a utility function comprising of a consumption bundle and private savings, in fixed shares, subject to the disposable income. In the second-level, the household maximizes a Stone-Geary utility function that accounts for the minimum subsistence requirements, and allows income elasticities to be different than one. The maximization problem is constrained by the residual disposable income.

The government receives income from collecting taxes and tariffs, and also receives (transfers) funds from domestic households and the rest of the world. It provides a public service by purchasing commodities, and saves a fixed proportion of income.

Firms produce a single good using a multi-level, differentiable, constant return to scale (CRS) production function that combines the factor inputs with intermediate goods. Similar to Rutherford et al. (2002) and Hosoe et al. (2010), a constant elasticity of transformation function is used to split production into export and domestic consumption. Then, domestic consumption and imports are aggregated to form the Armington final good, which is finally demanded by private and public consumption, investment, and/or as an intermediate good (Armington, 1969).[9]

Ghana is assumed to be a small open economy (SOE), which cannot affect world prices. Export and import prices quoted in foreign currency are exogenously given. It has unrestricted borrowing (lending), and international capital can freely flow between the domestic and foreign economies.

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[8] For any bundle of goods there is always another bundle of goods arbitrarily close that is preferred.

[9] Armington composite goods are used to account for cross hauling (two-way trading) in the same good, i.e., goods are both imported and exported.

Being a SOE, the domestic rental rate of capital is therefore fixed to world prices through the level of the foreign exchange rate. This is characterised by introducing two mutually exclusive functions that convert units of capital in (out) of the domestic economy to the ROW. For example, whenever the rental rate of capital is higher (lower) compared to that in the ROW, reflecting higher (lower) demand for capital compared to other non-transferable domestic inputs (*i.e.*, labour and land), capital will flow in (out) through the capital account. This, therefore, imposes capital price equalization. Furthermore, it affects the level of demand for investment, *e.g.*, too much capital will dampen the demand for investment.

The rest of the world (ROW) is modelled as a simple agent that demands foreign savings (in the domestic economy). Its budget is equal to ownership of domestic capital (if any), net remittances, and demand for net imports.[10]

Finally, a virtual investment firm builds new capital stock for the next period. Its budget is comprised of the private, public and foreign savings, and it demands (Armington) final consumption goods in fixed proportion, as inputs for investment.

4.4.2 Recursive dynamics

The model uses a recursive dynamics approach, where agents are assumed to be myopic rather than forward-looking. This means that they do not change saving-consumption behaviour in the present, due to knowledge of future expectations. The model is solved sequentially for 30 years, where stock variables are updated exogenously, at each period, based on the health models, and other assumptions that are described in detail in Chapter 5. The exception is capital accumulation, which occurs through endogenous linkages with previous-period investment.

There are four reasons for using a recursive model (rather than a forward-looking): First, the main purpose of our simulation is to link the role of health on the labour re-

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[10] A net export, from the perspective of the domestic economy.

source, and thus on the economy. Having households increase consumption today, due to their forward-looking expectations that they will have a healthier labour resource in the future, seems questionable.

Second, there is doubt whether developing countries, such as Ghana, can be characterised as forward-looking. Empirical observations suggest that low income agents are most often myopic, mainly because they are credit constrained (Deaton, 1991, 1992; Foster, 1995; Morduch, 1995). Therefore, they are unable to allocate resources optimally across time, which negates the, theoretically elegant, permanent income hypothesis.

Third, Babiker et al. (2009) compare the recursive versus forward-looking models and conclude that the recursive produces similar behaviour, but also provides greater flexibility in the details of the system that can be represented compared to a forward-looking approach.

Finally, given the complexity of the model in terms of the large numbers of production sectors and households, a fully forward looking dynamic model cannot be solved computationally.[11] Breisinger et al. (2009, 2011) report the same problem.

We therefore set up a capital accumulation assumption that resemble those modelled by Springer (2002), Klepper et al. (2003) and Thurlow (2007), whereby a virtual investment firm, as described previously, characterizes a competitive capital market. This assumption means that the purchasing price of one unit of new capital equals the rental earnings of that unit, plus the value of the remaining capital sold in the subsequent period, *i.e.*, zero profit condition.[12] An agent decides between consumption and investment, and the model resembles a Solow-type model, with savings proportional to household income. However, it also differs because the small open economy

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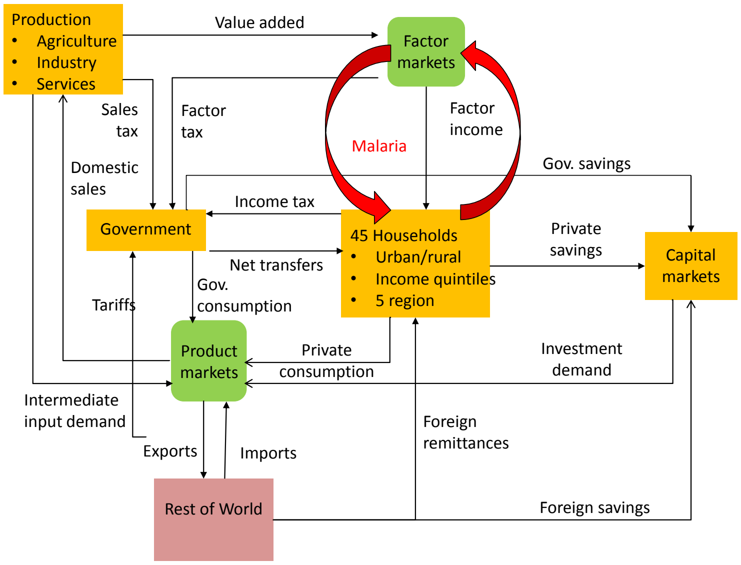
[11] A forward looking model was initially implemented, but became unfeasible when presented with more than three households.

[12] Kinnunen (2007); Breisinger et al. (2009, 2011); Diao (2009) use a different approach, whereby newly invested capital is influenced by each sector's initial share of gross surplus, and the final allocation depends on depreciation and sector specific profit-rate differentials.

Figure 4.5: A diagrammatic representation of the DCGE model



Note: Adapted from Li (2002).

(SOE) assumption fixes the rental rate of capital to world prices, as described previously.

Figure 4.5 illustrates the general structure of the economic model, and the way in which Malaria impacts the economy through the factor markets. This is further discussed in the next section.

4.4.3 Integrating health into the DCGE model

The stock of labour, $\bar{L}_{h,l,t}$, is assumed to be fully employed, and mobile across sectors with flexible real wages. It is disaggregated across 45 households, and three occupational categories, *i.e.*, self-employed, skilled, low skilled. The DCGE model integrates the effects that malaria has on labour by (1) projecting the stock of labour forward; and (2) estimating the labour effectiveness index, for each epidemiological zone.

Production is labour-augmenting, whereby total labour supply is the stock of household labour $\bar{L}_{hlt}$ multiplied by its effectiveness level, E_{hlt}. The labour augmenting supply, L_{hlt}, is therefore

$$L_{hlt} = \bar{L}_{hlt} \cdot E_{hlt} \tag{4.1}$$

and updated yearly by

$$L_{hl,t+1} = \underbrace{\bar{L}_{hl0} \cdot (1 + g_{hlt})}_{\text{workforce size}} \cdot \underbrace{E_{hl0} \cdot (1 + e_{hlt})}_{\text{effectiveness}} \tag{4.2}$$

with $\bar{L}_{hl0}$ defined as the stock of labour in the base year, and labour effectiveness in the base year as $E_{hl0} = 1$. Inputs into the DCGE model are (1) the household-specific labour growth g_{hlt}, which come from the demographic model; (2) changes to labour effectiveness e_{hlt}, which come from the labour efficiency model. The next two sections explain the health models in further detail.

4.5 Population projection model

The main purpose of the population projections component is to estimate the size of the workforce in Ghana, and the changes that would follow from malaria prevention. Because the core of the research is the link between health, labour efficiency, and economic outcomes, we require a simplified, yet realistic and uncontroversial approach to estimating the mortality impact of malaria prevention. We have, therefore, deliberately selected a widely used platform for linking maternal and child survival interventions with health interventions and demographic projections.

This platform, called *Spectrum,* which includes various modules (Stover et al., 2010). *DemProj*, being the core module, projects the population using a cohort-component method that is a commonly used approach to project population size, composition, and structure (Stover and Kirmeyer, 2008). A second module, Lives Saved Tool (*LiST*), is used when malaria interventions are introduced in the counterfactual scenarios (Winfrey et al., 2011). DemProj and LiST interact simultaneously to estimate the number of < 5 deaths that can be averted by interventions of eleven different diseases, with malaria being one of them.

Spectrum contains a database that provides instant access to population estimates and projections for Ghana at country level, as well as for 192 other countries and regions from the United Nations Population Division.[13] In this Ghana case study, we 'borrow' the basic structure of Spectrum, but introduce the regional specific information that correspond to the previously mentioned epidemiological zones. The following sections describe the main methodology and the assumptions.

4.5.1 Baseline projections using a cohort-component method

The cohort-component model requires assumptions for life expectancy at birth, total fertility rates, age distribution of fertility, sex ratio at birth, and the number and distribution by age and sex of international migrants. DemProj uses a Coal-Demeny North model life table with age and sex specific patterns of mortality. Using the base year age structure, age cohorts incrementally move forward in time, and amend according to a set of age-specific fertility rates, age-specific survival rates, and migration rates, by rural urban location (Pearl and Reed, 1920; Bowley, 1924; Dorn, 1950).

The population for each age cohort $i \in N$, region $r \in R$, for time $t \in T$ is expressed by

$$Pop_{i,r,t} = Pop_{i,r,t-1} + B_{i,r,t-1} - D_{i,r,t-1} + M_{i,r,t-1} \tag{4.3}$$

with $Pop_{i,r,t-1}$ being the stock of population in the previous year, which will rise (fall) by the flows of $B_{i,r,t-1}, D_{i,r,t-1}, M_{i,r,t-1}$, which are the births, deaths, and net migration, respectively. The total regional population is, therefore, $pop_{r,t} = \sum_i pop_{i,r,t}$.

For each region, we use the national average migration values for Ghana, which are given in the DemProj database. Fertility, mortality, and urbanization are estimated

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[13] Spectrum and its modules and manuals can be downloaded from: http://www.healthpolicyInitiative.com.

Table 4.7: Total fertility rates for epidemiological zones for selected year

	Coastal	**Forest**	**Southern Savannah**	**Northern Savannah**	**Accra**
1970	7.0	7.2	7.6	5.9	5.9
1979/80	6.6	6.5	6.7	N/A	5.1
1988	6.3	6.3	7.5	6.9	4.7
1993	5.1	5.3	4.9	6.0	3.4
1998	4.4	4.7	4.9	5.9	2.7
2003	4.3	4.3	4.7	6.1	2.9
2008	3.7	4.0	4.0	5.8	2.5

Note: Total fertility rates in the administrative regions from the Ghana Demographic and Health Surveys (GDHS). N/A = not available.

separately, for each epidemiological zone, and are applied to Equation (4.3) with the following assumptions:

Regional fertility

For regional fertility, we use a statistical software package in the R statistical language that is based on a Bayesian hierarchical model (Raftery et al., 2009; Alkema et al., 2011; Sevcikova et al., 2011).

Empirical data from the Ghana Demographic and Health Surveys (GDHS), going back to 1970, is used to estimate the total fertility rates (TFR). Table 4.7 presents the TFRs for the epidemiological zones for specific years. Further details on the method and its application are explained by Raftery et al. (2009).

Due to the lack of better data, we assume that each epidemiological zone in Ghana uses the national age distribution of fertility, and that the sex ratio was held constant at 105 males per 100 females. These data were taken from the UN Population Prospects (UN, 2010).

Regional mortality

Mortality requires assumptions for male and female life expectancy over the course of the modelling period. We use life expectancy for districts from the Ghana Statistical Service (Agyeman-Duah et al., 2006) and the projection of life expectancy for Ghana as a whole until 2035 from the UN World Population Prospects (United Nations, 2010). We then assume that the relative annual increase in life expectancy for each region is equivalent to the percentage increase of national life expectancy. This is a simple assumption, but given the lack of regional projections, as well as the lack of sufficient historical time series, it is infeasible to project region-specific life expectancy trends.

Regional urban and rural population

Using the DemProj module, we also project urban and rural populations for each of the epidemiological zones (Coastal, Forest, Northern Savannah and Southern Savannah), with the exception of Accra, which is assumed to be entirely urban.

With $U_{r,t}$ defined as the urban population of a region, $R_{r,t}$ the rural population, $Pop_{r,t}$ the total regional population, and $\Delta\lambda$ as the difference in the urban and rural growth rates, the urban population is projected by

$$U_{r,t} = U_{r,t-1} \cdot \frac{(Pop_{r,t} + \triangle\lambda \cdot R_{r,t-1})}{Pop_{r,t-1}} \tag{4.4}$$

For a further detailed description, see the DemProj Manual (Stover and Kirmeyer, 2008).

The data for the base-year population per district were taken from Ghana Statistical Service (GSS, 2010) and the age distribution per region for the rural and urban population by sex from the Ghana Demographic and Health Survey (GSS, 2009). The product of these provides estimates for the rural and urban population by age and sex per district. Furthermore, lacking better data, the rate of urbanization,$\Delta\lambda$, is assumed to be the same across all epidemiological zones, and follows the national trend.

4.5.2 Malaria prevention scenarios for children under 5 years

We use the LiST module that interacts with the cohort-component model, DemProj, to estimate the impact of a malaria intervention on children < 5 years old.

At the beginning of each projection year, DemProj provides LiST with the number of deaths for children aged 0, 1, 2, 3 and 4 years. LiST disaggregates those deaths into age bands: 0-1, 1-5, 6-11, 12-23 and 24-59 months by fitting a double log function to the neonatal, infant, and < 5 mortality rates. The equation has the following form:

$$\ln(u) = a + b\ln(age) + c \cdot age\ln(age) \tag{4.5}$$

where u is the cumulative mortality at the corresponding age (Stover et al., 2010).

A hypothetical intervention of malaria prevention is introduced through changes to the *efficacy* of the intervention in reducing mortality, adjusted for the impact of *coverage*. The following sets are defined: prevention scenario $sc \in SC$, region $r \in R$, age bands by months for < 5 year old $a \in$ [0-1, 1-5, 6-11, 12-23, 24-59 months], and time $t \in T$.

Following Winfrey et al. (2011) the proportional reduction $PR_{sc,r,a,t}$ in malaria mortality is a function of the efficacy of the intervention $E_{sc,a}$, the increase in the coverage of intervention $(C_{sc,r,a,t} - C_{sc,r,a,0})$ and the affected fraction $AF_{sc,a}$,[14] adjusted for the unrealized potential impact $(1 - E_{sc,a,0} \cdot C_{sc,r,a,0})$ and is defined as

$$PR_{sc,a,t} = \frac{E_{sc,a} \cdot (C_{sc,r,a,t} - C_{sc,r,a,0}) \cdot AF_{sc,a}}{1 - E_{sc,a,0} \cdot C_{sc,r,a,0}} \tag{4.6}$$

Based on the cohort-component method, the DemProj module calculates the num-

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[14] Affected fraction is the percent of death directly caused by malaria.

ber of births each year from the number of women 15-49 years old, the total fertility rate, and the age distribution of fertility. New births are subject to the estimated mortality rates as they age each year. Simultaneously, the LiST module estimates the impact that the malaria prevention has on the mortality rates of children, which is used by the cohort-component module. Together, LiST and DemProj estimate the number of children saved by the intervention at each year.

As previously described in Section 4.4, we assume that the *efficacy* of the hypothetical malaria prevention is 50%, and that the *coverage* for each counterfactual intervention scenario varies over time, as summarized in Table 4.6. Projections are made for each zone, separately, under the different scenario conditions.

Malaria mortality assumptions

LiST furthermore requires a distribution of < 5 mortality by cause, where malaria is one of eleven possible causes. To do so, we multiply the < 5 average case fatality rate of 2.6%, (*i.e.*, the probability of dying from an episode of malaria,)[15] with the regional average of < 5 yearly incidence rate (GSS, 2004; GHS, 2007), to estimate the < 5 yearly probability of dying from malaria per epidemiological zone. This is then divided by the total < 5 mortality rate for that zone, to estimate the percentage of deaths caused by malaria per zone. The remaining percentage is then distributed among the other causes of death by keeping their original respective ratios constant. Figure 4.6 depicts the resulting proportions of death causes for < 5 mortality, which were used for the base year in LiST.

Using a fixed malaria case fatality rate, 2.6%, for Ghana as a whole, does not consider any regional variability. However, given the lack of reliable empirical data on the number of malaria incidences and deaths by region, this provides the best available assumption.

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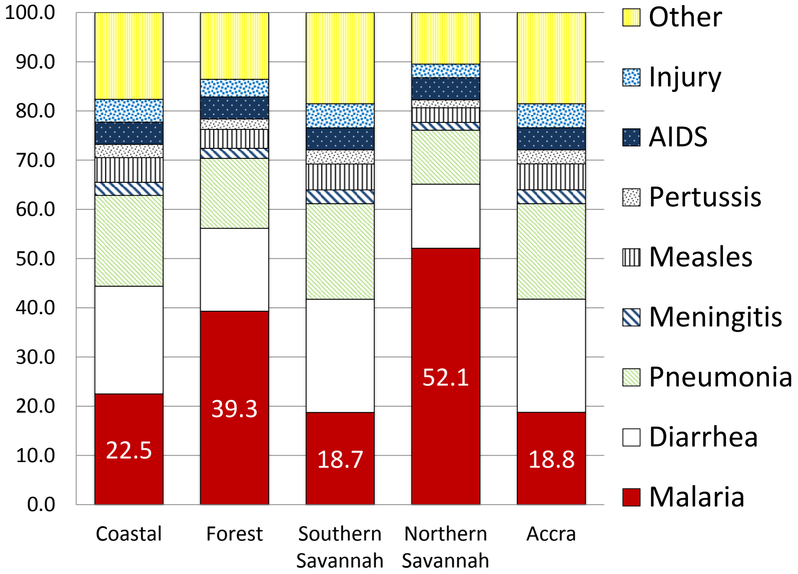
[15] Ghana Health Survey (GHS, 2007) reports malaria case fatality was 2.8%, 2.7%, and 2.4% for the years 2005,2006 and 2007, respectively.

Figure 4.6: Proportion of death by cause by zone



Note: Authors' calculations using Ghana Demographic and Health Survey (2003)

4.6 Labour efficiency model

Based on the discussion in Section 4.2 (illustrated in Figure 4.1), we review three potential effects that contribute to workforce efficiency: (a) malaria status of an adult worker, (b) malaria status of the child of an adult worker, and (c) malaria history of an adult worker as a child. Each of these contributes to the loss of production, *i.e.*, the amount of output lost from days *off* work (absenteeism), and loss to productivity, *i.e.*, the amount of output lost per day *at* work (presenteeism).

We refer to status as the number of malaria incidences per year, $x \in [0, 9]$, for three agents $[a,c,a25] \in i$, *i.e.*, adult, child, and adult's status 25 years previous, respectively. For each rural-urban location $ru \in RU$, at time $t \in T$, the labour efficiency loss $l_{i,ru,t}(x)$ is a function of x incidents of malaria that have a Poisson distribution $P(x, \mu_{i,ru})$ with mean incidents $\mu_{i,ru}$.[16] Presenteeism and absenteeism is differentiated by $j \in$ [presenteeism, absenteeism].

Suppressing the rural-urban location index (for simplicity), the labour efficiency

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[16] As an example, if $x = 0$ then $l = 0$.

index is defined as:

$$E_t = \underbrace{\left(1-\sum_j\sum_x p_a\left(x_a\right) l_{j,t}\left(x_a\right)\right)}_{\text{Malaria status of an adult worker}} \underbrace{\left(1-\sum_j\sum_x p_c\left(x_c\right)\cdot l_{j,t}\left(x_c\right)\right)}_{\substack{\text{Malaria status of the child}\\ \text{of an adult worker}}} \underbrace{\left(1-\sum_x p_{ac25}\left(x_{ac25}\right)\cdot l_t\left(x_{ac25}\right)\right)}_{\text{Malaria history of an adult worker}} \tag{4.7}$$

Each internal component represents the weighted average loss, normalized to labour output per year. Furthermore, the efficiency loss from the malaria history of an adult worker as a child, 25 years previous, is only affected by having two or more incidents per year as a child. Therefore,

$$l_{ac25}\left(x_{ac25}\right) = \begin{bmatrix} l_{ac25} = 0 \text{ if } 0 \leq x \leq 1 \\ l_{ac25} > 0 \text{ if } 2 \leq x \leq 9 \end{bmatrix}$$

The components within Equation 4.7 are assumed to be *independent*, *i.e.*, an intervention in children would affect the probability to acquire malaria in children independently to that in adults. Given that only the < 5 are treated, this simplified assumption seems reasonable for the following reasons: the parasite reservoir relies on the adult population, rather than the children. A recent study by the Swiss Tropical Institute finds that administering a vaccine to < 5 will have no impact on adults when delivered through an expanded programme on immunisation (EPI) process (Amek et al., 2011). Another study finds that the impact of insecticide treated net (ITN) distribution to the < 5, also has a limited, or no impact on transmission to adults (Unpublished computation based on Killeen and Smith (2007)). Most studies on eradication recommend targeting the whole population to clear parasites at regular intervals, including vaccination (Griffin et al., 2010; Maire et al., 2011). Targeting adults, rather than children, would probably have the largest impact on transmission.

Table 4.8 summarises the key parameters previously identified that are used to

Table 4.8: Key assumptions and parameter values of the labour effectiveness index

Assumptions	**Value**
Number of working days	235
Range of number of incidents per person-year with a Poisson distribution	0-9
Lost days per malaria episode	
For Absenteeism	
Adult is ill	3
Child is ill, and adult absent from work to take care of child	2
For Presenteeism	
Adult is at work but ill	2
Productivity factor (as proportion of output compared to malaria-free)	
Adult at work, but ill	90%
Having a year with 2 or more malaria episodes as a child	90%
Having 3 or more malaria episodes as a child	75%
Malaria case fatality for < 5 (probability of death given having a malaria episode)	2.6%
Years delay for improved productivity of adults due to incidences as children	25

derive the efficiency index: (1) production days lost by adults that have taken off work due to being ill with malaria, or for caring for a child with malaria, *i.e.*, absenteeism. (2) The productivity lost from being ill, but working, *i.e.*, presenteeism, and (3) the change in labour efficiency for adults that have had malaria as children, 25 years previous.

4.7 Limitations and discussion

As with every modelling approach, the method used here has a number of limitations, and is only a simplified version of reality. There are, therefore, aspects regarding malaria and its effect on production and economic growth, which have not been included in the analysis. First, the model does not incorporate contagion assumptions because the medical literature has an ambiguous consensus about the epidemiological consequences of malaria prevention. After careful deliberation, we decided not to enter the medical debate.

Second, both the malaria yearly duration and transmission varies across geographical zones, and agricultural production varies by type of sector, season, and geography. As discussed by Weil (2010), the effect of malaria and malaria prevention on production, therefore, depends on whether the height of agricultural production is pro-cyclical (or counter-cyclical) with the height of the malaria season.

Third, agricultural production tends to be a communal activity, in which extended families may reside together and pool resources. If any one worker needs to stay home with an illness, another person in the home may replace him or her. This reduces the effect that improving malaria prevalence has on the overall household production.

Fourth, childcare is often shared among extended family in Ghana; therefore, when children get malaria, they may stay home with someone who is already taking care of younger children and/or other ill children. This similarly reduces the impact that improving malaria prevalence may have on agricultural production.

Finally, the informal economies tend to constitute a relatively large proportion of the overall economy in developing countries. In this research, the SAM considers the informal economy, but is probably incomplete due to lack of reliable data. Therefore, the results of the model are likely to underestimate the economic benefits of malaria intervention in areas that exhibit a high proportion of the informal sector, especially in rural areas.

Scenarios revisited

Many possible preventative strategies could be assessed to evaluate the impact of malaria reduction on the labour force. In this paper, we simulate cases where children < 5 years receive a malaria preventative intervention. This leads to two issues that need clarification. First, because adults are not included in the intervention, the immediate economic benefit that could have been gained from healthier adults is not measured, *i.e.*, the first component in Equation (4.7), “Malaria status of an adult worker,” is omitted. Therefore, economic benefits are only gained through the reduced

Table 4.9: Additional value compared to baseline, year 1-30

Indicator	**Scenario 1**	**Scenario 2**	**Scenario 3**
Additional annual GDP growth rate	0.067%	0.070%	0.070%
Additional income (cumulative, million 2007 US$)	8,382	8,926	8,874
Annual additional income (average, million 2007 US$)	279	298	296

Source: Authors' own calculations

days in caring for children, and through changes to the units of effective labour when treated children become adults later in life.

Second, because prevention is "taken away" when children reach an age > 5, the hypothetical preventative scenarios are short-lasting prophylaxis, similar to insecticide treated nets or anti-malarial preventative drugs, rather than a long-lasting vaccine. The scenarios alter the probability of the < 5 deaths from malaria, but do not change malaria endemicity overall. A hypothetical vaccine to children, for example, would have had a compounding effect on the economy because the prevention would continue even after the children are > 5. This would resemble some of the effects if adults were added into the intervention. However, a hypothetical vaccine was not tested mainly because it is not yet known how long the new candidate-vaccine protects against malaria.

4.8 Results

The results overall show that even under a limited intervention to only < 5 years old, economic growth and income inequality improve. Furthermore, malaria prevention is best viewed as a long-run investment strategy. As Table 4.9 reports for the hypothetical scenarios of this research, annual GDP growth rate would rise by approximately 0.7% (above baseline). This is an additional cumulative income to the Ghanaian households of approximately \$8.3 to \$9.9 billion (2007 US\$) over a 30 year period. Equivalently, this is an additional yearly average income of US\$ 279 to 298 million.

In the first 10 years of the intervention, however, the dependency ratio rises and income per capita falls. This process is halted when the first cohort of healthier children reaches the working age population, approximately at age > 15. As they reach their prime working age, of approximately > 25 years, the economy gains the full benefit of the prevention, which raises income per capita (as illustrated in Figure 4.7).[17] Therefore, 25 years later, the economy reaches a new long-run path of income per capita above baseline.

In the baseline scenario (with no intervention), the model projects a rise in income inequality for the top 20% richest to the lowest 20% poorest households. In the counterfactual simulations, this rise in income inequality slows down, as illustrated in Figure 4.8, which compares the income inequality ratio relative to that in the baseline. Similar to income per capita, the first 10 years of the intervention actually leads to a minimal rise in income inequality due to the increase in dependency ratio. But as the healthier children reach working age, they enter the work force with more valuable, productive, labour resources. Therefore, even with a limited malaria preventative strategy to the < 5, income inequality ratio falls by approximately 1.3% after 30 years.

Using a DCGE model, rather than econometric approaches, enables us to incorporate diminishing returns. For example, given a stock of land and capital, improvement in labour size and labour efficiency will initially raise welfare. But, as "more lives are saved," competition within the labour market reduces their marginal labour productivity, and hence, erodes the marginal rise in income. The interaction of these opposing forces gives a truer picture of the economic value of an intervention. This is illustrated in Figure 4.7, in which income per capita is lower for the "comprehensive" intervention scenarios, compared to the "basic" intervention.

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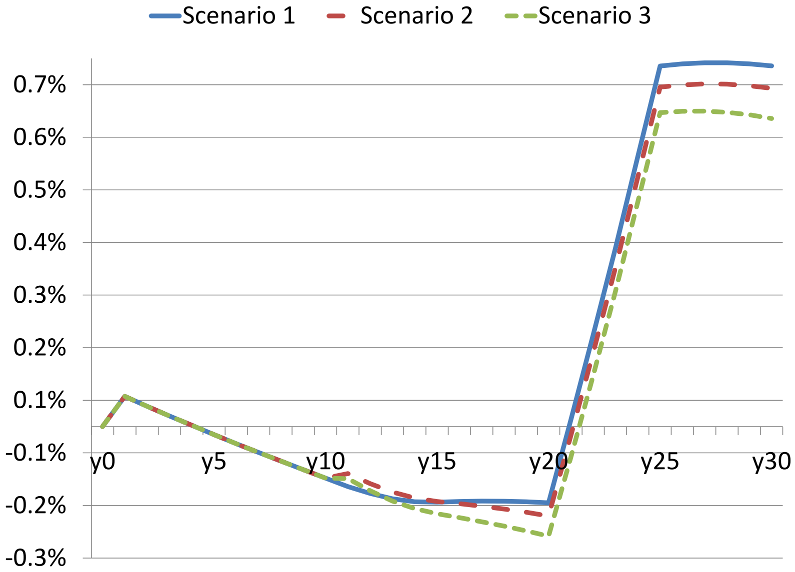
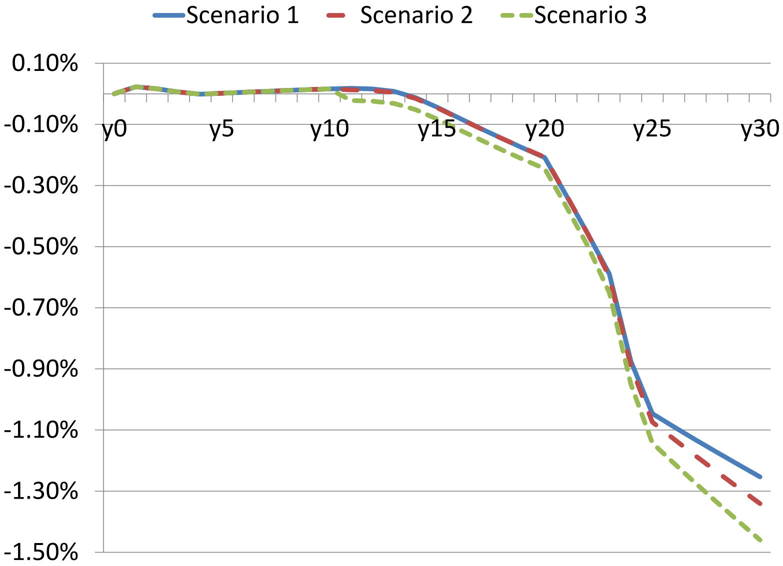
[17] A cohort includes children ages 0-5. We have assumed that the full effective units of labour is reached at the age of 25. Therefore, a proportion of the < 5 will reach this age 20 years after the intervention first began.

Figure 4.7: Income per capita relative to baseline (% change)



Source: Authors' own calculations

Figure 4.8: Richest 20/poorest 20 income relative to baseline (% change)



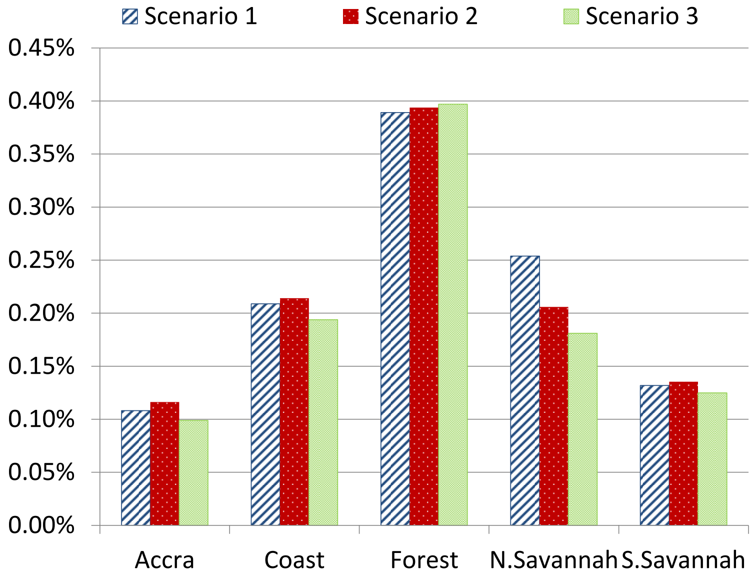
Source: Authors' own calculations

Furthermore, and related to the above, not all zones benefit in the same way from malaria intervention. Forest, which is a high prevalence zone, receives the largest economic benefits from malaria intervention (illustrated in Figure 4.9). The labourers in Forest have the same potential to produce and earn income as other zones, but malaria disadvantages them. The intervention, therefore, raises the value of the labour resource, which improves their income per capita, and even more so for the “comprehensive” scenario 3.

This rather intuitive result is, however, not necessarily true for all regions. For example, North Savannah, which is also a high prevalence zone, gains less from the comprehensive scenario 3, compared to the basic scenario 1 (see Figure 4.9). The key driver of welfare variation between households, in this model, is the heterogeneity in labour skill-type endowments and their overlap with the epidemiological zones. From a purely economic point of view, when households reside in high malaria prevalence zones, which coincides with having a high proportion of skill-types that are less in demand as inputs of production, they are expected to suffer from malaria intervention. The reason is that lives saved by malaria intervention might not be matched with the increase in demand for their labour resource. Poverty is exacerbated if the dependency ratio rises, while income rises less than sufficiently.

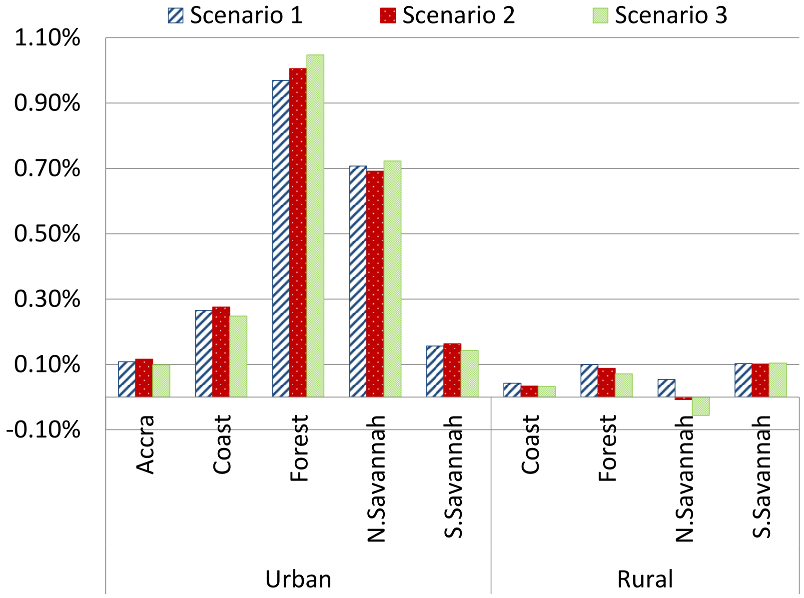
This situation also occurs in the rural households in Ghana, who benefit economically *less* from malaria intervention (as shown in Figure 4.10), especially with the higher coverage scenarios. However, as discussed in the model limitations (Section 4.7), the value of the informal sector is higher in rural areas in developing countries, and the benefits of malaria intervention in those regions are most likely an underestimate. Furthermore, we do not consider the social value of malaria prevention in this model.

Figure 4.9: Annual average income per capita relative to baseline (% change)



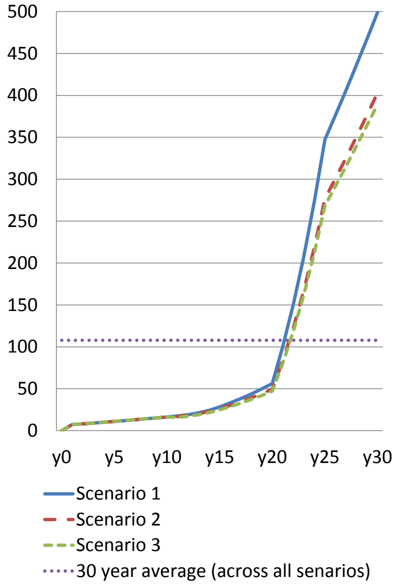
Source: Authors' own calculations

Figure 4.10: Income per capita relative to baseline, by zone and urbanity (average over 30 years)



Source: Authors' own calculations

Figure 4.11: Income-benefit per covered individual, 2007 US$



Indicator	Sc 1	Sc 2	Sc 3
Year 1	7	7	7
Year 5	11	11	11
Year 10	16	16	16
Year 15	28	26	25
Year 20	56	50	47
Year 25	347	277	268
Year 30	499	403	389
Average y1-y30	**124**	**102**	**98**

Source: Authors' own calculations

4.8.1 The benefit of treatment per individual covered

The economic benefit of a treatment given to individual children is reported in Figure 4.11, which is in terms of income per < 5 covered. The main results are that the benefit of a treatment rises from US$ 7 (2007 prices) to approximately US$ 16 per child covered, in the first 10 years. These welfare gains (per child) are mainly a result of the reduction of lost working days that parents have to make for taking care of sick children.

In later years, the benefits per covered child rises considerably higher, as the children mature and enter the work force as healthier and more productive, individuals. In other words, because they were treated as children, they will directly benefit as adults. The 30 year annual average benefit per covered child is between US$ 98 to US$ 124 (depending on the scenario).

Furthermore, as reported in Figure 4.11, the benefit per covered child is highest for the "basic coverage" Scenario 1, which again is precisely the result of diminishing returns to effective units of labour.

Table 4.10: Regional benefit per treated individual (2007 US$, average of year 1-30)

	Scenario 1	**Scenario 2**	**Scenario 3**
		Urban	
Accra	131	111	125
Coast	135	111	130
Forest	176	143	128
North Savannah	101	82	75
South Savannah	120	101	115
		Rural	
Accra	n/a	n/a	n/a
Coast	18	15	17
Forest	143	116	102
North Savannah	64	52	46
South Savannah	68	56	68
		Region Total	
Accra	131	111	125
Coast	74	61	72
Forest	162	131	117
North Savannah	76	62	55
South Savannah	94	78	91
National Average	**124**	**102**	**98**

4.8.2 Variation in benefit by epidemiological zone

Table 4.10 reports the 30 year average regional benefits per covered child, and indicates which zones stand to gain most from the treatment. It shows, for example, that individuals in the Forest zone benefit the most; while individuals in North Savannah gain the least.

From a purely economic point of view, an optimal provision would be to increase coverage to those children in zones that benefit the most from prevention, while reduce coverage to the areas below average. Health provision is maximized when all children have the same benefits across all zones.

However, this is of course an unacceptably narrow approach because it only provides a partial view of the optimal provision, as it does not consider aspects that have intrinsic non-economic value, *e.g.*, moral, social, and equity implications. A better method to rank policy would be to include a social agenda within the provision, and evaluate it within this predefined framework; for example, assessing an optimal provision strategy within a pro-poor health subsidization policy.

4.8.3 Sensitivity analysis

To test the sensitivity of results, many robustness checks were conducted on the key parameters of the economic model. We applied low and high values of the income elasticities and Frisch parameters, which may influence results of the scenarios compared to the baseline. These are described in Table 4.11, and are well above/below the accepted values within the literature.

Overall, the results are very close to the main results, and suggest that the model is well behaved. For example, the values presented in Figure 4.11 for the income-benefit per covered individual vary by approximately US$ 2, for the low sensitivity values, but are nearly the same for the high values. The percentage difference of GDP above baseline (compared to the main model result) is approximately 0.01 percentage points until year 25, when it increases to a 0.05 percentage point difference. The results for high values are even more similar to the main results, and would alter our results from 25 years onwards by less than 0.015 percentage points. These provide some confidence that changing the deep parameters of the DCGE model do not alter the overall conclusions.

The model is, however, sensitive to some of the labour unit efficiency parameters that were summarized in Table 4.8. For example, increasing the loss to adult productivity from 90% to 75%, which had two bouts of malaria as a child, would raise the benefits per child covered in the final year by approximately US$ 150 (but not in the first 25 years). This raises the average benefit per covered child. Our results are, therefore, the conservative estimates.

Finally, sensitivity analysis was preformed on the demographic model and its

Table 4.11: Sensitivity analysis

		Parameters used in model		
	Low	**Urban**	**Rural**	High
Income elasticity of demand				
Agriculture	0.3	**0.66**	**0.68**	1
Manufacturing	0.45	**0.91**	**0.86**	1
Services	1	**1.52**	**1.30**	2
Frisch Parameter	-2	**-3**	**-5**	(respectively) -5,-6

interaction with the DCGE model. However, the overall effect that malaria has on the general demographic trends is relatively small. Therefore, the major economic effects are a result of the labour efficiency index, and not the demographic model.

4.9 Conclusion

The analysis of malaria and its link with economic growth using econometric approaches has, so far, been too broad and not particularly useful for policy analysis. To fill the gap, we developed a recursively dynamic computable general equilibrium (DCGE), and used Ghana as a case study. We find that malaria prevention clearly adds to economic growth and reduces income inequality, even under a limited intervention where only the under-five years old are treated. Our results are conservative estimates because health is only linked to labour resources, while leaving out the other possible effects. Furthermore, immediate economic benefits would be obtained had the intervention included adults.

Public, private, and third-sector organisations require a more detailed picture of how malaria influences various households and production sectors over time. On the same token, pharmaceutical firms, who are negotiating with government and donors on the provision of drugs and vaccines, have an interest in understanding market demands and communicate opinions.

The scenarios developed here were hypothetical, but in the “real world,” policy makers decide on the most appropriate health provision within a framework of a limited budget and social goals. Our approach is useful for policy makers to assess the expected benefits, and target towards a certain desired level of return on (health) investment, because framing the results as a cost-benefit analysis is rather straight froward. All that is needed is to compare the results with the cost of the various provisions. Moreover, designing complex health provision policies, *e.g.*, pro-poor health subsidies, require assessing the treatment benefits per individual covered, which is an natural outcome of out approach.

This methodology is a step forward in the *a priori* impact assessments of alternative malaria interventions. Malaria intervention has a key role in the economic development of endemic countries. However, it is a long-term investment, and governments and donors must view it as such.

Chapter 5

The malaria model

In the previous Chapter 4, the economic value of malaria reduction was imputed by synthesising a dynamic general equilibrium (DCGE) model with two health models. However, the DCGE model was discussed in only general terms. The aim of this chapter, therefore, is to make the modelling process fully transparent. It will present the complete analytical DCGE model, its main assumptions, and deep parameters.

The chapter is structured as follows: Section 5.1 introduces the model and the set of variables. Section 5.2 and Section 5.3 describe the production function, and the Armington assumption. Section 5.4 through Section 5.7 describe the agents in the model (*i.e.*, the government, households and the rest of the world,) and the small open economy assumptions. Section 5.8 and Section 5.9 discuss investment and the recursive dynamics in this model. Section 5.10 summarises the parameters used in the model, and the literature review behind them. Finally, Section 5.11 concludes.

5.1 The model

A multi-sector multi-agent recursive dynamic CGE model is developed. I follow Mathiesen (1985) and Rutherford (1995, 1999), and setup an Arrow–Debreu equilibrium as a mixed complementarity problem (MCP). Therefore, three types of weak inequality conditions must be satisfied: (1) zero profits, (2) market clearance, and (3) income balance, each associated with three non-negative variables, *i.e.*, $y^* \geq 0$, $p^* \geq 0$ and $M^* \geq 0$, respectively.

The model is coded in GAMS using MPSGE, which allows handling of CGE models in a consistent and compact format (Rutherford, 1995, 1999). It is furthermore calibrated to the 2007 Ghanaian Social Accounting Matrix (SAM),[1] and characterises six activities Y_j: four agricultural, which represent the main agro-ecological Ghanaian zones, industrial, and services. These six activities are aggregated into three main commodities, Y_i: agricultural, industrial, and services. A portion of the commodities are used domestically and the rest exported. An Armington final good, A_i, is assembled by combining the domestically used commodities with imports (Armington, 1969).

Final consumption is then demanded by a virtual investment-firm, as intermediate inputs, and/or by three type of agents: households, government, and the rest of the world (ROW). Each agent has a utility function $\{U_h, U_{gov}, U_{row}\} \in U$, which is rational, locally non-satiated, and continuous.

The model has 45 households, which were identified by five income level quintiles, and nine epidemiological urban-rural regions. Households are endowed with factor resources: capital, land and labour, $\{K_{jt}, Lnd_{jt}, L_{ljt}\} \in F_j$, of which there are three labour skill-types, *i.e.*, $\{$self-employed, skilled, unskilled$\} \in l$.

Finally, I use a recursive dynamics approach to project the model sequentially forward for 30 years. Stock variables are updated exogenously, at each period, based on the health models and other assumptions. The exception is capital, which accumulates through endogenous linkages with previous-period investment and international capital flow. Ghana is assumed to be a small open economy (SOE) that cannot affect world prices.

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[1] The original SAM was developed by Breisinger et al. (2009, 2011).

The following is a summary of the main sets used in the model,

$$\begin{aligned} h &\in H \quad \text{(45 households)} \\ \{\text{self-employed, skilled, unskilled}\} &\in l \quad \text{(3 labour)} \\ \{K_{jt}, Lnd_{jt}, L_{ljt}\} &\in F \quad \text{(5 factors)} \\ j &\in M \quad \text{(6 activities)} \\ i &\in N \quad \text{(3 commodities)} \\ t &\in T \quad \text{(30 time periods)} \end{aligned}$$

In the next sections, the model is described in further detail.

5.2 Production

We use the Armington assumption, similar to Rutherford and Light (2001) and Hosoe et al. (2010), which is diagrammatically illustrated in Figure 5.1.

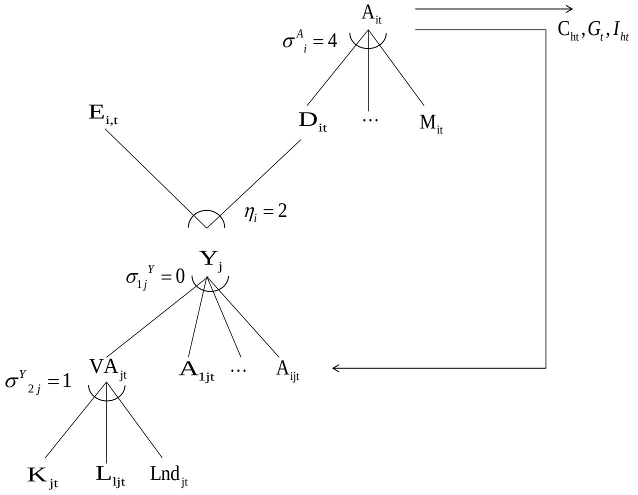
5.2.1 Domestic production

Activities are produced using a two-level nested Leontief-Cobb Douglas technology, $\forall t$. Both are homogenous of degree one and thus characterised as constant returns to scale (CRS). In the top-nest, value-added and intermediate inputs are aggregated into an activity. Firm j's profit-maximisation problem is

$$\begin{aligned} \underset{Y_j, VA_i A_{ji}}{\text{maximise}} \quad \pi_{jt}^{Y} = {} & p_{Y,jt} Y_{jt} - \left(p_{VA,jt} VA_{jt} + \sum_i p_{it} A_{ijt} \right) \\ \text{s.t.} \quad Y_{jt} \geq {} & \min \left\{ \frac{VA_{jt}}{a_{jt}^{VA}}, \frac{A_{ijt}}{a_{ijt}^{A}}, \cdots, \frac{A_{Njt}}{a_{Njt}^{A}} \right\}, \qquad \forall j \end{aligned} \tag{5.1}$$

In the bottom-nest, the maximisation problem of the value added is obtained by

Figure 5.1: The production function



Note: Activity production inputs have a two level nested function. The lowest level combines capital, labour, and land into an aggregate value added, VA_{jt}. The second level combines intermediate goods, A_{it}, with the value added to form output, Y_{jt}. Production output is then transformed into Export, E_{it}, and domestic consumption, D_{it}. Finally, domestic consumption and imports, M_{it}, are aggregated to form the Armington final good. This good is then demanded for private and public consumption, investment, or as an intermediate good.

aggregating capital, labour, and land inputs, by

$$\begin{aligned} \underset{VA_j, K_j, Lnd_j, L_{lj}}{\text{maximise}}\ \pi_j^{VA} &= p_{VA,j} VA_j - \left(r_K K_{jt} + p_{Lnd} Lnd_j + \sum_{l=1}^{3} w_{lt} L_{ljt} \right) \\ \text{s.t. } VA_j &\geq \theta_j^{VA} K_{jt}^{\alpha_K} Lnd_{jt}^{\alpha_{Lnd}} \left(\Pi_l L_{ljt}^{\alpha_l} \right), \qquad \forall j, \forall l \end{aligned} \tag{5.2}$$

Notations are:

π_j^Y: profit of the j'th firm producing gross domestic output Y_j in the top nest,

π_j^{VA}: profit of the j'th firm producing composite factor VA_j in the second nest,

Y_j: activity output of the j'th firm,

A_{ij}: intermediate input of the i'th Argmington good used by the j'th activity firm,

VA_j: value added composite of capital, land, and labour inputs,

$\{K_j, Lnd_j, L_{lj}\} \in F_j$:	input factors: capital, land and labor, with [self-employed,skilled,unskilled] $\in l$,
p_j^Y:	price of the activity output,
p_j^{VA}:	price of the value added composite,
$w_{lj} \in p_f$:	labour wage rates (with subscript f meaning a factor),
$p_j^{Lnd} \in p_f$:	rental price of land,
$r_j^K \in p_f$:	rental price of capital,
a_j^{VA}, a_{ij}^A:	input requirement coefficients for the j'th activity,
α_{jf}:	share coefficient in the value added function, with constant returns to scale implying that $\alpha_k + \alpha_{Lnd} + \sum_l \alpha_l = 1$,
θ_j^{VA}:	scaling coefficient.

The explicit definition of the complementarity constraint is that for two scalar variables x and y, their is a solution such that $x \cdot y = 0,\ x \geq 0,\ y \geq 0$. This will be compactly expressed as $0 \leq x \perp y \geq 0$.

Recall that index j refers to a set of activities, while index i refers to a set of commodities. Solving these two maximisation problems $\forall t$, $\forall j$, and $\forall i$ leads to the following demand for inputs:

$$0 \leq p_{jt}^{VA} \quad \perp \quad VA_{jt} \geq a_{jt}^{VA} Y_{jt} \tag{5.3}$$

$$0 \leq p_{jt}^{A} \quad \perp \quad A_{ijt} \geq a_{ijt}^{A} Y_{jt} \tag{5.4}$$

$$0 \leq p_{ft} \quad \perp \quad F_{jt} \geq \frac{\alpha_f p_{jt}^Y}{p_{ft}} Y_{jt} \qquad \forall F \tag{5.5}$$

Zero profit conditions lead to the price indexes:

$$p_{jt}^{Y} \leq \left(a_{jt}^{VA} p_{jt}^{VA} + \sum_{i=1}^{N} a_{ijt}^{A} p_{ijt}^{A} \right) \quad \perp \quad Y_{jt} \geq 0 \tag{5.6}$$

$$p_{jt}^{VA} \leq \theta_{j}^{VA} \prod_{f} \left\{ \left(p_{j}^{f} \right)^{\alpha_{jf}} \right\} \quad \perp \quad VA_{j} \geq 0 \tag{5.7}$$

These equations, as do the other equations in the the next sections, express the *complementarity* problem in the following way: using Equation (5.4) as an example for a *market clearing condition*, if $0 < p_j^A$, then supply equals demand, $A_{ij} = a_{ij}^A Y_j$. Otherwise, if $0 = p_j^A$, it would mean that the supply of good A_{ij} is infinitely larger than demand, $A_{ij} > a_{ij}^A Y_j$, which has driven the price down to zero.

Similarly, the complementarity problem for the *zero profit condition* is exemplified in Equation (5.6). If $Y_j > 0$, the unit revenue equals the unit cost of production, $p_{jt}^Y = a_{jt}^{VA} p_{jt}^{VA} + \sum_{i=1}^{A} a_{ijt}^A p_{ijt}^A$, and therefore, the firm makes zero profits. However, if $Y_j = 0$, the unit cost of production is greater than revenue, $p_{jt}^Y < a_{jt}^{VA} p_{jt}^{VA} + \sum_{i=1}^{A} a_{ijt}^A p_{ijt}^A$, and the firm does not produce because of the losses it would have had incurred.

5.2.2 Transformation between domestic use and exports

The decision of producers to supply to the domestic market, D_i, or foreign markets, E_i, is governed by a constant elasticity of transformation (CET) function. The profit-maximisation problem for the i'th commodity is divided into two parts:

In the first-stage, activities j are assembled into a commodity i using a Leontief function by[2]

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[2] Recall that in this model, there are four agricultural activities, which are assembled into one aggregate agricultural commodity. Furthermore, the industrial and service commodities are equivalent to the activities.

$$\begin{aligned} \underset{Y_i, Y_j}{\text{maximise}} \quad \pi_{it}^{Y} = & \; p_{it}^{Y} Y_{it} - \sum_{j}^{M} p_{jt}^{Y} Y_{jt} \\ \text{s.t.} \quad Y_{it} \geq & \; \min \left\{ \frac{Y_{jt}}{a_{jt}^{Y}}, \cdots, \frac{Y_{Mt}}{a_{Mt}^{Y}} \right\} \end{aligned} \tag{5.8}$$

In the second-stage, the CET function splits the commodities into domestic use and exports by

$$\begin{aligned} \underset{Y_{it}, D_{it}, E_{it}}{\text{maximise}} \; \pi_{it} &= \left(p_{it}^{D} D_{it} + \left(1 - \tau_i^{E}\right) p_{it}^{E} E_{it} \right) - p_{it}^{Y} Y_{it} \\ \text{s.t. } Y_{it} \geq g\left(D_{it}, E_{it}\right) &= \theta_{it} \left(\gamma_i^{Y} D_{it}^{\phi} + \left(1 - \gamma_i^{Y}\right) E_{it}^{\phi} \right)^{\frac{1}{\phi}} \end{aligned} \tag{5.9}$$

Notations are:

π_i: profit for commodity i,

Y_j: gross domestic output of the j'th good,

D_i: domestic supply (use) of good i,

E_i: export supply of good i,

p_i^D: price of the i'th gross domestic output,

p_i^E: price of the i'th exported good in terms of domestic currency, with $p_i^E = p_{fx,i}\left(1 - \tau_i^E\right)$,

τ_i^E: export tax,

θ_i: scaling coefficient,

a_j^Y: share coefficients for activity j, calibrated from the SAM,

γ_i^Y: share coefficients for commodity i's transformation, calibrated from SAM,

ϕ: parameter defined by the transformation elasticity η, expressed as $\phi = 1 + \frac{1}{\eta}$.[3]

Solving the maximisation problem leads to the following supply functions for exports and domestic goods:

$$0 \leq p_{it}^Y \quad \perp \quad Y_{it} \geq a_{jt}^Y Y_{jt} \tag{5.10}$$

$$0 \leq p_i^E \quad \perp \quad E_{it} \geq \left(\theta_{it} \gamma_{it}^Y \frac{p_{it}^Y}{\left(1 - \tau_i^E\right) p_i^E} \right)^{\frac{1}{1-\phi}} Y_{it} \tag{5.11}$$

$$0 \leq p_i^D \quad \perp \quad D_{it} \geq \left(\theta_{it} \left(1 - \gamma_{it}^Y\right) \frac{p_{it}^Y}{p_i^D} \right)^{\frac{1}{1-\phi}} Y_{it} \tag{5.12}$$

The zero profit conditions lead to the unit cost of production,

$$p_{it}^Y \leq \sum_{j \in agr} a_{jt}^Y p_{jt}^Y \quad \perp \quad Y_{it} \geq 0 \tag{5.13}$$

$$p_{it}^Y \leq \left(\gamma_i^Y \left(p_{it}^D\right)^{1+\eta} + \left(1 - \gamma_i^Y\right) \left(p_{it}^E\right)^{1+\eta} \right)^{\frac{1}{1+\eta}} \quad \perp \quad Y_{it} \geq 0 \tag{5.14}$$

where Equation (5.10) and Equation (5.13) are redundant with regards to the industrial and service sectors, *i.e.*, $a_j^Y = 1$.

5.3 The Armington assumption

In order to model exports and imports of the same good, known as cross-hauling, we assume that imports and domestically produced goods are imperfect substitutes, and are combined by a virtual firm, *i.e.*, an Armington aggregate good (Armington, 1969). This final good is consumed domestically by private or public agents, invested

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[3] The transformation elasticity is defined by $\eta = \frac{d(D_i/E)}{(D_i/E)} / \frac{d\left(p_i^D/p_i^E\right)}{\left(p_i^D/p_i^E\right)}$

to produce new capital stock, and/or used as an intermediate input in domestic activity production (as previously described in Section 5.2.1). This allows to model import competition and export opportunities that reflect the ability by producers and consumers to shift between domestic and foreign markets depending on changes in the relative prices of imports, exports and domestic goods.

The optimisation problem for the i'th final good is to

$$\begin{aligned} \underset{A_{it},M_{it},D_{it}}{\text{maximise}}\ \pi_{it}^{A} &= \left(1-\tau_i^S\right) p_{it}^{A} A_{it} - \left(1+\tau_i^M\right) p_{it}^{M} M_{it} - p_{it}^{D} D_{it} \\ \text{s.t. } A_{it} \geq g\left(M_{it}, D_{it}\right) &= \theta_{it}^{A}\left(\gamma_i^A M_{it}^{\eta_i^A} + \left(1-\gamma_i^A\right) D_{it}^{\eta_i^A}\right)^{\frac{1}{\eta_i^A}} \end{aligned} \tag{5.15}$$

Notations are:

π_i^A : profit of the virtual firm producing the i'th Armington composite good,

A_i: the i'th Armington composite good,

M_i: the imported good,

D_i: the domestic good,

p_i^A: consumer price of the Armington composite good. Producer price is therefore $p_i^{A,p} = \left(1-\tau_i^S\right) p_i^A$,

p_i^M: price of the imported good in terms of domestic currency,

p_i^D: price of the domestic good,

τ_i^S: sales tax on good i,

τ_i^M: import tariff on the i'th commodity,

θ_i^A: scaling coefficient,

γ_i^A: input share coefficients calibrated from SAM,

η_i^A: parameter defined by the substitution elasticity σ_i^A, having $\eta_i^A = 1 - \frac{1}{\sigma_i^A}$.

The first-order conditions for the optimality of the above problem $\forall t$ leads to the following demand functions for imports and domestic goods:

$$0 \le p_{it}^M \quad \perp \quad M_{it} \ge \left[\theta_i^A\right]^{\sigma_i^A - 1} \left(\gamma_i^A \frac{\left(1 - \tau_i^S\right) p_{it}^A}{\left(1 + \tau_i^M\right) p_{it}^M} \right)^{\sigma_i^A} A_{it} \tag{5.16}$$

$$0 \le p_i^D \quad \perp \quad D_{it} \ge \left[\theta_i^A\right]^{\sigma_i^A - 1} \left(\left(1 - \gamma_i^A\right) \frac{\left(1 - \tau_i^S\right) p_{it}^A}{p_{it}^D} \right)^{\sigma_i^A} A_{it} \tag{5.17}$$

$$p_{it}^A \le \left(\gamma_i^A \left[\left(1 + \tau_i^M\right) p_{it}^M \right]^{1 - \sigma_i^A} + \left(1 - \gamma_i^A\right) \left(p_{it}^D\right)^{1 - \sigma_i^A} \right)^{\frac{1}{1 - \sigma_i^A}} \perp Y_{it} \ge 0 \tag{5.18}$$

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5.4 Government behavior

The government receives income from collecting direct tax, τ^D, and sales tax, τ^S, including import and export tariffs, τ^M, τ^E (respectively). It also transfers (receives) funds from domestic households and the rest of the world. The government purchases commodities, and saves the remaining income.

In order to compare scenarios and properly assess welfare, it is assumed that the government's budget is always balanced. If it is was not balanced, it would be impossible to distinguish between a change in household welfare, which is due to efficiency improvements, or one which arises solely because the government is running a deficit. In the long-run, the government budget has to be balanced, and only in that setting does the model provide consistent welfare estimates that can be compared.

To account for this, tax revenues and the proportion of real government consumption expenditures is assumed to be fixed, but rises proportionately with the population growth rate to maintain a fix level of government services per capita. Furthermore, in order to keep a budget-balance, households transfer (receive) an endogenous lump-sum fund, $govdef$, so that fiscal surplus adjusts to ensure that revenues equal expenditure on goods and public investment, *i.e.* a balanced budget. The size of the transfer (receipt) that each household makes is set by the share of household consumption from total private consumption, Φ_{ht}, with $\sum_h \Phi_h = 1$, *i.e.*, households with higher consumption contribute more to cover the government budget deficit. (The household is discussed further in Section 5.5.)

Government income, $\forall t$, is

$$\begin{aligned} GOVINC_t &= \sum_i T_{it}^S + \sum_i T_{it}^M + \sum_j T_{jt}^E + pfx_t \cdot (GR_t - RG_t) \\ &+ p_{gt} \cdot \left(\sum_h T_{ht}^D + \sum_h (GH_{ht} - HG_{ht}) + govdef_t \right) \qquad \forall i, \forall j \quad (5.19) \end{aligned}$$

with tax collected by

$$\begin{aligned} T_i^S &= \tau_i^S p_{it}^A c_{iht} \qquad \forall i & (5.20) \\ T_i^M &= \tau_i^M p_i^M M_i \qquad \forall i & (5.21) \\ T_j^E &= \tau_j^E p_j^E E_j \qquad \forall j & (5.22) \end{aligned}$$

The government spends a fixed proportion of income on consumption and savings,

$$\begin{aligned} \underset{GSV_t, c_{git}}{\text{maximise}}\ G_t &= \min \left\{ \frac{GSV_t}{s_g}, \frac{c_{it}^g}{a_i^g}, \cdots, \frac{c_{Ngt}^g}{a_N^g}, \right\} \\ \text{s.t. } GOVINC_t &= p_t^{Inv} GSV_t + \sum_i p_{it}^A c_{it}^g \qquad (5.23) \end{aligned}$$

with $0 \leq s_g, a_i^g \leq 1$ and $s_g + \sum_i a_i^g = 1$, characterizing a CRS function.

The notations are:

T^D, T_i^S, T_i^M, T_i^E: Revenue from direct tax, sales tax, import and export tariff (respectively),

$\tau_i^S, \tau_i^M, \tau_i^E$: sales tax, import tariffs and export tariffs,

$GOVINC$: government income,

G, p_g: level of government services and unit cost of government services,

$(GH_{ht} - HG_{ht})$: net government receipts from households,

$(GR_t - RG_t)$: net government receipts from the rest of the world,

$govdef$: total household transfers to cover government deficit,

c_i^g, a_i^g: government demand for final good, and the share coefficient,

GSV, p^{Inv}, s_g: government savings, unit cost of investment, and savings rate.

The solution to this problem, $\forall t$, leads to the government demand for the i'th good and savings:

$$0 \leq p_{it}^A \quad \perp \quad c_{it}^g \geq a_i^g \frac{GOVEXP_t}{p_{it}^A} \qquad \forall i \tag{5.24}$$

$$0 \leq p_t^{Inv} \quad \perp \quad GSV_t \geq s_g \frac{GOVEXP_t}{p_t^{Inv}} \tag{5.25}$$

and the unit cost of government services is

$$p_{gt} \leq s_g p_t^{Inv} + \sum_{i=1}^{N} a_{igt} p_{it}^A \quad \perp \quad G_t \geq 0 \tag{5.26}$$

5.5 Household behaviour

There are h households, each endowed with capital, labour and land resources. They accumulate capital, transfer or receive funds from the government and the rest of the world, and pay taxes.

As mentioned previously (in Section 5.4), it is assumed that in each period, the household transfers (receives) an endogenous fraction of income to cover any government deficits (surplus), with the proportion defined as the share of household's consumption of total private consumption

$$\Phi_{ht} = \frac{C_{ht}}{\sum_h C_{ht}}, \qquad \text{with } \sum_h \Phi = 1 \tag{5.27}$$

Household h's disposable income, $\forall t$, is

$$\begin{aligned} Z_{ht} &= r_t^K K_{ht} + p_t^{Lnd} Lnd_{ht} + \sum_{l=1}^{3} w_{lt} L_{lht} + pfx_t \cdot (HR_{ht} - RH_{ht}) \\ &+ p_{gov,t} \left((HG_{ht} - GH_{ht}) + \Phi_{ht} \cdot govdef_t - T_{ht}^d \right) - \sum_i p_{it}^A \bar{c}_{iht} \end{aligned} \tag{5.28}$$

and note that income is net of the minimum subsistence expenditure, $p_i^A \bar{c}_{ih}$ (also called the survival requirement level).

The household demand structure has two levels, and uses an extended linear expenditure system (ELES).[4] In the top-level, a household consumes a composite consumption bundle, C_h, and saves a fixed share of disposable income, PSV_h. The problem is to

$$\begin{aligned} \underset{S_{ht}, C_{ht}}{\text{maximise}} \quad U_t = & \min \left\{ \frac{PSV_{ht}}{s_h^p}, \frac{C_{ht}}{1 - s_h^p} \right\}, \qquad \text{with } 0 \leq s_h \leq 1 \\ \text{s.t.} \quad Z_{ht} \geq & \; p_t^{Inv} S_{ht} + p_{ch,t} C_h, \qquad t \in T \end{aligned} \tag{5.29}$$

---

[4] This method is equivalent to Howe (1975), who had formalized savings into the Stone-Geary utility function. Here, a Leontief function is used in the top level.

In the second-level, the household maximises a Stone-Geary utility function, which allows income elasticities to be different than one. The residual disposable income is equal to the disposable income net of savings, $M_{ht} = Z_{ht} - p_{inv,t}S_{ht}$. The problem is to

$$\begin{aligned} \underset{c_{iht}}{\text{maximise}}\ C_{ht}\left(c_{iht}\cdots c_{nht}\right) &= \prod_{i=1}^{n}\left(c_{iht}-\bar{c}_{ih}\right)^{\beta_{ih}} \qquad \text{where } \textstyle\sum_{i=1}^{n}\beta_{ih}=1 \\ \text{s.t.} \qquad M_{ht} &\geq \sum_{i=1}^{n} p_{it}^{A} c_{iht} \end{aligned} \tag{5.30}$$

The notations are:

T^D_{ht}: Direct tax by household h,

PSV_h, p^{Inv}: household h's private savings and unit cost of investment,

C_h, p_{ch}: demand for composite consumption by household h, with price index,

Z_h: disposable income, net subsistence level,

Lnd_h, p^{Lnd}: land endowments by household h, unit rental price,

L_{lh}, w_l: labour endowments and wage rates for $\{\text{self, skilled, unskilled}\} \in l$,

K_{ht}, r^K_t: capital and rental price of capital,

$(HG_{ht} - GH_{ht})$: net household receipts from the government,

$(HR_{ht} - RH_{ht})$: net household receipts from the rest of world (ROW),

$\Phi_h \cdot govdef$: endogenous transfer to cover government deficit, with $0 \leq \Phi_h \leq 1$,

τ^{sales}_i: sales tax,

c_{ih}, p^A_i: demand for good i by household h, and commodity i consumer price,

$\bar{c}_i, p^A_i$: subsistence level, and commodity i consumer price,

M_h: residual disposable income, *i.e.* net of taxes, transfers, and savings,

β_{hi}: household h's share parameter for good i, with $0 \leq \beta_i \leq 1$ and $\sum_i \beta_i = 1$,

p^U_{ht}: unit cost of household utility.

Solving the problem of the household, $\forall t$, the first-level demands for private savings and consumption bundle are:

$$0 \leq p_{ch,t} \quad \perp \quad C_{ht} \geq (1 - s^p_h) \frac{Z_{ht}}{p_{ch,t}} \tag{5.31}$$

$$0 \leq p_{inv,t} \quad \perp \quad PSV_t \geq s^p_h \frac{Z_{ht}}{p^U_{ht}} \tag{5.32}$$

with households utility price index of

$$p^U_{ht} \leq s^p_h p^{Inv}_t + (1 - s^p_h) \, p_{ch,t} \perp U_{ht} \geq 0 \tag{5.33}$$

In the second-level, the demand function for good i is

$$0 \leq p_{it} \quad \perp \quad c_{iht} \geq \bar{c}_{ih} + \beta_{ih} \frac{\left[M_{ht} - \sum_{j=1}^{n} p_{jt} \bar{c}_{jh}\right]}{p_{it}} \tag{5.34}$$

with household's consumption price index of

$$p^c_{ht} \leq \Phi^h \Pi^N_{i=1} \left\{ \left(p^A_{it}\right)^{\beta_{hi}} \right\} \perp C_{ht} \geq 0 \tag{5.35}$$

Note that $M_{ht} - \sum_i^n p_{it} \bar{c}_i$ is the supernumerary income, which is the residual income net of subsistence expenditure, and $c_{iht} - \bar{c}_{ih}$ is the supernumerary consumption, which is the residual consumption net of subsistence level.

5.5.1 Recalibrating the SAM with subsistence level

In order to account for the subsistence level, $\bar{c}_{ih}$, the SAM is recalibrated in the following steps:

1. In the original SAM, $\sum_{i=1}^{n} p_i^A c_{ih} = M_h$. Therefore, the average budget share is

$$s_i = \frac{p_i^A c_{ih}}{M_h} \tag{5.36}$$

2. Good i income elasticity of demand is defined as $\epsilon_{i,h}^{M} = \frac{\partial c_{ih}}{\partial M_h} \frac{M_h}{c_{ih}}$. Differentiating the consumption demand Equation (5.34) with respect to disposable income, obtain $\frac{\partial c_{ih}}{\partial M_h} = \frac{\beta_{ih}}{p_i}$, and therefore, $\epsilon_{i,h}^{M} = \frac{\beta_{ih}}{p_i} \frac{M_h}{c_{ih}}$. Finally, combine with the average budget share, Equation (5.36), and rearrange to estimate the marginal budget share by

$$\beta_{ih} = s_i \cdot \epsilon_{i,h}^{M} \tag{5.37}$$

   where we use values for $\epsilon_{i,h}^{M}$ from previous econometric studies, and s_i is given from the SAM.

3. To calibrate a minimum subsistence requirement $\bar{c}_i$, the values for the Frisch parameter are used from previous studies of African countries. The Frisch parameter is defined as

$$\phi_h = \frac{-M_h}{M_h - \sum_{j=1}^{n} p_j \bar{c}_{jh}} \tag{5.38}$$

   and reflects the marginal utility of total income with respect to income (Frisch, 1959; Howe, 1975; De Melo and Tarr, 1992; Creedy, 1998), which tends to become smaller in absolute value as income rises. It measures the willingness of consumers to substitute between consumption of essential and non-essential goods.

4. Placing the Frisch Equation (5.38) into Equation (5.34) rearranging to solve for

$\bar{c}_{ih}$, obtain the calibrated subsistence level

$$\bar{c}_{ih} = c_{ih} + \frac{\beta_{ih}}{p_i} \cdot \frac{M_h}{\phi_h} \tag{5.39}$$

5. Finally, the benchmark social accounting matrix is revised so that a consumer is initially "endowed" with $\bar{c}_i$, and the second-level composite utility function C_i is a Cobb-Douglas function with inputs of $c_{ih} - \bar{c}_{ih}$, with β_i re-scaled so that that $\sum \beta_i = 1$.

5.6 Market clearing conditions

The market clearing conditions, $\forall t$, are

$$A_{it} = c_{iht} + c_{it}^{g} + c_{i}^{Inv} + \sum_j A_{ij} \qquad \forall i, \forall j, \forall h \tag{5.40}$$

$$\sum_j L_{ljt} = \sum_h L_{lht}^{s} \qquad \forall l, \forall h \tag{5.41}$$

$$\sum_j K_{jt} = \sum_h K_{ht}^{s} + K_{gov,t}^{s} + K_{ROW,t}^{s} \qquad \forall j, \forall h \tag{5.42}$$

$$\sum_j Lnd_{jt} = \sum_h Lnd_{ht}^{s} \qquad \forall j, \forall h \tag{5.43}$$

5.7 Rest of the world (ROW), international trade, and capital flow

This model assumes a small open economy with unrestricted borrowing (lending), characterized by equalization of the domestic and international interest rates. This also means that the country cannot affect world prices, and that export and import prices quoted in foreign currency are exogenously given.

The rest of the world (ROW) is modelled as a simple agent that demands foreign savings in the domestic economy. Its income is determined by

$$ROWINC_t = r_t^K K_{row,t} + pfx_t \cdot \left[\sum_h (RH_{ht} - HR_{ht}) + (RG_t - GR_t)\right] - NX_t^{base} \tag{5.44}$$

and the simple maximisation problem is

$$\begin{aligned} \text{maximise} \quad & FSV_t && (5.45) \\ \text{s.t.} \quad ROWINC_t & \geq p_{inv,t} FSV_t && (5.46) \end{aligned}$$

The notations are:

$ROWINC$: rest of the world (ROW) income,

$\sum_h (RH_{ht} - HR_{ht})$: net total remittances from households,

$(RG_t - GR_t)$: net remittances from the government,

FSV: foreign savings,

NX^{base}: initially endowed net imports (a net exports from the perspective of domestic economy),

K_{row}, r^K: domestic capital owned by foreign agents and rental rate of capital.

Therefore, demand function for foreign savings is given by Equation (5.47), with unit cost given by Equation (5.48),

$$\begin{aligned} 0 & \leq p_{row,t} \perp FSV_t \geq \frac{ROWINC_t}{p_{row,t}} && (5.47) \\ p_{row,t} & \leq p_{inv,t} \perp FSV \geq 0 && (5.48) \end{aligned}$$

5.7.1 International trade

Export and import prices quoted in foreign currency are also exogenously given in this small economy. The following two equations link foreign prices with domestic prices $\forall t$. First, converting a unit of a foreign good, denominated in foreign exchange, into domestic prices is

$$0 \leq M_{it} \perp \varepsilon_t \cdot pfx_t - p^M_{it} \geq 0, \qquad \forall i \tag{5.49}$$

where M_i is the units of imported good i, p^M_i the unit price of the foreign good in domestic currency and pfx is the unit price of the good in foreign currency. Note that ε is the nominal exchange rate (domestic currency in terms of foreign currency), which is always assumed to be fixed (*e.g.* $\forall t$, $\varepsilon_t = 1$) and hence redundant.

Second, a unit of domestic good is exchanged (exported) for a unit of foreign currency by

$$0 \leq E_{it} \perp p^E_{it} - \varepsilon_t \cdot pfx_t \geq 0, \qquad \forall i \tag{5.50}$$

Notations are:

E_i, M_i:	exports and imports,
pfx:	unit price of a good in foreign currency,
p^E_i, p^M_i:	export and import prices in terms of domestic currency,
ε:	exchange rate (domestic/foreign),

5.7.2 Capital flow and net foreign assets

Capital is assumed to move freely between, and within, the domestic economy and the rest of the world (ROW). Therefore, the domestic rental price of capital is “pinned down” to the world prices via the foreign exchange rate. To characterize this, two mutually exclusive equations are introduced, which convert γ units of domestic capital into γ units of foreign exchange (and vise versa), $\forall t$.

Capital inflow into Ghana is represented by

$$0 \leq \gamma_t^{in} \perp pfx_t - \left(r_t^K - \epsilon\right) \geq 0 \tag{5.51}$$

where pfx is the cost of a unit of exchange rate, r^K is the rental price of a unit of capital, and γ is the number of units exchanged (a slack activity). Note that for computational purposes, $\epsilon \to 0$ is a small number used to differentiate between inflows and outflows, and avoid a problem of infinite solutions (a degenerate model).

As an example, capital inflow from the ROW to Ghana occurs when $pfx_t - \left(r_t^K - \epsilon\right) = 0$ with $\gamma^{in} > 0$,[5] but cease when $pfx_t - \left(r_t^K - \epsilon\right) > 0$ (a strict inequality) with a slack activity level $\gamma^{in} = 0$. At this point, capital inflow does *not* occur, Equation (5.51) is slack and Equation (5.52) is activated.

Therefore, *capital outflow* is represented by

$$0 \leq \gamma_t^{out} \perp r_t^K - (pfx_t - \epsilon) \geq 0 \tag{5.52}$$

If $r_t^K - (pfx_t - \epsilon) = 0$ and $\gamma^{out} > 0$, domestic capital is converted into foreign exchange.[6] But if $r_t^K - (pfx_t - \epsilon) > 0$ (strict inequality), the activity goes slack, $\gamma^{out} = 0$, and capital outflow does *not* occur, Equation (5.52) goes slack, and Equation (5.51) is reactivated.

Whenever the rental rate of capital is higher (lower) than in the rest of the world, reflecting higher (lower) demand for capital compared to other domestic inputs of production, (*i.e.*, land and labour,) capital flows in (out) of the domestic economy. This maintains a fixed capital-labour ratio in production. In other words, when the

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[5] This is considered to be foreign direct investment (FDI) into Ghana

[6] This is considered to be domestic direct investment (DDI), *i.e.*, the domestic economy invests abroad.

marginal productivity of capital is too high, the ROW invests in domestic capital in the form of foreign direct investment (FDI). Foreign exchange is converted into domestic capital, which raises the supply of capital, and reduces its rate of return. These net foreign asset flows pin down the domestic capital price with that of the ROW.

5.7.3 Trade balance and the current account

In the benchmark of 2007, Ghana is a net exporter to the rest of the world (ROW). In the long-run, however, trade must balance, though the timing is unknown. Furthermore, the assumption is that changes in malaria do not directly affect trade. Therefore, without additional foresight for the medium-run of 30 years, the closure rule for both the baseline and counterfactual scenarios is to raise the level of NX^{base} by the same growth rate as the ROW 15-65 population, who are assumed to demand Ghanaian goods.

However, the current account, which is the sum of net export and factor income, is endogenous because the flows of net foreign capital are endogenous as discussed previously in Section 5.7.2.

5.8 Investment and savings in the capital market

A virtual firm is assumed to invest in new capital in fixed proportion. The level of savings for the government and households are determined by Equations (5.25) and (5.32). The level of foreign savings, in domestic currency, is determined by Equation (5.47). Therefore, $\forall t$, total savings is

$$TSV_t = PSV_t + GSV_t + FSV_t \tag{5.53}$$

We assume that the virtual investment firm builds new capital stock with fixed proportion of final (Armington) consumption goods. The problem is to

$$\begin{aligned} \underset{c_{it}^{inv}}{\text{maximise}} \quad I_t &= \min\left\{\frac{c_{it}^{Inv}}{a_{it}^{Inv}}, \cdots, \frac{c_{Nt}^{Inv}}{a_{Nt}^{Inv}}\right\} \\ \text{s.t.} \quad TSV_t &\geq \sum_i p_{it}^A c_{it}^{Inv} \end{aligned} \tag{5.54}$$

Notations are:

PSV, GSV, FSV: Private, government and foreign savings,

I: investment level,

c_i^{Inv}: demand for investment of the i'th Armington good,

p_i^A: price of the i'th Armington good,

p_t^{Inv}: unit cost of the investment good,

a_i^{Inv}: expenditure share of the i'th good in total investment, with $0 \leq a_i^{Inv} \leq 1$, $\sum_i a_i^{Inv} = 1$

Similar to the solution for the government, $\forall t$, demand for investment is obtained by,

$$0 \leq p_{it}^A \perp c_{it}^{Inv} \geq a_{it}^{Inv} \frac{(PSV_t + GSV_t + FSV_t)}{p_{it}^A} \tag{5.55}$$

$$p_t^{Inv} \leq \sum_i a_{it}^{Inv} p_{it}^A \perp I_t \geq 0 \tag{5.56}$$

5.9 Recursive dynamics

Several researches have argued that developing countries are not forward-looking (e.*g*., Breisinger et al. (2008b) for Ghana). When agents are assumed rational and forward-looking, they can change their consumption/savings behaviours as new knowledge of the future becomes available in the present. But myopic agents are unable to account for future expectations in their current optimal decisions. This assumption seems consistent with empirical observations that suggest that low income agents are "borrowing constrained," and that a large fraction of their consumption is based entirely on current income (Deaton, 1991, 1992; Foster, 1995; Morduch, 1995). As a result, low income agents are unable to allocate resources optimally across time, which negates the theoretically elegant permanent income hypothesis.

The main purpose of this simulation is to link the role of health on the labour resource, and thus on the economy. Having households increase consumption today, due to their forward-looking expectations that they will have a healthier labour resource in the future, seems questionable. Furthermore, the dynamic evolution of capital accumulation is not directly relevant for poor countries if most households are poor and rely on low-skilled labour or public transfers as their main source of income. The use of a forward-looking optimization framework might not actually yield an accurate description of the evolution of capital in a developing country.

Practically, a forward-looking model would need to be calibrated on a *balanced growth path*, with endpoint conditions imposed on the finite horizon, so that agents can form expectation that approximate the infinite horizon. But a balanced growth path assumption for developing countries seems questionable when households have varying incomes, borrowing constraints, and health conditions. Approaching a steady-state long run growth is a process of at least a century, while our aim is to describe the impacts of malaria in a shorter time frame of 30 years. This model accounts for empirical facts that include a separate health model, which specifies exogenous population growth for each household that are associated with five epidemiological zones. Households, therefore, are mostly likely not on a steady state growth path in the medium-run.

For the above reasons, a recursive dynamic computable general equilibrium (DCGE) model is developed. Capital accumulation assumptions are more similar to those modelled by Springer (2002); Klepper et al. (2003); Thurlow (2007), who use a virtual firm that characterizes the capital market as described in Section (5.7).[7]

Our model solves a sequence of static one-period equilibria, in which future periods are connected through capital accumulation. The focus is on how malaria impacts the labour force and labour efficiency. Future malaria preventive scenarios are not integrated into the current optimal decision of agents. Instead, it "surprises" them.

The model somewhat resembles a Solow-Swan model, which has exogenous savings rates and human capital accumulation (Obstfeld and Rogoff, 1996; Barro and Sala-i Martin, 2003; Acemoglu, 2009). It is, however, different because it is a small open economy (SOE) with the rental rate of capital pinned to the world level, and with flexible capital in-flows (out-flows) as described in Section (5.7). The following summarizes the main elements which are incorporated into the recursive behaviour of the DCGE model.

5.9.1 Capital accumulation

The standard capital accumulation assumption is used, where

$$K_{t+1} = (1-\delta)\,K_t + I_t \tag{5.57}$$

and δ as the depreciation rate.

In addition, it is assumed that a price next period relative to its current price is equal to a fixed discount rate in the model. Therefore, all one-year future prices in terms of present value are

$$p_{t+1} = \frac{p_t}{1+r} \tag{5.58}$$

Similar to Lau et al. (2002), capital has two types of prices at each time period:

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[7] Kinnunen (2007); Breisinger et al. (2008a,b); Diao (2009), for example, have a different class of assumptions in which newly invested capital is influenced by each sector's initial share of gross surplus, and the final allocation depends on depreciation and sector specific profit-rate differentials.

(1) the rental price of capital, r_t^K, and (2) a unit purchase price of new capital, $p_{K,t}$. Assuming capital markets are competitive, the purchasing price of one unit of new capital equals the rental earnings of that unit plus the value of the remaining capital sold in the subsequent period, *i.e.*, a zero profit condition. The complementarity formulation of this problem is

$$0 \leq K_t \perp p_{K,t} \geq r_t^K + (1-\delta)\, p_{K,t+1} \tag{5.59}$$

Furthermore, an agent decides between using goods for consumption or investment, and as in Section 5.8, p_t^{Inv} is the unit cost of building an investment good. Assuming that this model would have been fully dynamic, the Euler condition equates the marginal utility of investment and capital accumulation by

$$0 \leq I \perp p_t^{Inv} \geq p_{K,t+1} \tag{5.60}$$

Since goods prices of two adjacent time periods are $p_t^{Inv} = (1+r)\, p_{t+1}^{Inv}$, it implies that the capital purchase price equals $1+r$ times the current cost of investment consumption,

$$(1+r)\, p_t^{Inv} \geq p_{K,t} \tag{5.61}$$

Combining equation (5.61) with equation (5.59) leads to

$$r_t^K = (r+\delta)\, p_t^{Inv} \tag{5.62}$$

Normally, social accounting matrices do not supply capital stock, but rather the capital earnings from services denoted by VK_t, which equals the capital stock, K_t, times the rental price of capital, r_t^K,

$$VK_t = r_t^K \cdot K_t \tag{5.63}$$

Thus finally, using equation (5.62) with equation (5.63) into the capital accumulation equation (5.57) yields

$$
\begin{aligned}
VK_{t+1} &= \frac{1}{1+r}\left[(1-\delta)\,VK_t + (r+\delta)\,p_t^{Inv} I_t\right] \qquad (5.64)\\
I_0 &\geq 0\\
VK_0 &\geq 0
\end{aligned}
$$

and initializing the model using VK_0 and I_0 from the SAM, and with $p_0^{Inv} = 1$ and $r_0^K = r + \delta$. Equation (5.64) is used for all agents in the model: h households, government, and the rest of the world.[8]

Notations are:

VK:	capital earnings from services,
K:	capital stock,
I:	investment level,
r:	exogenous discount rate,
r^K:	rental price of capital,
p_K:	unit cost of building an investment good
p^{Inv}:	unit cost of the investment good.

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[8] Being a developing country, it is expected that the social accounting matrix of Ghana is less than perfect. In the 2007 Ghana SAM, government is not endowed with capital, and therefore we do not use Equation (5.64) with the government. However, in the original SAM, the rest of the world (ROW) is also not endowed with capital, a fact that seems unreasonable because foreign direct investment is officially reported. Therefore, we had adjusted the SAM so that ROW, *i.e.*, a foreign entity owing domestic capital, is endowed with New Cedis 150 million of domestic capital, which is less than the official figures, but closer to reality. The SAM was slightly modified by assuming that instead of having Accra's high-income households owning all foreign capital, and transferring foreign capital earnings through remittances to ROW, some of the capital is directly owned by foreign imports of capital and foreign payments.

As mentioned previously, and discussed by Lau et al. (2002) and Paltsev (2004), a forward-looking model would require that the initial values in the SAM and especially investment, would be on a steady state growth path, so that the results in the final time period approximate the path of the infinite horizon. However, in a recursive model, these assumptions are not necessary.[9]

5.9.2 Updating labour recursively from the health models

The DCGE model is integrated with a health model that includes two main components to account for the impact of malaria disease: (1) a population projection component for the size of the labour force, using the cohort-component method that accounts for changes in fertility, migration, and mortality; (2) a labour effectiveness component that takes into account the impact of malaria on production and productivity for three malaria-specific health statuses: (a) malaria status of an adult worker, (b) malaria status of the child of an adult worker, and (c) malaria history of an adult worker (as a child). A probability and productivity factor is associated with each status, where the productivity factor accounts for absenteeism, presenteeism, reduced school attendance and cognitive ability. As described in Chapter 4, the impact on productivity of each status was retrieved from the literature. The probabilities were derived from a stochastic Poisson process as a function of the mean malaria in-

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[9] For example, if in the base year, an economy is on a steady-state growth path, then all quantities (capital, labour, output, consumption) grow at the same rate g_t, and capital stock would therefore grow by,

$$K_{t+1} = K_t \cdot (1 + g_t) \tag{5.65}$$

This would mean that combining equation (5.57) with equation (5.65), steady state investment should follow

$$I_t = K_t \left(\delta + g_t\right)$$

and using equation (5.62) with equation (5.63), steady state would mean that investment must be

$$I_0 = \frac{g_0 + \delta}{r + \delta} V K_0 \tag{5.66}$$

Assuming that growth rate is 5%, depreciation is 5%, and discount rate is 5%, the Ghanaian economy is approximately 14% over invested above the steady state levels.

cidence rate reported in each epidemiological zone. Finally, this disaggregated health model is mapped back onto households in the DCGE model.

In each period of time, labour $\bar{L}_{h,l,t}$ is disaggregated across three occupational categories

$$\{\text{skilled, unskilled, self-employed}\} \in l$$

and over nine epidemiological urban-rural regions by five income quintiles, *i.e.*, 45 households $\{h_1 \cdots h_{45}\} \in H$. Labour is assumed fully employed and mobile across sectors, with flexible real wages.

A Harrod-Neutral labor-augmenting production function $Y_t = F\left[K_t, \bar{L}_{lt} \cdot E_{lt}\right]$ is assumed, where $\bar{L}_{hlt}$ are the units of labour supply for household h and labour type l, with E_{hlt} as their level of labour effectiveness index (Barro and Sala-i Martin, 2003, p. 52). Recall that both enter exogenously into the DCGE model from the *satellite* health models, and depend on the regional epidemiological assumptions, and the specific scenario details, as discussed in Chapter 4. Therefore, labour supply, L_{hlt}, is derived by

$$L_{hlt} = \bar{L}_{hlt} \cdot E_{hlt} \tag{5.67}$$

and update yearly by

$$L_{hl,t+1} = \underbrace{\bar{L}_{hl0} \cdot (1 + g_{hlt})}_{\text{labor force}} \cdot \underbrace{E_{hl0} \cdot (1 + e_{hlt})}_{\text{effectiveness}} \tag{5.68}$$

with $\bar{L}_{hl0}$ supply given from the base year in the SAM, and base year effectiveness as $E_{hl0} = 1$. The household-specific labour growth, g_{hlt}, and labour effectiveness index, e_{hlt}, are inputs in the DCGE model from the health model.

5.9.3 Updating recursively other variables

In each period, exogenous stock variables in the model are updated based on their levels from previous periods, and growth assumptions that exogenously capture demographic and technological changes. The exception is capital accumulation, which occurs through endogenous linkages with previous-period investment as described in equation (5.64).

To maintain transparency and simplicity, we assume that net transfers from the government and the ROW to the various households rise by the rate of working age growth, g_{ht}, with a similar assumption to the minimum subsistence quantity, and the total direct tax paid to the government. These assumptions mean that the variables are fixed to the per-capita levels.

As discussed by Breisinger et al. (2011), agricultural growth in Ghana has been mainly driven by land expansion, rather than productivity, which continues to rise at an annual rate of 2.8%. This is currently higher than the average population growth rate. However, because such a high level of land expansion is not sustainable, and is expected to gradually decline, I assume that land expansion rises at the same rate as the working age population, *i.e.*, the effective quantity of land inputs are constant per capita. In other words, even though land is practically in fixed supply, their is an implicit technological improvement in land-use in this model.

Variables are updated exogenously by the following equations,

$$(HG_{h,t+1} - GH_{h,t+1}) = (HG_{ht} - GH_{ht}) \cdot (1 + g_{ht}) \tag{5.69}$$

$$(HR_{h,t+1} - RH_{h,t+1}) = (HR_{ht} - RH_{ht}) \cdot (1 + g_{ht}) \tag{5.70}$$

$$\bar{c}_{ih,t+1} = \bar{c}_{iht} \cdot (1 + g_{ht}) \tag{5.71}$$

$$T^d_{h,t+1} = T^d_{ht} \cdot (1 + g_{ht}) \tag{5.72}$$

$$Lnd_{h,t+1} = Lnd_{h,t} \cdot (1 + g_{ht}) \tag{5.73}$$

Recalling notation:

$HG_{ht} - GH_{ht}$: net household receipts from the government,

$HR_{ht} - RH_{ht}$: net household receipts from the ROW,

$\bar{c}_i$: subsistence level requirement,

T^d_{ht}: direct tax by household h,

Lnd_h: land endowments by household h.

Both the net transfers between the Government and the ROW $GR_t - RG_t$, and the base year net exports NX^{base}, rise at the same proportion to the ROW working age population. Total factor productivity increases by g_t^{TFP}, which we obtain from economic studies on Africa and Ghana. Finally, as discussed in Sections 5.4 and 5.5, a simple closure rule is used in equation (5.77) that transfers a share of household income to cover the government deficit. These are summarised by the following:

$$
\begin{aligned}
(GR_{t+1} - RG_{t+1}) &= (GR_t - RG_t) \cdot (1 + row_t) && (5.74) \\
NX_{t+1}^{base} &= NX_t^{base} \cdot (1 + row_t) && (5.75) \\
TFP_{i,t+1} &= TFP_{it} \cdot \left(1 + g_t^{TFP}\right) && (5.76) \\
\Phi_{ht} &= \frac{C_{ht}}{\sum_{ht} C_{ht}} && (5.77)
\end{aligned}
$$

Notations are:

$GR_t - RG_t$: net government receipt from ROW,

NX^{base}: initially endowed net imports (a net exports from the perspective of domestic economy),

C_h, Φ_h: household consumption and the share of consumption from total private consumption,

TFP_i: total factor productivity for sector i.

5.10 The values used for the model parameters

This section summarises the deep parameters used in the DCGE model: Frisch parameter, total factor productivity, and the long-run interest rates.

5.10.1 Income elasticities of demand

As discussed in Section 5.5, the household demand functions are derived from the Stone-Geary utility function, in which the income elasticity of demand is not necessarily unity. Al-Hassan and Diao (2007) and Breisinger et al. (2007, 2009) estimate values for the income elasticity of demand for specific sectors within Ghana, while

Table 5.1: The parameter values

	Income elasticity of demand		
Sectors	**Urban**	**Rural**	**Overall**
Agricultural	0.66	0.68	
Industrial	0.91	0.86	
Services	1.52	1.30	
Frisch parameter	-3	-5	
Total factor productivity (TFP)			1.6%
Long-run interest rate			5%

Nganou (2005); Hertel et al. (2008); Shimeles (2010) estimate these for sub-Saharan Africa in general.

In this study, however, production is aggregated into three general sectors: agriculture, industry and services, and I do not have the income elasticities of demand at this aggregate level. Therefore, in order to estimate them, I collect the income elasticity values for various sectors from the literature, and calculate a weighted average income elasticity based on the consumption shares of the specific sectors from within the original highly disaggregate Breisinger et al. (2009, 2011) Ghana SAM.

Using a simple average, for example, would be incorrect because a sector with a high income elasticity but a low consumption share would lead to an overestimate of the aggregated income elasticity of demand. Table 5.1 summarises the main values used in this model.

5.10.2 Other deep parameter

Equation (5.38) uses the Frisch parameter to estimate the subsistence levels. Nganou (2005) estimates the Frisch Parameter for Lesotho at -2.415, and in the GTAP 3 version, Hertel et al. (1997) use -5.85 for sub-Saharan Africa, and an approximate value of -3.3 for a middle income country. We therefore use a value of -3 for urban and -5 for rural agents (see Table 5.1).

For the purpose of analysing the welfare implication of malaria prevention, we do not actually need to add a total factor productivity (TFP) parameter into the model. This is because our analysis relies on comparing counterfactual scenarios of malaria intervention to a baseline with *no* additional intervention. In other words, we are not interested in a forecast model, but rather to compare one scenario to another. However, for the sake of making the model and its projections more realistic, we use a total factor productivity of 1.6%, which is an approximate figure reported by Arora and Bhundia (2003a); Bezabih et al. (2010), who have studied sub-Saharan Africa.

Finally, the long-run interest rate is fixed to 5%, which is a value used in many applied general equilibrium papers.

5.11 Conclusion

Chapter 4 is a synthesis of three models: (1) a Dynamic CGE model; (2) a cohort-component demographics model; and (3) a labour effectiveness model, which together impute the economic value of malaria reduction in Ghana. Chapter 5 provides a thorough description of the dynamic CGE model in order to make the conclusions discussed in Chapter 4 fully transparent.

As previously mentioned, the study finds that even under a limited intervention to only the under-five population, malaria reduction contributes to economic growth and development in Ghana. Furthermore, our approach can easily be framed as a cost-benefit analysis. Therefore, if governments and donor countries aim for a positive net present value (NPV), they must consider malaria prevention as a long-term investment strategy.

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