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A CGE Framework for Modelling the Economics of Flooding and Recovery in a Major Urban Area

by

Aaron B. Gertz and James Davies

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A CGE framework for modelling the economics of flooding and recovery in a major urban area

Aaron B. Gertz and James Davies[*,†]

September, 2015

Abstract

Coastal cities around the world have experienced large costs from major flooding events in recent years. Climate change is predicted to bring an increased likelihood of flooding due to sea level rise and a higher frequency of severe storms. In order to plan future development and adaptation, cities must know the magnitude of losses associated with these events, and how they can be reduced. Often losses are calculated by adding up insurance claims or surveying flood victims. However, this largely neglects the loss due to the interruption of economic activity caused by a flood. There have been some attempts to account for the output losses using input-output techniques, but these do not account for the mitigation achieved through flexible prices, changes in output composition, and factor substitution. Here, we use a computable general equilibrium (CGE) model to study how a local economy responds to a flood, focusing on the subsequent recovery/reconstruction. Initial damage is modelled as a shock to the capital stock and recovery requires rebuilding that stock. We apply the model to Metro Vancouver by considering a flood scenario causing total capital damage of $14.6 billion spread across five municipalities. Transportation and Warehousing are most severely impacted, followed by Manufacturing and Wholesale Trade. We find that the GDP loss relative to a scenario with no flood is 1.9% ($2.07B) in the first year after the flood, 1.7% ($1.97B) in the second year, 1.5% ($1.70B) in the fifth year and 1.1% ($1.42B) in the twentieth year. We also find that the losses tend to scale approximately linearly with the damage rate.

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1 Introduction

Climate change is expected to cause more extreme weather (including intense precipitation), sea level rise and melting snow caps [IPCC, 2014]. These factors can lead to an increased frequency and severity of flooding. This can further be exacerbated by land subsidence. As a result, cities face decisions about how to deal with the prospect of increased flooding. Possible adaptation measures to this threat include options like diking and sea walls, drainage and managed retreat from vulnerable areas. In order to make informed policy governments require estimates of the economic costs associated with flooding compared to the costs and benefits of various adaptation measures.

There are several aspects to the cost of flooding. The first and most obvious is physical damage to capital, such as homes, buildings, equipment and infrastructure. This can often be determined after the flood through insurance claims and disaster assistance payouts. Predicting flood damages typically uses information based on damages caused by previous floods. For example, engineers have developed damage formulas based on flood depth and the type of building called stage-damage curves. Apart from physical damages, there are also output losses as a result of lost economic activity.[1] For example, if a computer chip manufacturer has its output halved as a result of damaged equipment it will not be able to satisfy all of its orders. Consequently, a cellphone maker who had no damage from the flood may see a drop in output due to a shortage of inputs. Furthermore, incomes will be reduced leading to a decrease in consumption and savings of households. This can further impact trade and government revenues.[2]

This paper develops a framework for studying the economic impacts of flooding and the subsequent recovery. Consider a flood that strikes a particular geographic area of a city. For the duration of the flood, economic activity in that area will be suppressed.[3] Due to the localized nature of the flood, certain industries are more likely to be affected than other as industries tend to cluster together [Porter, 2000]. Goods produced by flood-impacted industries will be in short supply. This shortage will reverberate throughout the entire economy through supply chain linkages. Once the flood recedes, likely after a period of at least several days for a severe flood, damaged capital stock must be replaced or repaired and output in affected industries will remain below pre-flood levels. Investment will increase

[1] It is important not to naively add output losses to direct damages in order to estimate total losses. Part of the output loss is the loss of returns on damaged capital. Adding direct and output losses to get an estimate of total loss would involve some double-counting. See Davies [2015].

[2] Another potential economic effect may be to change beliefs about flooding resulting in changes in prices, including insurance premiums. However, that is not considered in this paper.

[3] Furthermore, people who live in the flooded area may be unable to travel to work even if their workplace is physically unaffected by the flood.

and flow to sectors with now higher marginal products of capital, notably those with capital damages. Exports will decrease along with production, meanwhile there may be an increase in demand for imports to satisfy the demand that cannot be met locally. Income tax revenues will fall from the decrease in output and incomes, however sales tax revenues may increase if damaged goods are being replaced. If tax revenues decrease overall, there must be either a reduction in government services or an increase in public debt. Public disaster assistance is another cost for government.

To examine the impact of a flood in a city and the subsequent recovery, we develop a dynamic multi-sector computable general equilibrium (CGE) model. A representative firm for each sector uses capital, labour and intermediate goods from other sectors as inputs. Capital and labour are sector-specific.[4] New capital for each sector is produced from a fixed bundle of goods (mostly construction). Forward looking households choose their stream of consumption, making investment endogenous. The Armington assumption is applied so that imports are imperfect substitutes for domestic goods. The model is calibrated to a balanced growth path. The flood is modelled as a shock to the capital stocks of the representative firms.[5] Consistent with a balanced growth model, the economy rebuilds the capital stock through investment and converges back toward the balanced growth path over time.

In this paper we consider the impact of a flood in Metro Vancouver,[6] a metropolitan area with about 2 million people on Canada's Pacific coast.[7] Vancouver has been identified as the 11^{th} most vulnerable coastal city in the world in terms of potential damage to capital from flooding [Hallegatte et al., 2013]. It is located on land that includes the delta of the Fraser River. About 20% of the population and considerable economic activity are located in the flood plain, and are protected by dikes. There have been two very severe floods in the last 125 years, in 1894 and 1948. With climate change expected to cause sea level rise, the severity of flooding is expected to increase. The region has a diversified economy and had a GDP of roughly $110B CDN in 2010.

We consider a flood scenario for the lower Fraser Valley causing total capital damage in Metro Vancouver of $14.6 billion (in our baseline scenario). Transportation and Ware-

[4]We are interested in near-term effects and use a 3-month timestep. It would be unrealistic for capital and labour to be able to flow freely between sectors over short time horizons. Sensitivity analysis is performed on the labour immobility.

[5]We ignore the losses *during* the flood period due to the unavailability of capital and labour because we focus on the long-term effects caused by capital damage.

[6]Metro Vancouver is made of up 23 jurisdictions, one of which is the City of Vancouver. In this paper all references to "Vancouver" or "the city" refer to Metro Vancouver, unless otherwise indicated.

[7]This work is part of the Coastal Cities at Risk Project which is an interdisciplinary study of flooding in Vancouver, Manila, Bangkok and Lagos.

housing are most severely impacted, followed by Manufacturing and Wholesale Trade. We find that the GDP loss relative to a scenario with no flood is 1.9% ($2.07B) in the first year after the flood, 1.7% ($1.97B) in the second year, 1.5% ($1.70B) in the fifth year and 1.1% ($1.42B) in the twentieth year. We also find that the losses tend to scale approximately linearly with the damage rate. In our baseline scenario, exogenous payments are made in the amount of the damages. These payments represent insurance payouts and disaster assistance.[8] We compare the baseline scenario to a situation with no payouts and find little impact on GDP, however there is a significant impact on welfare.

Aside from ex post surveys, three main approaches have been used to quantify the economic impacts of disasters: econometric techniques, input-output modelling and computable general equilibrium modelling (CGE). Guimares et al. [1993] used an econometric approach to estimate the damages in South Carolina from Hurricane Hugo. They began by estimating the relationship between the economies of South Carolina and the entire United States. They then compared South Carolina's economic performance in the aftermath of Hurricane Hugo to its simulated performance (without hurricane) based on that of the entire U.S. economy. The difference was attributed to losses caused by the hurricane. Xiao [2011] used a similar approach to estimate the cost of flooding in the midwestern U.S. in 1993. Strobl [2010] studied the impact of hurricanes on economic growth in U.S. coastal areas. However, such approaches are backward-looking and would be of limited value in cases such as Vancouver where the most recent severe flood was in 1948. Also, in order to answer counter factual questions regarding proposed adaptation measures, a model based on economic theory is required.

Modelling[9] the economic impacts of disasters is still a relatively undeveloped area of research. Cochrane [1974] published one of the first studies modelling the economic impact of natural hazards when he examined the potential impact of a California earthquake. His approach, which has become the most widely adopted in the study of natural disaster impacts, used an input-output model. Input-ouput models had been used in a variety of settings before being adopted for natural disasters. This included the impact of *man-made* disasters since World War II [Rose, 2004]. Boisvert [1992] and Cochrane [1997] developed models of earthquake impacts that allow for a more flexible treatment of imports, as in the event of a disaster it is normal for imports to the affected region to increase as local

[8] In Canada, both provincial and federal governments provide assistance in the event of natural disasters. Provincial governments take the lead but in the event of a large disaster have backup from the federal government under the Disaster Financial Assistance Arrangements [DFAA, n.d.], instituted in 1970. A province may request federal assistance when eligible expenditures exceed $1 per capita (based on provincial population). The rate of compensation rises with the extent of the disaster. For costs between $1 and $3 per capita, DFAA pays 50%, from $3 to $5 it covers 75%, and above $5 per capita it pays 90%.

[9] Here we differentiate models based on underlying economic theory from reduced form regression models.

production is disrupted.[10] Cochrane's approach has been incorporated into the HAZUS model developed by the Federal Emergency Management Agency in the U.S. [FEMA, 2012], which was initially applied to earthquakes and later extended to flooding. In this model, specific sectors' production is diminished by the disaster, but imports, exports and employment are able to adjust to make up for changes in supply and demand. The level of adjustment is constrained so that production losses are not all immediately recovered.

Hallegatte [2008] used an input-output approach to study the impact of Hurricane Katrina. A key innovation was to model damages as a shock to the capital stock, and the subsequent recovery as the rebuilding of that capital stock. Jonkman et al. [2008] used a detailed database to determine direct losses for flood scenarios in the Netherlands, with an input-output type model to quantify the output losses. Similar work has been done for Mumbai by Ranger et al. [2011]. Most recently, Hallegatte et al. [2013] applied the approach pioneered in Hallegatte [2008] to study the possible future impacts of coastal flooding on 136 cities worldwide under sea level rise caused by climate change.

There are downsides to input-output modelling such as its linearity, rigidity and lack of behavioural content. For example, input-output models do not allow for substitution between different goods in consumption or between capital and labour in production. Furthermore, the loss of capital after a disaster is likely to drive up demand for investment to replace what was damaged. In a market economy, the distribution of investment across sectors should depend on each sector's marginal product of capital. Any attempt to incorporate some of these features into an input-output model requires ad hoc assumptions that do not conform to an underlying theory, muddying the interpretation and robustness of the results. For these reasons, an increasing number of studies have used computable general equilibrium (CGE) models to study the economic impacts of disasters. Rose and Guha [2004] used a CGE model to study the impact of the loss of electricity due to an earthquake. Rose and Liao [2005] and Berrittella et al. [2007] followed with studies of disruptions in the water supply. Tsuchiya et al. [2007] and Tatano and Tsuchiya [2008] used a multi-region CGE model to quantify the economic impacts earthquake damage to transportation networks in Japan. Jonkhoff [2009], Pauw et al. [2011], Haddad and Teixeira [2013] and Carrera et al. [2015] applied the CGE approach to study the impacts of flooding in the Netherlands, Malawi, São Paulo Brazil and the Po Valley of Italy, respectively. Other researchers used CGE to predict the economic effects of sea level rise [see Pycroft et al., 2015, and the references provided therein].

This paper presents the first use of a *dynamic* CGE model to study the economic impacts

[10] In our model imports decrease as a result of the flood because the drop in incomes is not fully compensated for by disaster assistance, and thus the local economy cannot afford more imports.

of flooding. This allows us to study not just the immediate impact of the flood, but also the recovery process. Furthermore, the calibration approach offers a flexibility that would allow the model to be implemented at a variety of scales and in many different countries. We present new data derived for Metro Vancouver in order to perform the calibration exercise in this paper.

In some ways flooding lends itself very well to economic modelling because we can predict the physical damage based on a spatial flood scenario; damages from an earthquake can be unevenly distributed across a region and differ considerably depending on the source, size and other characteristics. Thus we do not have to consider limited scenarios like disruptions in only electricity or water. Damages in our study can be based on specific flood scenarios, which can respond to various adaptation measures, and impact every economic sector. We use the recovery mechanism from the input-output model of Hallegatte [2008]: investment using local production and imports rebuilds the capital stock. However, our CGE model innovates by allowing the pattern and speed of recovery to be determined endogenously. Specifically the level of investment is determined by a representative household choosing its lifetime stream of consumption to optimize welfare and new capital will be allocated to sectors based on its marginal products of capital. Furthermore, we examine how damage payouts (insurance and assistance) affect economic recovery.

The rest of the paper is organized as follows. Section 2 details the model. Section 3 describes Metro Vancouver, the local economy and its vulnerability to flooding. Section 4 outlines the data, section 5 presents simulation results and section 6 concludes.

2 The Model

The city's economy is modelled with a multi-sector balanced growth model. Each sector uses capital, labour and intermediate goods as inputs to production. The good produced by each sector is combined with an imperfectly substitutable import to create an Armington good. The Armington goods can be consumed by the household or government, invested, used as an intermediate in production or exported. The household - and government - each optimize their stream of consumption over an infinite horizon. The model is used to chart the effects of an unexpected flood that acts as a negative shock to the capital stock.

2.1 Production

In each sector, capital and labour (effective units) are combined with intermediate (Armington) goods to produce domestic goods:

$$Y_t^i = F_t^i(\{\tilde{Y}_{it}^j\}_{j\in J}, K_t^i, L_t^i) \tag{1}$$

Here, Y_t^i is the domestic output in sector i in time period t, $F_t^i(\cdot)$ is a nested CES production function, $\tilde{Y}_{it}^j$ is the intermediate good from sector j used to produce good i, K_t^i is capital and L_t^i is labour. The nesting structure is shown in figure 1. The firms also pay sector-specific sales tax rates on intermediate inputs, τ_{BST}^i, and sector-specific business income tax rates on capital income, τ_{BIT}^i.[11]

Capital and labour are sector specific. Since we are most interested in the most severe impacts of the flood, we are focused on the first few years following the event. Over this timeframe we do not expect labour, and especially capital, to be very substitutable across sectors. Note that new capital can be allocated to any sector according to demand. We also perform a sensitivity test where we allow labour to be mobile.

The domestically produced goods are combined with imports to produce Armington goods:

$$\tilde{Y}_t^i = H^i(Y_t^i, M_t^i) \tag{2}$$

M_t^i is an imported good and H^i is a CES function. The Armington goods are used as intermediate inputs or in final demand. The production structure is shown in figure 1.

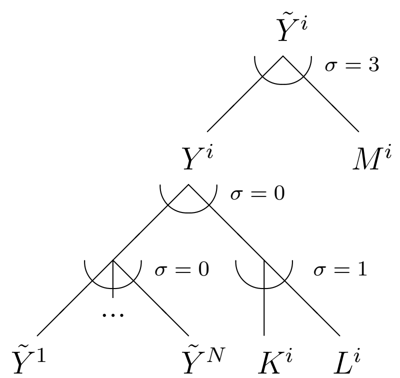

Figure 1: Production structure.

[11] BST stands for business sales tax; BIT stands for business income tax.

2.2 Household

The household consumes a good that is a composite of Armington goods:

$$c_t = g(\{\tilde{c}_t^i\}_{i \in J}) \tag{3}$$

Here, c_t is the consumption good and $g(\cdot)$ is a Cobb-Douglas function aggregating Armington goods $\tilde{c}_t^i$. The household is endowed with sector-specific labour (effective units), $\{l_t^i\}_{i \in J, t \in \{0,\infty\}}$, and initial capital, $\{k_0^i\}_{i \in J}$. Given prices, the representative household chooses its stream of consumption and investment to maximize utility subject to its budget constraint:

$$\max_{\{c_t, i_t^i\}_{t \in [0,\infty)}} \sum_{t=0}^{\infty} \beta^t u(c_t) \tag{4}$$

subject to

$$\sum_{t=0}^{\infty} \left[p_t(1+\tau_C)c_t + \sum_i p_t^{I^i}(1+\tau_I)i_t^i \right] = \sum_{t=0}^{\infty} \sum_{i=1}^{N} \left[(w_t^i - \tau_L)l_t^i + (R_t^i - \tau_K)k_t^i \right] \tag{5}$$

$$k_{t+1}^i = (1-\delta^i)k_t^i + i_t^i \tag{6}$$

We shall use the functional form $u(\cdot) = \ln(\cdot)$ for the utility function. β is the discount rate, which is between 0 and 1. p_t is the price of the composite consumption good, $p_t^{I^i}$ is the price of the investment good, w_t^i is sector-specific wages and R_t^i is the sector-specific return to capital. i_t^i is sector-specific investment and δ^i is the depreciation rate in sector i. τ_C and τ_I are rates of sales tax on consumption and investment goods, while τ_L and τ_K are tax rates on labour and capital incomes. Note that the p_t's are intertemporal prices and thus embody discounting in the budget constraint.

2.3 Investment and trade

Investment is sector-specific, however the bundle of goods that comprise the investment good is a fixed bundle across all sectors:

$$i_t^i = N \min_{j \in J} \{b_j \tilde{Y}_{i_t^i}^j\} \tag{7}$$

N is the number of sectors, $\tilde{Y}_{i_t^i}^j$ are the goods allocated to investment and b_j are the coefficients determining the composition of the investment bundle. In our simulations of Metro

Vancouver, investment is primarily made up of construction services and manufactured goods.

Exports generate "foreign currency", F_t. The amount of foreign currency generated from the sale of good X_t^i is denoted by $F_t^{X^i}$. Foreign currency can be used to purchase any foreign good; the amount of foreign currency used to purchase import M_t^j is denoted by $F_t^{M^i}$.

$$X_t^i = F_t^{X^i}, \qquad p_t^i X_t^i = p_t^F F_t^{X^i} \tag{8}$$

$$M_t^i = F_t^{M^i}, \qquad p_t^{M^i} M_t^i = p_t^F F_t^{M^i} \tag{9}$$

The above equations impose that the prices of all exported goods move together along with the prices of imported goods and the exchange rate, p_t^F. This establishes that there are world prices that cannot be changed by the local region (small open economy). However, if a good is not exported then its price can move freely. This occurs because domestic demand is so strong for the local good that it good cannot be met at world prices; recall that the equivalent foreign good is not a perfect substitute because of the Armington assumption.[12] The trade deficit, D_t, is exogenously supplied to the model for each time period.

$$\sum_i M_t^i = \sum_i X_t^i + D_t \tag{10}$$

2.4 Government

The government sector is an amalgam of all levels of government in the city studied. It levies labour and capital income taxes and sales taxes and uses the revenue to purchase goods and services, that is to "consume".[13] We assume that the government has a utility function defined over its stream of consumption, and maximizes it subject to its intertemporal budget constraint. In each period the government consumes a bundle of Armington goods:

$$G_t = N \min_{j \in J} \{ b_j^G \tilde{G}_t^j \} \tag{11}$$

The coefficients, b_j^G, determine the ratio of goods in the bundle. We assume the government bundle has fixed proportions because we do not believe policy regarding the relative provision of government services, like education and healthcare, is affected by relative price

[12] In our simulations it is rare for exports to be shut down.

[13] We do not include disaster assistance payments in the government budget or provision of services. We treat that as an exogenous endowment of foreign exchange from outside the local municipality.

changes. The government problem is given by:

$$\max_{\{G_t\}_{t\in[0,\infty)}} \sum_{t=0}^{\infty} \beta^t v(G_t) \tag{12}$$

subject to

$$\sum_{t=0}^{\infty} p_t^G G_t = \sum_{t=0}^{\infty} \left[T_t^L + T_t^K + T_t^{Sales}\right] \tag{13}$$

Again, we use the functional form $v(\cdot) = \ln(\cdot)$ for the utility function, with discount factor β (the same value as the household). p_t^G is the price of the government consumption bundle and T_t^{type} are the different types of tax revenues collected (labour and capital income taxes plus sales taxes). The amounts of tax revenue are determined by exogenous tax rates. That is, there is a tax rate for labour and capital (varying by sector for capital) and sales tax rates on intermediate inputs for each sector plus household and investment purchases (more detail is given in section 4).

We have left tax rates exogenous since changes in such rates are relatively infrequent. The level of government spending in each year is endogenous, however, and government has a choice about how to adjust its spending level from period to period in the face of the altered prices that may arise in the wake of a flood. How it reacts depends partly on the specification of the function $v(\cdot)$. Here we have assumed *log* utility, which gives constant expenditure shares across periods. However, a utility function that would generate less elastic demand could be assumed if that was determined to be more realistic. In addition, the coefficients in (11) could be allowed to change as a result of a disaster (perhaps accounting for the provision of disaster related services). While incorporating such features is technically possible, we do not pursue these aspects in this paper since work along these lines requires very careful study of how government spending actually is affected by flooding, which is outside the scope of this paper.

While the explicit government sector in our model may be considered rather passive in the face of flooding, the main public sector response to flooding, which is external, is captured separately. As noted earlier, we have assumed that all capital damage is compensated for through insurance payouts or public disaster assistance. Since little flood insurance is available in Canada, this means that a large amount of external disaster assistance from the provincial and federal governments is being assumed, as is realistic.[14] We study the

[14] Repairs or replacement of capital owned by households, small businesses or provincial or municipal governments are all eligible for federal assistance under the Disaster Financial Assistance Arrangements [DFAA, n.d.]. While assistance to large businesses and crown corporations is not covered by the federal plan, provinces are free to assist those organizations if they wish to do so. Thus the assumption of very

impact of that assistance in our simulations, thereby capturing the main expenditures of government in mitigating the economic impacts of flooding.

2.5 Market clearing

The goods, capital and labour markets all clear:

$$\tilde{Y}_t^i = \sum_{j=0}^{J} \left[\tilde{Y}_{it}^j + \tilde{Y}_{i_t^i}^j\right] + X_t^i + \tilde{c}_t^i + \tilde{G}_t^i \quad (14)$$

$$K_t^i = k_t^i \quad (15)$$

$$L_t^i = l_t^i \quad (16)$$

2.6 Solution to the model

An equilibrium given an initial capital stock, $\{k_0^i\}_{i \in J}$, is defined as the set of prices and quantities in the model such that given prices: firms maximize profits; the household and government maximize utility subject to their budget constraints; trade and investment satisfy the equations in section 2.3; and all markets clear (goods, capital, labour, trade including deficit).

The equilibrium solution converges toward a balanced growth path.[15] That is:

- The quantities Y_t^i, $\tilde{Y}_{it}^j$, K_t^i, M_t^i, X_t^i, c_t^i, i_t^i, G_t, T_t^{inc}, T_t^{Bus} and T_t^{Sales} all have growth rates of g as $t \to \infty$;

- The prices p_t^i, $\tilde{p}_t^i$, p_t^F, $p_t^{M^i}$, R_t^i, w_t^i, $p_t^{I^i}$ and p_t^G all have growth rates of $\frac{\beta}{1+g} - 1$ as $t \to \infty$ (for log utility);[16]

- $R_t^i \to R$ for all i as $t \to \infty$; $r = R - \delta$.

Note that due to the constant growth rates, quantities and prices have constant ratios in the limit. In the quantitative exercise, we assume that the economy is following the balanced growth path prior to the flood in order to calibrate the model. Once the parameters are determined, we perform counter-factual analysis of flood scenarios.

large government response via disaster assistance is realistic.

[15] Note that the effective units of labour, L_t^i, grow at the exogenously supplied growth rate, g. For details of balanced growth, see Acemoglu [2009].

[16] Note that $\tilde{p}_t^i$ is the price of the Armington good i.

3 Scenario - Vancouver

Metro Vancouver is a large urban area that is of considerable importance to the Canadian economy. It is situated at the mouth of a major river, the Fraser. A significant portion of the city is on the river's floodplain, including the large delta on which the cities of Richmond and Delta are mainly located (see figure 2). The Fraser tends to flood in the spring, as a result of snow melt in the mountains and spring rains. But the area is also threatened by coastal flooding. Weather systems from the Pacific sometimes cause large storm surges on the coast and some distance up the river. While the area is protected by dikes, dike breach can occur and is difficult to repair under flood conditions. The seriousness of the threat is expected to increase as sea level rises due to climate change. Study of Vancouver is facilitated by its inclusion in a large interdisciplinary research project on Coastal Cities at Risk funded by Canada's three major research granting agencies. The approach used here could be adapted to other cities facing flood risk.

It is unfortunately difficult to get many standard economic indicators, such as output by industry, and imports or exports for geographical areas smaller than a province in Canada. GDP numbers were not available by city until experimental estimates were released in November 2014 [Brown and Rispoli, 2014]. This leaves knowledge of the economic structure of any city in Canada, and even its largest metropolitan areas, incomplete. There is information on the size and composition of the labour force, both from the monthly Labour Force Survey and, in more detail from the decennial census and the supplementary census conducted halfway between the main censuses. In section 4, we use the 2006 census National Household Survey [Statistics Canada, 2006] to estimate that 86% of employment was in the service sector in 2010. Just 10% was in manufacturing, only 1.1% in agriculture and other primary activities, and 0.7% in utilities. Construction accounted for 2.5% of the labour force. The largest labour force in the service sector belonged to retail trade (12%); professional scientific and technical services made up 10%, while finance and real estate accounted for 8% of the workforce. For more detail see Table 1. Assuming productivity within industries was the same in Metro Vancouver as in the province as a whole, we estimate Metro Vancouver's GDP to have been $110 billion in 2010 (see section 4 for details), which represents about half of the provincial total.[17]

The industrial composition of Metro Vancouver as a whole does not provide a guide to the activities that would be directly affected by flooding since the representation of industries in the floodplain is somewhat different. In the floodplain areas, transportation

[17]Brown and Rispoli [2014] estimate GDP for Metro Vancouver at $103 billion in 2009. Since GDP for B.C. as a whole grew 5% in 2010, our estimate of $110 billion for Metro Vancouver's GDP in 2010 is well aligned with the Statistics Canada number. We also match their service sector share of value added, 83%.

and warehousing and agriculture are relatively more important. Vancouver International Airport, for example, is built on Sea Island at the mouth of the Fraser where ground level is about a metre below sea level at high tide. Some of Port Vancouver's extensive facilities are also located in the floodplain. The agricultural sector includes expensive facilities such as very large greenhouse complexes in Delta and Surrey that are vulnerable to flooding.

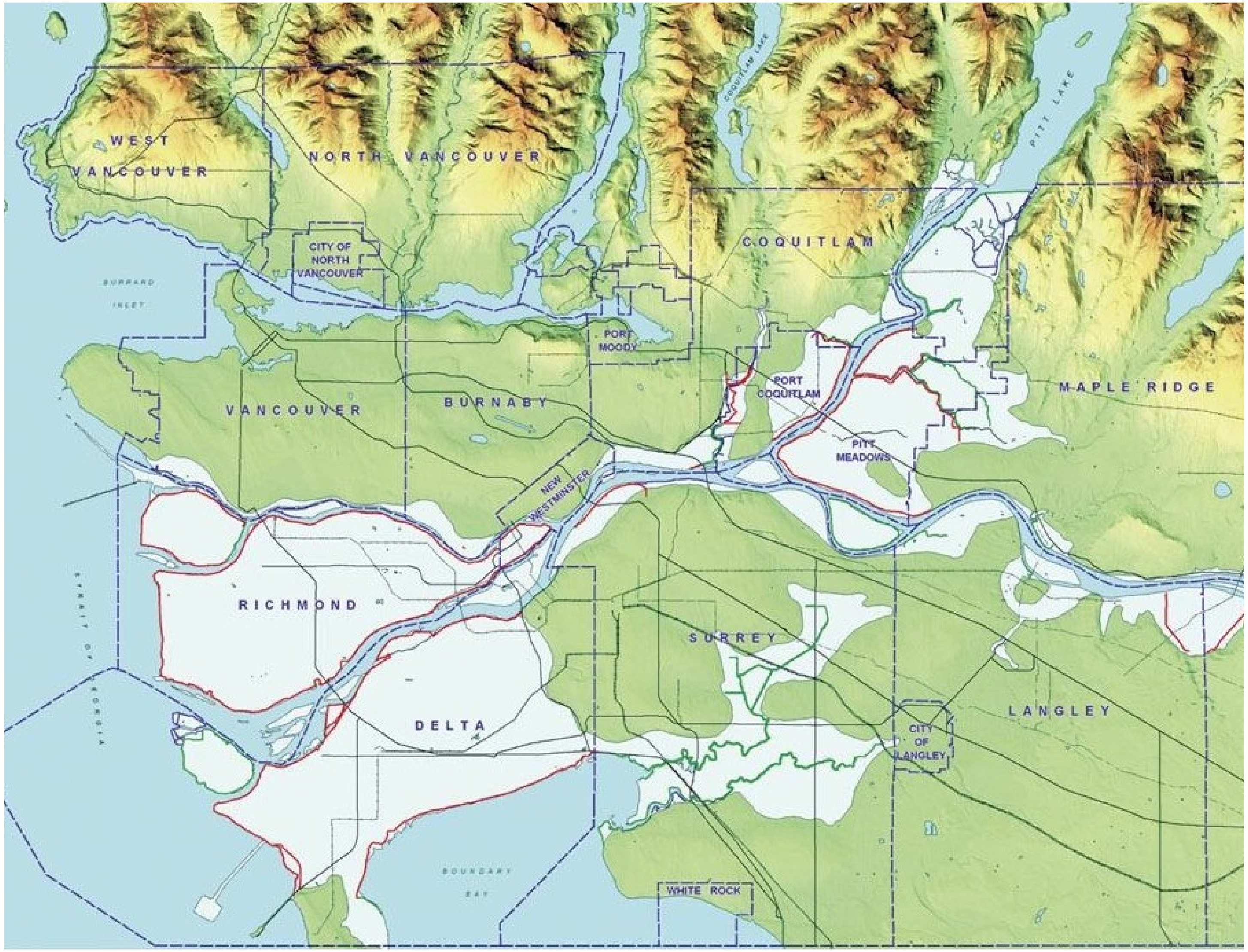

Figure 2: Metro Vancouver floodplain map (white indicates floodplain). Source: Fraser Basin Council [n.d.].

The importance of Vancouver's port and airport has been analyzed in recent economic impact studies. While we discount the estimates of indirect jobs and output that are a common feature of such studies, the numbers they provide on direct impacts are helpful. In 2012 it is estimated that Port Vancouver provided 38,000 jobs directly and contributed $3.5 billion to GDP directly [InterVISTAS Consulting Inc., 2013]. Vancouver International Airport was estimated to provide 23,614 direct jobs and to contribute $1.8 billion to GDP directly in 2010 [Economic Development Research Group, Inc., 2011]. Using these numbers, the port and airport together would account for 5% both of Metro Vancouver's labour force and its GDP in 2010.

Other transportation aspects are also important. Canada's major road and rail networks originate/terminate in Vancouver, and there are also important links to the U.S. The Trans Canada highway and the main roads to the U.S. pass through the floodplain, as do the CPR, CNR, the Southern Railway and the BNSF railway from the U.S. Highway 99, one of the most important north-south road links, passes through the Massey Tunnel under the Fraser River, close to its mouth, and would be vulnerable in a major flood. For many kilometres the main line of the CNR follows the south bank of the river, and the CPR has a significant stretch that runs close to the north bank. The BNSF hugs Boundary Bay from its entry into Canada to Surrey, and delivers large volumes of U.S. coal to the Roberts Bank coal export terminal at Tsawwassen, reportedly the busiest coal terminal in North America. Closure of these road and rail links for any significant period of time would cause costly interruption/reduction in the supplies of food, other consumer goods, and industrial inputs in Metro Vancouver. It would also impose costs spread over B.C., Western Canada, and the Northwest U.S. Impacts on the U.S. coal industry, for example, could be serious as coal exports have been banned from most U.S. west coast ports.

There have been two especially severe floods on the Fraser River in the last 125 years. The first occurred in May 1894 and caused wide inundation but little damage in economic terms since the area was still relatively undeveloped. At that time use of the floodplain was largely confined to agriculture and fishing. By the time of the next major flood, in May 1948, the situation had changed, with the development of light industry, sawmills and other enterprises, as well as a sizable increase in population. It is recorded that 10% of the Fraser Valley, in total 200 square kilometres, was flooded. There were 10 fatalities, 16,000 people were evacuated, 3,000 buildings were destroyed, and 82 bridges were washed out. Total damages are estimated at $210 million in 2010 dollars [Fraser Basin Council, n.d., BC Ministry of Forests, Lands and Natural Resource Operations, n.d.]. It has been estimated by Canadian agencies that a repeat of the 1948 flood today would cause "several billions" of dollars in damage to the City of Richmond alone, and "tens of billions" of dollars of damage in total to communities on the Fraser River. Hallegatte et al. [2013] apply a uniform methodology to estimate the flood risks faced by 136 coastal cities around the world. They rank Vancouver as the city with the 11^{th} greatest exposure of capital to a one hundred year flood, estimating that in 2005 it had exposure of $33.4 billion.[18] If 25% of this capital were destroyed in such a flood, damage would be $8.4 billion, agreeing roughly with the level of damage assumed here (see section 5).[19]

While a flood of equal magnitude to that of 1948 has not yet recurred, this remains a constant possibility. After the 1948 flood, dikes were constructed or raised to a height that would protect against another flood of that order. There are currently over 600 km of dikes and 100 pumping stations [Fraser Basin Council, n.d.]. However, much of the diking was originally designed to protect farmland, whereas it now serves urban areas, which may need a higher standard of protection. Also, climate change is expected to result in sea level rise (SLR); 26 cm to 82 cm in the 21^{st} century [IPCC, 2014]. The mid point of this range would bring high tide levels to 1.5 metres above ground level in the lower reaches of the Fraser. Further factors that may exacerbate flooding in the future are land subsidence, which is ongoing at a slow but steady rate, higher storm surges from the sea due to more extreme weather, and stronger/higher wave action as the waters being held back by the dikes deepen.

Here we model the economic impacts of a flood of the 1948 dimension assuming a "worst case" scenario in which dike breaches occur in a number of locations, leading to general inundation of the flood plain. We assume the population, assets, and economic activity seen in 2010, the most recent year for which the necessary data are available. Based on the floodplain map, we assume the areas flooded are 100% of Richmond, 70% of Delta, 5% of the City of Vancouver, 10% of Surrey, and 5% of Burnaby. Effects on some smaller communities, such as Coquitlam, are not considered. In our central case it is assumed that 25% of the capital - buildings, machinery and equipment - in each area is destroyed. This results in a loss of 4.4% of Metro Vancouver's total capital stock, with the greatest damage being 10% in the transportation and warehousing sector. Sensitivity testing is done assuming lower and higher levels of capital damage.

[18] Hallegatte et al. [2013] also estimate that the expected annual cost of flooding as of 2005 was $107 million for Vancouver. Considering that floods that cause more than a few million dollars in damage have not been experienced since 1948, this figure likely reflects a forecast in which infrequent major floods cause billions of dollars of damage.

[19] In related exercises, some have estimated the damage that would be done by sea level rise (SLR) if flood defences are not improved. Given the SLR typically predicted for the next century one would expect inundation similar to what would be caused by a one hundred year flood. The National Roundtable on the Environment and the Economy [2011] estimated that for Canada SLR would cause between $1 and $8 billion in annual damage by 2050, based on a rise in sea level ranging from 0.28 to 0.85 metres. Harford [2014] claims that a 1 metre SLR could cause $12 billion in damage for the city of Vancouver alone.

4 Data

The model is calibrated to the Metro Vancouver economy assumed to be following a balanced growth path. That is, in the absence of a flood all inputs and outputs are assumed to grow at a constant annual growth rate, g, which we set at 2%; this determines other key parameters in the model. When the flood hits, the capital stock is shocked and the economy is knocked off the balanced growth path at $t = 0$ and asymptotically converges back toward the balanced growth path over time.

The most important data needed for a multi-sector model is a social accounting matrix (SAM) with details on sector-specific intermediate inputs, labour, capital and taxes, as well as final demand (private consumption, government consumption, investment, imports and exports). These data are used to determine share parameters for the sector-specific production functions, the consumption bundles and the investment good, as well as tax rates and trade shares. The starting point for constructing our SAM is the 2010 British Columbia input-output table and final demand table [Statistics Canada, 2010]. However, we require this data at the municipal level. We use the method of Heijman and Schipper [2010], briefly explained in the next subsection, to derive the Metro Vancouver social accounting matrix. This requires output by sector at the municipal level. We do not have this data, however we have employment by sector at the municipal level from the 2006 census [Statistics Canada, 2006]. We use BC Stats [n.d.] employment data to adjust the employment by sector for the year 2010. We assume sectoral output-employment ratios are the same in Metro Vancouver as the rest of B.C. to estimate output by sector in Metro Vancouver.

To complete our SAM we need data on direct taxes, which is not provided in the B.C. input-output table. Therefore, it is assumed that the shortfall between government spending and revenues is covered by taxes on labour and capital income. This is explained in more detail below.

Metro Vancouver comprises 23 jurisdictions: 21 municipalities, one electoral area (University of British Columbia) and one treaty First Nation. The census provides sectoral employment data for each municipality. Assuming sectoral capital-employment ratios are constant across municipalities we can estimate the division of each sector's capital stock across municipalities. This allows us to incorporate the spatial dimension of damage scenarios.

4.1 Local input-output table

The B.C. 2010 symmetric input-output table is comprised of 25 private business sectors, 6 government sectors and 1 non-profit sector. The table also provides spending on labour income, operating surplus (which we consider to be capital income), taxes and subsidies.

We construct a local input-output table for Metro Vancouver in two stages (the actual tables are given in the Appendix). First we estimate total output by sector. Then we fill in the flows of intermediate inputs by an imputation procedure.

To obtain estimates for local sectoral output, we calculate each sector's output-employment ratio for B.C. as a whole and then multiply Metro Vancouver's sectoral employment numbers[20] by these ratios. If output-employment ratios differ significantly between Metro Vancouver and B.C. as a whole there will be error in our output estimates. However, since we are accounting for sectoral differences, and Vancouver makes up half of the B.C. economy, we do not believe the error would be very large.[21] Table 1 shows our estimates of employment, output and value added by sector in Metro Vancouver for 2010.[22] Note that the sectors expected to suffer the highest rate of capital damage - transportation and warehousing and agriculture - make up a relatively small fraction of the economy but still account for output of $14.8B and value added of $7.4B.

[20]The most reliable sectoral employment numbers are provided by the census. We adjusted the 2006 census figures for Vancouver to a 2010 basis by imposing the overall growth of Vancouver employment (8.25%) and assuming the same sectoral shifts as shown for the province as a whole in the BC Stats [n.d.] employment report.

[21]One indication of accuracy is agreement between the goods vs. services split in our numbers and those in Brown and Rispoli [2014]. We each get an 83% service share.

[22]We combine some of the 32 sectors in the B.C. input-output table to get the sectors listed in the table. This is necessary because Vancouver sectoral employment numbers are only available for 20 sectors.

Sector	Employment	Output ($ million)	Value Added ($ million)
B11 Agriculture, forestry, fishing and hunting	8,110	1,599	515
B21 Mining and oil and gas extraction	3,774	3,921	2,404
B22 Utilities	6,830	2,677	1,358
B23 Construction	26,136	15,430	13,284
B31-B33 Manufacturing	105,345	20,901	1,546
B41 Wholesale trade	62,105	8,017	5,004
B44-B45 Retail trade	126,441	9,126	7,270
B48-B49 Transportation and warehousing	48,598	13,153	6,881
B51 Information and cultural industries	36,448	7,807	4,045
B52-B53, B55 Finance, insurance, real estate	85,605	42,295	28,366
B54 Professional, scientific and technical services	103,248	10,675	4,146
B56 Administrative and support, etc.	38,133	4,375	367
B61 Educational services (private)	3,829	494	351
B62 Healthcare and social assistance (private)	46,397	4,199	2,108
B71 Arts, entertainment and recreation	24,009	1,839	1,417
B72 Accommodation and food services	75,645	5,780	4,630
B81 Other services (except public administration)	52,791	5,886	4,581
G61 Educational services (public)	82,266	6,321	6,142
G62 Healthcare and social assistance (public)	74,535	4,255	3,968
G91 Public administration	48,062	13,002	11,692
Total	1,058,311	181,750	110,074

Table 1: Metro Vancouver employment, output and value added (GDP) for 2010.

4.2 Demand table

In the model we have five final demand categories: private consumption, government consumption, investment, imports and exports (the derived final demand table for Metro Vancouver can be found in the Appendix). The final demand table in the industry accounts has a more disaggregated detail. We combine the detailed categories of final demand from the latter table into our five broad demand categories as follows:

- Private consumption: household consumption and non-profits;
- Government consumption: government consumption;
- Investment: all construction, machinery and intellectual property columns;
- Exports: international and inter-provincial exports, re-exports and inventory additions;
- Imports: international and inter-provincial imports, and inventory withdrawals.

Local total demand and intermediate demand are determined by the input-output table.[23] Local *final* demand is the difference between total demand and intermediate demand. The ratio of consumption of each good to GDP is calculated for the province as a whole, then those ratios are assumed to hold for Metro Vancouver giving household consumption by good at the local level. To determine the distribution of government consumption, we multiply the province level government consumption by sector by the fraction of B.C. workers who are employed in Metro Vancouver (54%). We do this because we expect government services to be more closely related to employment (population) levels than to income levels. The local investment and exports are determined by multiplying province-level values by the fraction of that industry's production concentrated in Metro Vancouver. For example, 20% of B.C.'s agricultural output is in Metro Vancouver, therefore we assume 20% of agricultural investment goods and exports are from Metro Vancouver. Imports are treated in a similar fashion, except using only the local fraction of *domestic* demand.

To this point, we have not yet accounted for intra-provincial trade (on which there is no data). Furthermore, using the above approach to get the local final demand table, there are small residual differences between the sum of total demand in each sector/good and the total demand needed to ensure that all output is sold (zero profits). The residual could arise either due to (inescapable) errors in the imputed amounts for consumption, investment, and exports and imports with the rest of the world and Canada, or because we have ignored

[23]For zero profits in each sector, total demand is equal to the total cost of all inputs.

intra-provincial trade. Since we have no way of knowing what errors may have been made in the imputations we attribute the entire residual to intra-provincial trade. Our estimates of net intra-provincial trade are therefore given simply by the residual. Gross intra-provincial trade flows are estimated using the following procedure. Consider two extreme cases for gross trade flows:

1. Minimum trade: Trade is in one direction - imports only or exports only. If the residual is negative there will be intra-provincial exports; if it is positive then there will be imports. In either case the trade flow will be just enough to offset the residual.

2. "Maximum" trade: Each good produced in Metro Vancouver has a random chance of being consumed in Metro Vancouver or the rest of B.C., weighted by the demand for that good in the two places. This assumption dictates the amount of intra-provincial exports. Intra-provincial imports are the difference between the estimated intra-provincial exports and the residual.

The minimum trade case gives relatively small exports or imports across all sectors and is helpful in setting a lower bound. The "maximum" trade case gives the amount of intra-provincial trade that would occur, theoretically, if no additional transport or other costs were incurred when goods or services were traded intra-provincially rather than produced and used within Vancouver. Even more trade could occur if, for example, the first source of supply for all goods and services in the rest of the province was Vancouver and vice versa - but that is implausible.

To estimate intra-provincial trade flows, we start with case 2, which clearly implies too much intra-provincial trade since there are in fact additional transport costs of trading with the rest of the province rather than transacting only within Vancouver. This maximum total trade is then multiplied by a "trade coefficient", where a coefficient of 0.25 would imply, for example, there is a quarter the trade of the maximum case.

We started with a baseline coefficient of 0.5, however in some sectors this results in a disproportionate level of intra-provincial trade compared to trade with the rest of the world and Canada. Consideration of characteristics of many sectors suggested a lower coefficient was needed, and we have used a value of 0.1 in most such cases (see the first column of Table 2). For finance, insurance and real estate, and for public administration we use a coefficient of 0.25. For manufacturing, which is highly trade-oriented, we use 0.75. For construction we expect very little trade and use a value of 0.01.

Note that for B.C., international trade is 50% of GDP and inter-provincial trade is an additional 41% of GDP. Our trade data is given in Table 2. For our Metro Vancouver estimates, international plus inter-provincial trade is 84% of GDP (compared to 91% for

B.C.), and intra-provincial trade is an additional 44% of GDP. Trade differs considerably in importance across sectors, from a very low level in construction and some service industries like health and education, to a high level in transportation and warehousing and manufacturing. Note that total manufacturing exports (intra-provincial plus those to the rest of Canada and the world), at $22.3B, exceed the manufacturing output of $20.9B shown in Table 2. This reflects the high level of imports and re-exports of manufactured goods.

Sector	Trade coefficient	Intra-provincial			Rest of Canada and world		
		Total	Exports	Imports	Total	Exports	Imports
B11 Agriculture, forestry, fishing and hunting	0.5	1,285	530	-755	1,100	534	-566
B21 Mining and oil and gas extraction	0.1	584	324	-260	4,117	2,908	-1,209
B22 Utilities	0.1	241	138	-103	496	254	-243
B23 Construction	0.01	169	49	-120	67	20	-47
B31-33 Manufacturing	0.75	14,435	7,279	-7,156	45,333	14,987	-30,345
B41 Wholesale trade	0.5	2,406	1,774	-631	5,443	2,790	-2,653
B44-45 Retail trade	0.1	909	106	-803	1,962	1,368	-594
B48-49 Transportation and warehousing	0.5	4,905	2,795	-2,110	9,916	6,797	-3,119
B51 Information and cultural industries	0.5	2,202	1,597	-605	3,729	1,962	-1,766
B52-53, 55 Finance, insurance, real estate	0.25	7,670	5,880	-1,790	6,753	2,268	-4,484
B54 Professional, scientific and technical services	0.5	3,499	2,447	-1,053	5,039	2,981	-2,058
B56 Administrative and support, etc.	0.1	369	260	-109	2,372	1,120	-1,251
B61 Educational services (private)	0.1	44	20	-24	80	74	-6
B62 Health care and social assistance (private)	0.1	411	365	-46	96	21	-75
B71 Arts, entertainment and recreation	0.5	875	385	-490	910	453	-456
B72 Accommodation and food services	0.5	2,835	1,210	-1,625	3,725	1,961	-1,764
B81 Other services (except public administration)	0.1	528	209	-319	702	435	-267
G61 Educational services (public)	0.1	569	296	-273	391	198	-193
G62 Healthcare and social assistance (public)	0.1	416	105	-311	182	115	-66
G91 Public administration	0.25	3,815	134	-3,680	556	239	-317
Total		48,167	25,903	-22,263	92,969	41,485	-51,479

Table 2: Estimated Metro Vancouver trade with rest of B.C. and elsewhere ($M) in 2010.

4.3 Government and taxes

There are two types of taxes (and subsidies) given in the industry accounts data for British Columbia: taxes on products and taxes on production. We treat the taxes on products net of subsidies as sales taxes applied to intermediate and final goods.[24] We determine the tax rates for B.C. as a whole for intermediate inputs in each sector plus private consumption and investment, and apply them to Metro Vancouver. We treat the taxes on production net of subsidies as capital income taxes.[25] We determine the tax rates as a percentage of capital income in each sector for B.C. as a whole and apply them to Metro Vancouver.

The industrial accounts data does not include any direct taxes. As a result, the tax revenue (\$12.7B) falls significantly short of government spending (\$22.7B) for Metro Vancouver.[26] Therefore we calculate the average tax rate on personal income needed to cover the government deficit. The resulting (average) personal income tax rate is 12.8%, which is low because our analysis ignores pure transfers from the government to households. For modelling purposes, we divide this personal income tax burden between labour and capital income.[27]

4.4 Assumed parameter values

Several parameters must be set exogenously: the growth rate, the rate of depreciation and the elasticity parameters. Standard values are chosen for these parameters and sensitivity is tested in section 5.3. The growth and deprecation rates are used (along with the initial capital stock, initial investment and the tax rate on investment) to determine the interest rate (as described below). Key parameter values are given in table 3.

We assume the economy follows a balanced growth path (BGP), so we can use the growth rate to determine the interest rate along the BGP. From the local final demand table we know investment in the first period, I_0, and the capital earnings net of taxes, VK_0. We have also calculated the sales tax rate on investment goods, τ_I. Since $K_{t+1} = (1-\delta)K_t + I_t$ and $K_{t+1} = (1+g)K_t$ along the BGP, we get that $I_t = (\delta+g)K_t$. Furthermore, $VK_t = R_t K_t$, and along the BGP $R_t = (\delta+r)/(1+\tau_I)$ where r is the interest rate. Using $g = 2\%$, $\delta = 5\%$

[24]We disregard taxes on exports and imports to simplify the model as the amounts are tiny.

[25]The major item in taxes on production is property tax. This category of tax also includes all other taxes levied on production or the assets used in production. It does not include taxes on business income which we treat as being included with direct taxes on capital.

[26]Recall that this includes the contribution to Metro Vancouver from all three levels of government.

[27]In dividing the personal income tax burden, we assume that capital income is taxed at half the rate applied to labour income. This is intended to reflect the sheltering of capital income through pension plans, RRSPs, TFSAs and the like, as well as the relief afforded by the 50% inclusion rate on capital gains and the dividend tax credit.

and $\tau = 5.5\%$ along with appropriate values for I_0 and VK_0, we solve for $r \approx 7.6\%$. The discount factor is calibrated using the long run interest rate: $\beta = \frac{1}{1+r}$.

Table 3: Key parameters (fixed across sectors).

Parameter	Value	Notes
g	0.02	Growth rate.
δ	0.05	Rate of depreciation.
r	0.076	Interest rate.
β	0.929	Time discount rate.
$\sigma_{K,L}$	1	Elasticity of substitution between capital and labour.
$\sigma_{\tilde{Y}^i,\tilde{Y}^j}$	0	Elasticity of substitution between intermediate goods.
σ_{Y^i,M^i}	3	Elasticity of substitution between domestic and foreign goods.
σ	0	Elasticity of substitution between value added and composite good.
$\sigma_{\tilde{c}^i,\tilde{c}^j}$	1	Elasticity of substitution between consumption goods.
$\sigma_{\tilde{G}^i,\tilde{G}^j}$	0	Elasticity of substitution between government goods.
ϕ	1	Inter-temporal elasticity of substitution.

4.5 Flooding

We model the flood event as a shock to the sector-specific capital stock. Assuming that the capital-labour ratios in each sector are initially the same across municipalities, we can use the Census municipality-level sectoral employment data to estimate the distribution of the capital stock across municipalities. For example, we calculate that 12.5% of all agricultural workers in Metro Vancouver work in Delta, so we assume that 12.5% of the agricultural capital stock is located in Delta.

Next, for a flood scenario we determine what proportion of each municipality's capital stock is exposed. In this paper we consider a flood of the lower Fraser valley and use flood plain maps to approximate capital exposure in each municipality. Based on the flood map (see figure 2), we consider this to be a flood of 100% of Richmond, 70% of Delta, 10% of Surrey, 5% of the city of Vancouver and 5% of Burnaby.[28] Each sector's capital is exposed at the same rate *within* a municipality, however due to different distributions of capital across municipalities the exposure is heterogeneous across sectors when aggregated back up to the Metro Vancouver level. The distribution of exposure is given in figure 3.

The Transportation and Warehousing sector (BS48) is most exposed in percentage terms because the airport in located in Richmond and the region's largest seaport is located

[28]These figures are based on both the amount of land area in floodplains and the urban density in those areas. There would be flooding in other municipalities but we do not include them as they are small or the flood areas are small and thus would have little impact on the results.

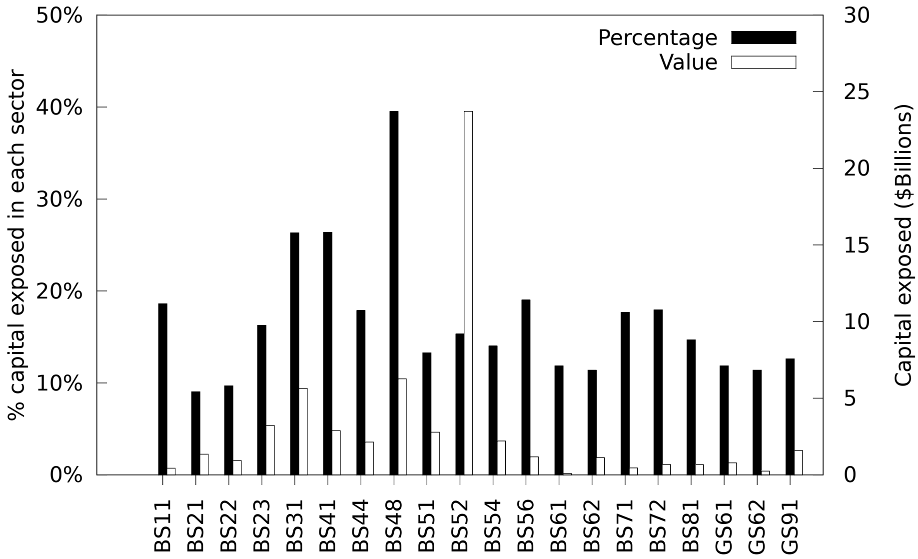

Figure 3: Aggregate capital exposed in percentage and value terms across industry.

in Delta. The Manufacturing (BS31) and Wholesale Trade (BS41) sectors are also hit disproportionately hard. In terms of value, the Finance and Real Estate sector (BS52) is hit by far the hardest simply because it is an extremely capital-intensive sector.

Not all exposed capital is damaged. For our baseline scenario, we consider a damage rate of 25%. For example, we consider that 10% of Surrey's capital stock is exposed to the flood, but only $25\% \times 10\% = 2.5\%$ of the capital stock is damaged. In this paper we use the same damage rate across all municipalities. A plot of the damage distribution would be the same as figure 3 except at 25% of the magnitude.

5 Simulations

We simulate a flood of the lower Fraser River in Metro Vancouver, as described in section 4.5. We compare economic indicators, in particular GDP, from the flood scenario(s) to the baseline scenario with no flood. We assume that damages are completely covered by the government or private insurance. Specifically, the total damage is paid out over the course of two years with equal payments coming each time period. Since there is no money in the model, this is achieved through an endowment of foreign exchange. This approach captures the idea that the local economy is physically constrained in terms of available capital and labour, however it allows for an increase in imported goods.

The simulations are run using GAMS/MPSGE following the implementation of Paltsev and Rutherford [2004] for a dynamic growth model. A quarterly timestep is used out to 55 years after the flood. We focus on the near-term impacts of the flood but maintain a long time horizon so the model returns very closely to the balanced growth path by the end of the simulation.

We quantify economic losses from the flood and the degree of recovery at different points in time. We also examine sectoral and government impacts, as well as impacts on trade. The baseline scenario (25% damage rate) is discussed first, followed by a comparison with other damage rates (5%, 10%, 15%, 20%, 35%, 50%, 75% and 100%) to see how the results scale with level of damage. We also study the sensitivity of the results to the assumption that losses are fully compensated and to the assumption of no labour mobility.

5.1 Baseline scenario

In a balanced growth model, the long-run behaviour of the economy is determined by the parameters of the model and not the initial endowments. Therefore when the capital stock is shocked it does not affect the long-run behaviour but there is a transition back to balanced growth. Figure 4 shows GDP over time for a no-flood case and two damage scenarios. We see that the gap between cases with a flood and no flood narrows over time and is virtually gone after 20 years.

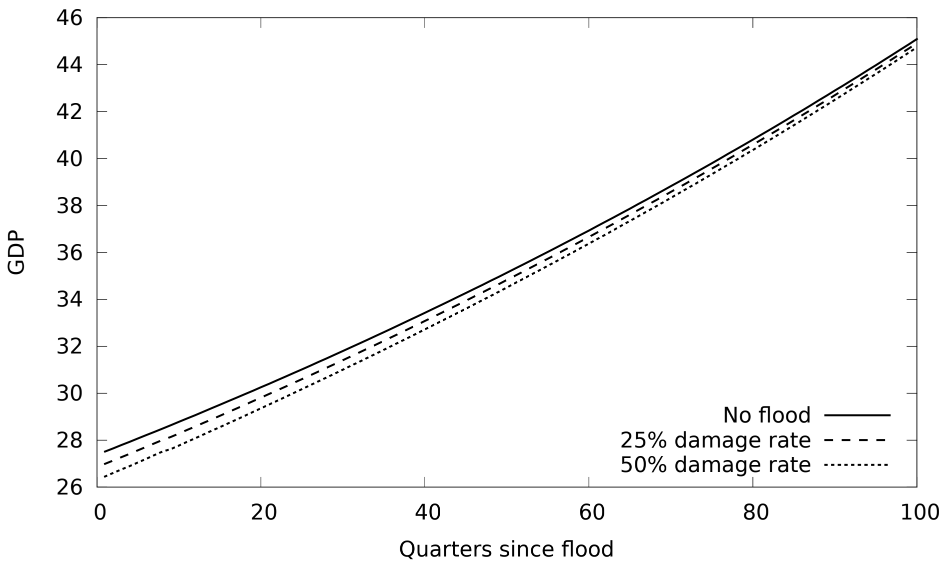

Figure 4: GDP timeseries for different scenarios.

In order for the capital stock to rebound so that the economy can return to the balanced growth path, a higher rate of investment is required in flood scenarios to make up for the loss of capital (this is shown in figure 5). In steady state, about 21% of GDP goes toward investment, which replaces depreciated capital and produces new capital needed for growth.

In the 25% damage scenario, the investment percentage increases but remains below 21.5%. There is a ramp-up in the first couple of quarters as the economy adjusts to deal with the higher demand for investment.

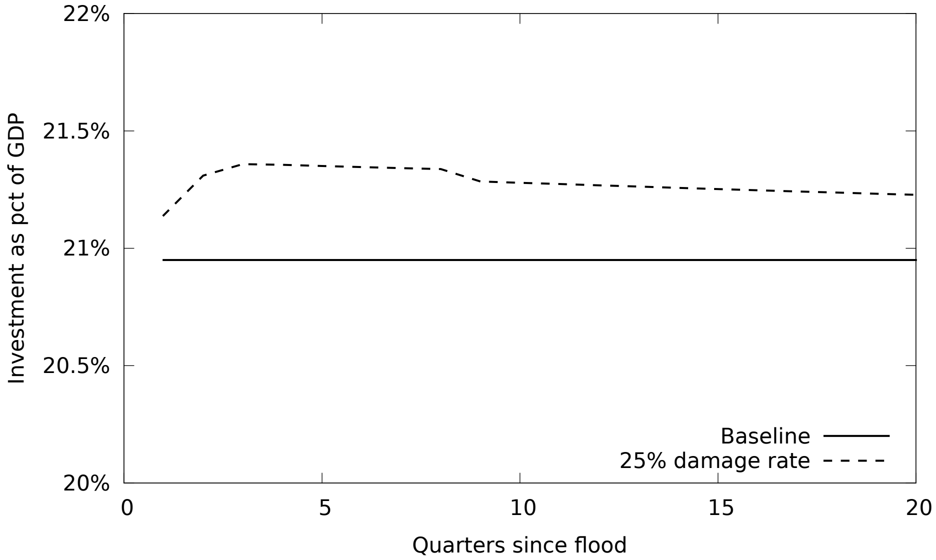

Figure 5: Real investment as a percentage of real GDP.

As a result of the higher investment, the growth *rate* is higher in the flood scenarios as seen in figure 6. It is important to note the distinction between GDP and GDP growth. Often after a disaster it is noted that GDP growth increased and some argue that there are positive impacts due to reconstruction. However, this misses the fact that the GDP level is necessarily lower and consumption must have decreased ceterus paribus. Furthermore, by spending more on investment there is less available for consumption and lower consumption results in lower welfare. While certain sectors may benefit, the loss of physical capital, and possibly human capital in the case of loss of life, cannot improve the overall economy.[29]

In the first few time periods the growth rate is fairly volatile as the capital stock is re-balancing across the different sectors of the economy. A dip occurs in the 9^{th} quarter, coinciding with the ending of assistance payments. This occurs because trade must rebalance at a lower level and fewer intermediate goods are available for production.

Figure 7 shows the capital stock recovery for a few key sectors. We see that Construction and Manufacturing, the two most important sectors for producing investment goods, recover rapidly. Transportation and Warehousing, the most damaged sector, also recovers rapidly. Meanwhile, Finance and Real Estate actually sees a relative *decrease* in its capital

[29]It may be possible for the disaster to improve the economy if it somehow results in eliminating inefficiencies. However, that is generally not the reason cited for a disaster having positive economic effects.

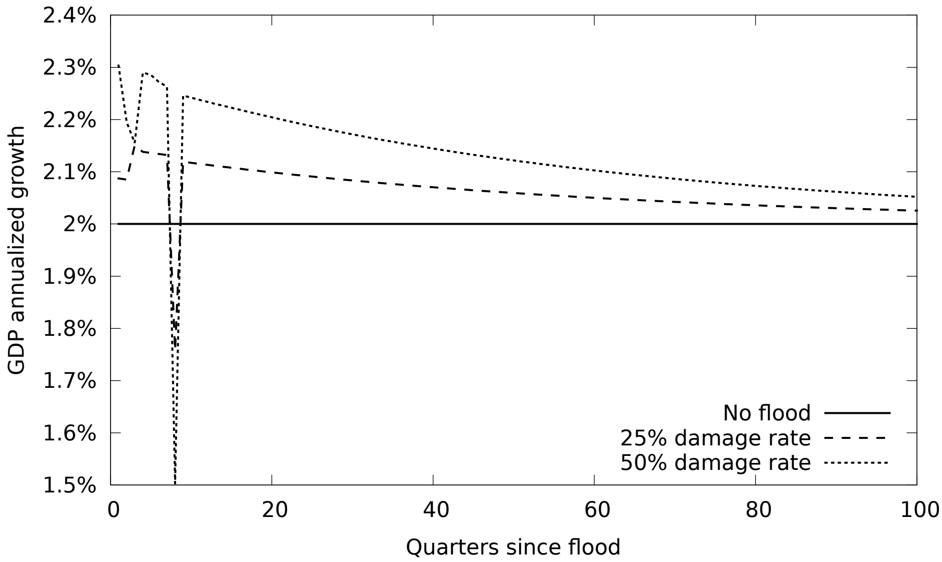

Figure 6: GDP growth rates for different scenarios. The dip in the 9^{th} quarter is due to assistance payments being finished.

stock. This occurs in the most capital-intensive industries after the flood damage because their marginal product of capital becomes smaller than other industries and thus there is little investment in capital-intensive industries. Notice that the biggest adjustment occurs in the first year after the flood and then there is a small adjustment after two years when the assistance payments end.

Next we examine the impact on trade. Figures 8 and 9 show the relative change in imports and exports, respectively. Imports of construction actually increase in the first quarter due to the demand for investment goods. Other goods follow the pattern of domestic output (which follows the capital stock) due to prices of imports and domestically produced goods being the same. That is, there is no need to change the ratio of domestically produced to imported goods if the price ratio remains unchanged. Construction exports actually shut down completely, and as a result the domestic price is higher than the imported price. On aggregate imports must decrease if exports decrease, however the disaster assistance offsets some of that loss. After the disaster assistance payments end in the 9^{th} quarter, construction exports resume and there is a small dip in construction imports. This occurs because there is a shortage in "foreign exchange" needed to pay for imports. Nonetheless, construction exports remain low which shows the importance of construction in the recovery process.

Finally, we study the impact of the flood on government. Figure 10 shows the loss of (real) tax revenue in the aftermath of the flood. The initial loss is around 2% and

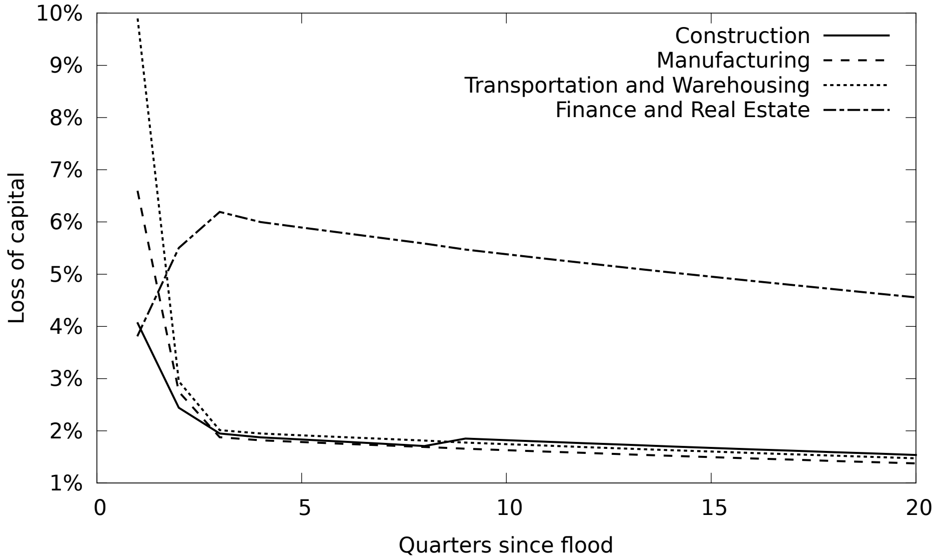

Figure 7: Capital stock relative to no-flood scenario for key sectors.

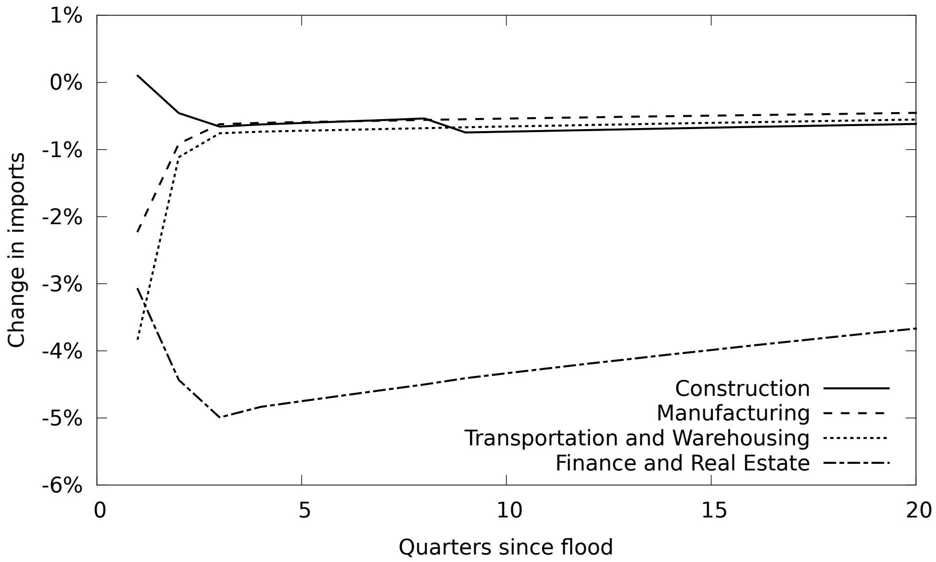

Figure 8: Imports relative to no-flood scenario for key sectors.

increases over the following year before revenue begins to recover (similar to GDP). Recall that different sectors are taxed at different rates and thus the nonlinear response of the economy in the immediate aftermath of the flood results in nonlinear (and non-monotonic) tax revenues. Furthermore, tax revenues briefly flatten out in quarters 8-9 after the flood due to the expiration of assistance payments.

Figure 11 shows that overall the impact on government services is small, with the greatest impact being on Administration at an initial loss of less than 0.8%. The flood does

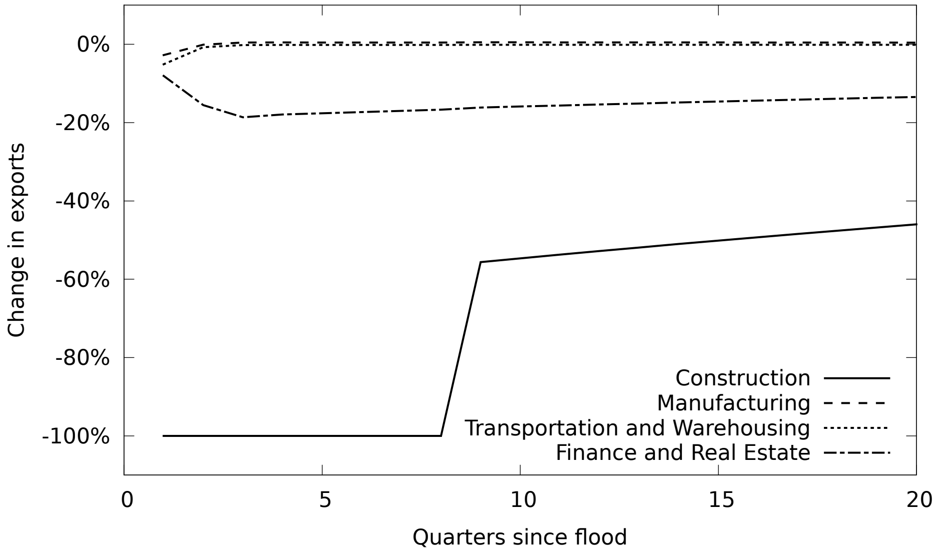

Figure 9: Exports relative to no-flood scenario for key sectors.

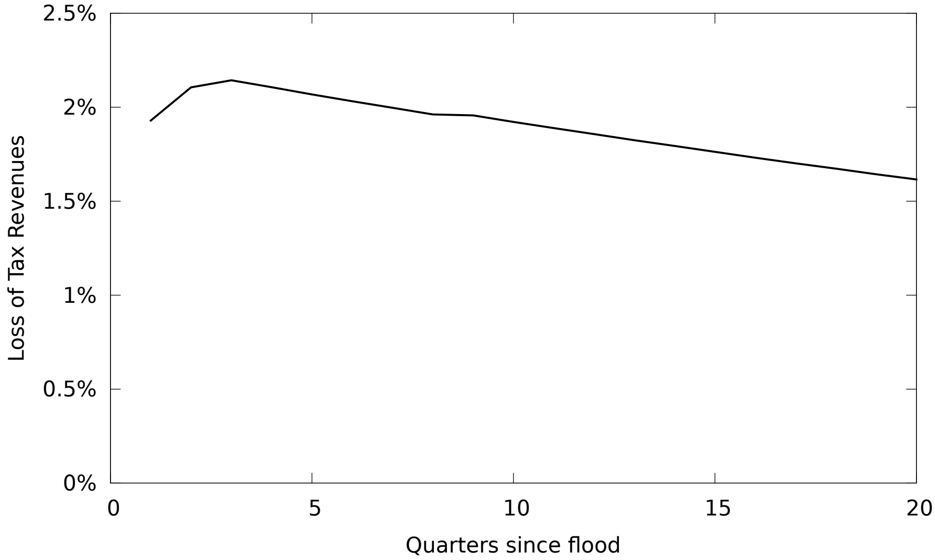

Figure 10: Real tax revenue relative to no-flood scenario.

not have a big impact because the capital damage is small as seen in figure 3. However, there is also a rapid recovery because government is very labour-intensive, not capital-intensive, and thus the marginal product of capital is relatively high during the recovery process.[30] The impact on government services is not as severe as that on tax revenues because the households and firms increase their direct purchase of government services.

[30]For more labour intensive industries, a small change in the capital stock has a larger impact on the marginal product of capital.

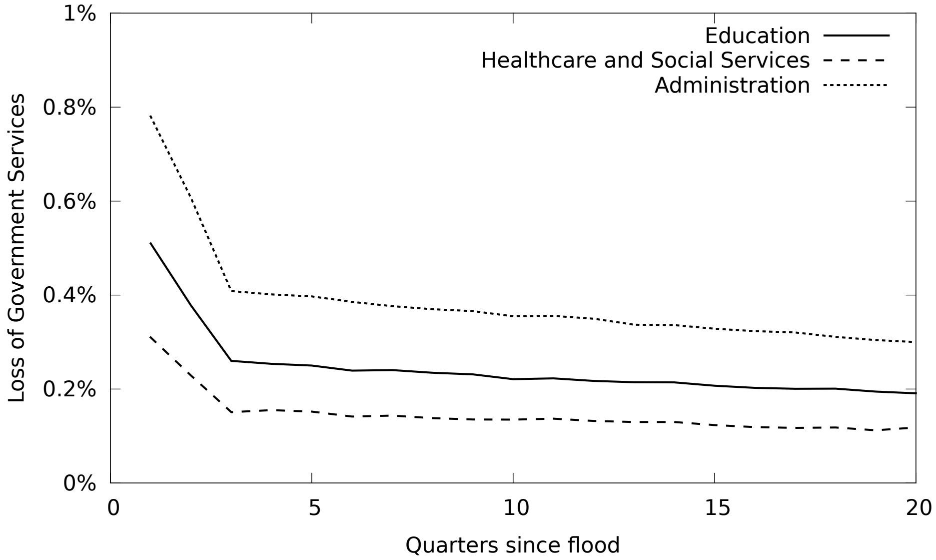

Figure 11: Government services relative to no-flood scenario for key sectors.

5.2 Different damage levels

In the previous section we presented several details from the baseline simulation with a 25% damage level. Next we investigate the relationship between the economic impacts and the damage level. We are motivated by the observation of Hallegatte [2008] that indirect losses (output loss) increase exponentially with direct losses (damage). Here we consider damage rates of 5%, 10%, 15%, 20%, 25%, 35%, 50%, 75% and 100%.

Figure 12 shows the relationship between direct and indirect losses (output losses) where indirect losses are summed over the first 12 years and all 55 years (we consider the 12-year loss because Hallegatte's simulations reach full recovery in that timeframe).[31] The plot in figure 12 has the same axes as the plot found in Hallegatte's paper.

Our simulations appear to yield a linear relationship between direct and indirect losses, however there is in fact a slight exponential relationship. Table 4 shows the total indirect losses (summed over years) for each damage level and the slopes between the points. The slope is in fact increasing between consecutive points which demonstrates an exponential relationship. However, the slight non-linearity found in our study is very small compared to what Hallegatte found. Furthermore, we find that whether we look at the 12-year window or the 55-year window, the indirect losses are always greater than the direct losses. Hallegatte found that direct losses dominate except at very large damage.

In Hallegatte's input-output model, there is very little flexibility to substitute. This

[31] We use a discount rate of zero when summing the output losses. "Indirect loss" is the terminology used by Hallegatte for output losses.

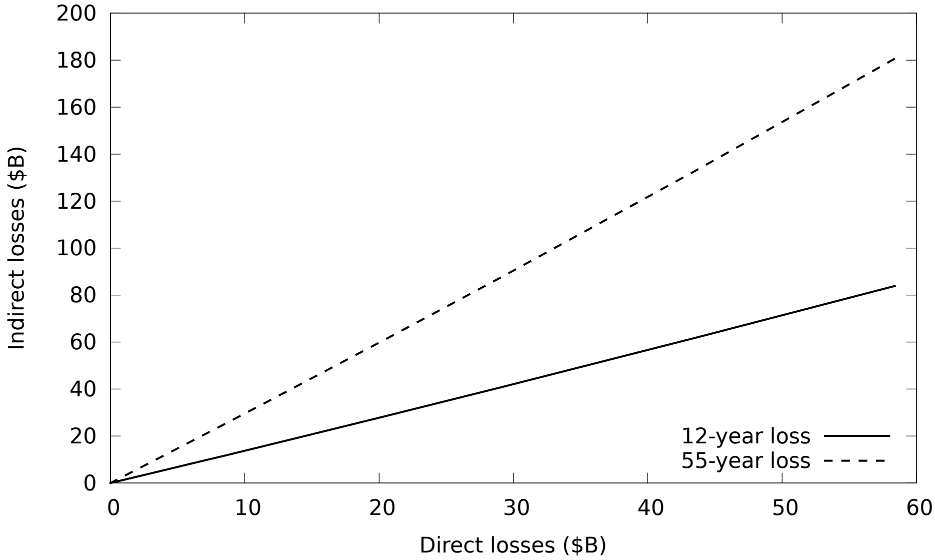

Figure 12: Aggregate indirect (GDP loss) vs. direct (damage) losses.

Table 4: Aggregate output losses for different damage scenarios ($B).

Damage level	12-year loss	slope	55-year loss	slope
0	0	-	0	-
3 (5%)	4	1.36	9	2.94
6 (10%)	8	1.37	17	2.95
9 (15%)	12	1.38	26	2.97
12 (20%)	16	1.39	35	2.99
15 (25%)	20	1.40	43	3.02
20 (35%)	28	1.41	61	3.03
29 (50%)	41	1.42	88	3.06
44 (75%)	62	1.46	134	3.14
58 (100%)	84	1.49	181	3.22

means that for twice the damage, the construction sector's capacity is halved and as a result reconstruction takes relatively longer. In our model, prices drive an efficient allocation of investment which can mean more resources being focused on the construction sector initially. With the efficient allocation of resources and smooth recovery path, the relationship between the direct and indirect damages is much more linear.

5.3 Sensitivity to key assumptions

We test the impact of three key assumptions on our results:

1. Disaster assistance payments;

2. No labour mobility;

3. Key parameter choices.

We have assumed that the cost of damage will be fully covered via private insurance and public disaster assistance. However, it is possible that this disaster assistance could change in the future and not all countries have the same institutions. Therefore it is interesting to see what impact changing the level of damage compensation has on the economic cost of flooding and the recovery.

We find that the financial assistance makes very little difference in terms of GDP. Table 5 shows GDP levels for different years after the event in no-flood, baseline and a no-compensation scenario (all use a 25% damage rate). The assistance generates only a tiny increase in GDP initially, and after two years the gap is virtually wiped out. It is somewhat surprising that an injection of $7.3B per year for two years into the local economy has such a small effect, however the household and government do not have to spend their income during the period in which they receive it. Consequently, they choose to delay some spending in order to smooth their consumption over time.

Table 5: Real GDP ($B) for different scenarios in years following the flood.

Year	No flood scenario	Baseline scenario	No disaster compensation	Labour mobility
1	110.90	108.83	108.72	108.84
2	113.14	111.17	111.05	111.11
3	115.42	113.44	113.42	113.33
5	120.12	118.32	118.30	118.08
12	138.12	136.82	136.81	136.14

Next we consider the assumption of no labour mobility. We made this assumption because we are most interested in the first few years after the flood, and in the short run we expect little labour mobility across sectors. However, the fact that we necessarily restrict labour mobility in the distant future as well impacts the expectations of the agents in the model which could lead to different behaviour even in the short term. Here we allow complete labour mobility and compare the results (still using a 25% damage rate).

In table 5 we can see that real GDP actually *falls* after the first year relative to baseline when labour mobility is introduced. This is somewhat surprising since added flexibility should be good for the economy. However, our real GDP measure does not reflect changes in patterns of consumption driven by relative price changes. A better social measure is the welfare effect shown in figure 13. The increased flexibility of labour mobility allows for significant welfare gains in the early-going. In the long-run within-period welfare becomes higher than in the baseline case but this is misleading. The household is maximizing its *lifetime* utility which puts more weight on earlier periods. Thus having higher welfare in early periods is more valuable. In the case of labour mobility, the household smooths its welfare loss over all time as is expected when households have the ability to smooth.

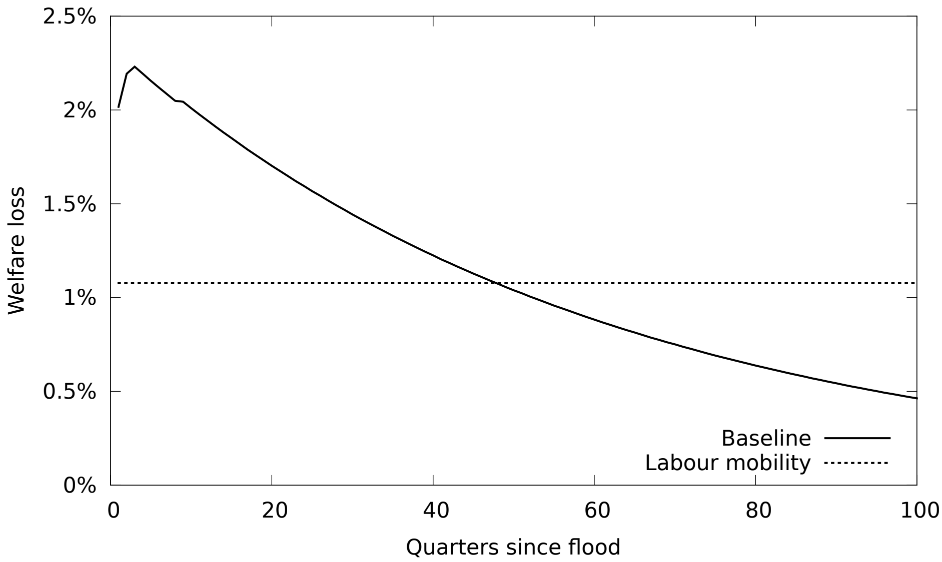

Figure 13: Period-by-period welfare loss compared to no flood.

Finally we have made parameter choices for the growth rate, depreciation and various elasticities of substitution (intertemporal, imports and domestic goods, capital and labour, consumption goods). We vary each of these parameters independently at the 25% damage level to see how our results are affected. Note that where applicable, we varied the elasticities for all goods at the same time; we did not individually test the elasticities for all 20 goods.

Table 6: Parameter sensitivity tests.

Parameter	Low	Base	High	GDP change at 5 years Low value	High value
Elasticity - Armington	2	3	4	0.0%	-0.5%
Elasticity - Capital & Labour	0.5	1	1.5	0.0%	0.0%
Elasticity - Consumption Goods	0.5	1	1.5	0.0%	0.0%
Elasticity - Inter-temporal	0.5	1	1.5	-0.1%	0.0%
Growth rate	-	2%	5%	-1.31%	
Depreciation	-	5%	10%	-1.16%	

We initially selected an Armington elasticity of 3 for our simulations because it's a common choice in the literature, although some studies choose higher values like 4. In our sensitivity tests, we found that varying this elasticity between 2 and 4 had virtually no impact on the results (table 6 shows the change in GDP at 5 years for the high and low parameter values). For the elasticity of substitution between capital and labour, it is common in the literature to choose a value of 1 which reflects the stylized fact that the capital and labour income shares are roughly constant. As we varied this parameter between 0.5 and 1.5, it also had no meaningful impact on GDP and welfare levels (less than 0.1% change in GDP and welfare through time). For the elasticity of substitution between consumption goods, we initially chose a value of 1 which is common in CGE studies. We found that varying this parameter had virtually no impact as well. Finally, even varying the inter-temporal elasticity had little effect on GDP. It had more of an effect on welfare than the other elasticities, but that difference remained below 1%.

Compared to the elasticities, varying the growth and depreciation rates had larger impacts. In order run these sensitivity tests, we had to recalibrate the model because these parameters affect the determination of the BGP interest rate. In the base case, GDP is 1.50% behind the no-flood scenario at the 5-year mark. When the steady state growth rate is increased to 5%, GDP only lags by 1.31% at the 5-year mark (going from 137.66 in the no-flood case to 135.86 in the 25% damage scenario). The loss from the flood drops because the economy is more productive and thus can recover more rapidly. When depreciation is increased from 5% to 10%, the GDP loss at the 5-year mark decreases to 1.16%. This occurs because in the calibration, r increases with δ, and K_0 decreases as r increases. Thus less total rebuilding is required to return to the BGP. While the growth rate and depreciation parameter choices affect the results, the impact is relatively minor in magnitude. The findings in the paper appear to be very robust to parameter changes.

6 Conclusion

This paper has developed a novel dynamic CGE framework for modelling the economic impacts of flooding and the subsequent recovery. Damages in our framework are based on specific flood scenarios which can respond to various adaptation measures, and affect every economic sector. The model incorporates the recovery mechanism from the input-output model of Hallegatte [2008]: investment using local production and imports rebuilds the capital stock. In our model, investment and resource allocation decisions are endogenized and we solve for the efficient recovery path.

We calibrate the model to data for Metro Vancouver, which is considered to be one of the most vulnerable cities in the world with respect to possible flood damage. In our baseline scenario, flooding of the lower Fraser Valley causes total capital damage in Metro Vancouver of $14.6 billion. Transportation and Warehousing are the most severely affected industries, followed by Manufacturing and Wholesale Trade. The construction sector plays a very important role in the recovery process. Capital intensive industries, even those not directly affected by the flood, suffer from a higher cost of capital goods during recovery.

We find that the GDP loss relative to a scenario with no flood is 1.9% ($2.07B) in the first year after the flood, 1.7% ($1.97B) in the second year, 1.5% ($1.70B) in the fifth year and 1.1% ($1.42B) in the twentieth year. We have also found that the losses tend to rise at a mildly increasing rate with the size of aggregate damage. In total, in our base scenario, output loss over our full 55 year horizon is $43 billion, which is close to being three times as great as the capital damage of $14.6 billion caused by the flood. While Vancouver residents benefit from the modelled disaster assistance, we find that the latter has relatively little impact on the time path of output. That is because we have assumed well-functioning capital markets, so that when there is less assistance there is simply more borrowing and the rebuilding of capital remains efficient. Results are also relatively insensitive to allowing free labour mobility and to changes in most of the freely-chosen parameters of the model. Results are more sensitive to the assumed depreciation rates and growth rate but are relatively robust even in the face of those changes.

Appendix

The Metro Vancouver input-output and final demand tables derived in the paper are given below. The sector definitions can be found in tables 1 and 2. Note that while the tables are derived with separate investment for the private sector and government, they are merged in the model calibration.

Table 7: Metro Vancouver Input-output table (continued on next page).

	B11	B21	B22	B23	B31	B41	B44	B48	B51	B52
B11	98	2	2	20	834	4	3	11	3	11
B21	6	124	32	472	704	24	25	29	4	36
B22	16	55	3	27	410	34	75	90	34	168
B23	15	43	165	28	50	28	58	214	21	967
B31	321	470	36	4,303	6,015	347	259	2,072	630	635
B41	45	78	10	609	694	117	112	189	122	153
B44	13	23	7	221	246	48	69	76	54	81
B48	70	96	9	268	1,092	331	267	2,419	145	467
B51	13	27	5	60	126	269	195	182	933	751
B52	90	240	85	601	761	689	1,288	881	386	5,807
B54	42	167	23	1,291	207	383	401	218	265	1,286
B56	33	57	14	123	104	213	235	281	187	1,217
B61	0	0	0	5	0	4	10	2	25	13
B62	0	0	0	0	0	0	0	0	0	5
B71	1	3	1	7	25	33	26	12	56	41
B72	4	16	4	15	74	68	72	173	69	149
B81	14	15	2	41	56	19	21	143	58	218
G61	1	3	0	23	6	7	11	8	7	21
G62	1	1	0	1	3	5	5	4	5	14
G91	8	11	2	45	57	53	67	78	42	220
Net tax on products	3	28	4	187	96	42	45	-357	-11	526
Net tax on production	30	22	145	162	189	230	217	269	-22	2,740
Labour costs	461	431	824	4,241	6,264	3,596	4,049	4,021	1,965	5,872
Capital costs	314	2,009	1,303	2,677	2,889	1,475	1,615	2,138	2,830	20,896
TOTAL	1,599	3,921	2,677	15,430	20,901	8,017	9,126	13,153	7,807	42,295

Table A.1: Metro Vancouver Input-output table (continued).

	B54	B56	B61	B62	B71	B72	B81	G61	G62	G91
B11	6	2	0	1	2	32	3	1	3	44
B21	8	4	1	3	2	6	15	11	4	6
B22	44	12	5	46	15	57	114	29	21	63
B23	26	13	2	30	10	22	56	134	68	195
B31	490	329	29	264	130	1,129	560	244	407	684
B41	147	64	5	54	27	162	105	42	97	178
B44	90	49	5	42	180	246	92	42	85	186
B48	221	95	11	57	30	66	154	106	27	340
B51	388	134	9	136	41	87	129	90	47	140
B52	712	303	61	412	142	588	499	26	26	332
B54	977	203	15	106	61	102	150	69	27	536
B56	341	130	17	62	64	134	196	45	75	481
B61	13	4	1	8	1	6	4	4	2	41
B62	0	0	0	3	0	0	0	2	414	1,666
B71	17	12	1	3	75	39	27	4	2	39
B72	149	53	6	28	35	37	69	35	29	64
B81	107	81	8	70	48	41	86	24	75	180
G61	26	3	1	5	4	4	8	7	1	31
G62	11	3	1	2	2	2	5	1	3	216
G91	66	18	5	30	19	36	62	17	56	418
Net tax on products	-162	54	3	-25	1	97	66	55	41	63
Net tax on production	66	59	6	28	26	127	54	0	0	24
Labour costs	4,801	1,917	207	1,502	578	2,250	2,814	4,441	2,452	5,370
Capital costs	2,131	832	95	1,330	347	508	618	890	291	1,705
TOTAL	10,675	4,375	494	4,199	1,839	5,780	5,886	6,321	4,255	13,002

*Note: Sector definitions can be found in tables 1 and 2.

Table 8: Metro Vancouver final demand table.

	Consumption	Government	Investment (private)	Investment (government)	Exports	Imports	Total
BS11	769	0	3	2	1,063	-1,322	515
BS21	131	0	463	47	3,232	-1,469	2,404
BS22	1,280	0	23	9	392	-345	1,358
BS23	44	0	10,505	2,833	69	-167	13,284
BS31	12,956	0	3,306	519	22,266	-37,501	1,546
BS41	3,137	0	447	140	4,565	-3,284	5,004
BS44	6,906	0	244	43	1,474	-1,397	7,270
BS48	2,402	0	99	16	9,592	-5,229	6,881
BS51	2,431	0	337	90	3,559	-2,371	4,045
BS52	24,661	0	1,811	19	8,149	-6,274	28,366
BS54	498	0	1,072	258	5,427	-3,111	4,146
BS56	316	0	21	11	1,380	-1,360	367
BS61	285	0	2	1	94	-31	351
BS62	1,828	0	10	6	386	-121	2,108
BS71	1,516	0	6	3	838	-946	1,417
BS72	4,844	0	3	1	3,171	-3,389	4,630
BS81	4,488	0	27	7	645	-586	4,581
GS61	923	4,616	294	281	494	-466	6,142
GS62	351	3,770	4	1	220	-378	3,968
GS91	934	14,284	63	34	373	-3,997	11,692
Sales tax	5,864	0	1,234	42	149	304	7,593
TOTAL	76,564	22,669	19,975	4,362	67,538	-73,441	117,667

*Note: Sector definitions can be found in tables 1 and 2.

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