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SYSTEM DYNAMICS APPROACH TO ASSESS IMPACTS OF DISASTER RISKS ON INVESTMENT IN INFRASTRUCTURE

Jishnu Subedi [1,2]
[1] School of Construction, Southern Alberta Institute of Technology, Canada
[2] jishnu.subedi@sait.ca

Abstract: This paper presents a system dynamics approach to analyze reinvestment in maintenance and upgrading of infrastructure for a sustained long-term growth of the infrastructure stock subjected to disaster risks. Infrastructure comprises of individual infrastructure components, such as bridges, roads, water and sewer lines, oil and gas pipelines, and power lines. As a region or country's security, well-being, and prosperity rely on smooth, efficient and optimal functioning of the infrastructure components, continuous investment in the new infrastructure and reinvestment in maintenance and upgrading of the existing infrastructure is critical. However, investment in new infrastructure gets more attention compared to that in maintenance and upgrading of the existing infrastructure. Reports of existing infrastructure in the United States and Canada show that there is a substantial gap in the investment on maintenance and upgrading of existing infrastructure. Moreover, risks such as disaster events frequently damage the infrastructure resulting in diversion of the already scarce resources for the restoration of the damaged infrastructure. A system dynamics model is used to investigate impact on maintenance and upgrading resources for long-term sustained infrastructure growth in the presence of disaster risks. The model uses a sensitivity analysis to analyze the impact on available funding when disaster events impact the economy and damage the infrastructure. The results show that disasters cause further underinvestment in maintenance and upgrading of the infrastructure. This approach may be useful for all levels of governments to make informed decisions for optimal allocation of resources and for projecting long- term investment for infrastructure.

1 INTRODUCTION

The debate around public investment in infrastructure is philosophical (consequentialism vs deontologism, for example), political (public investment in infrastructure vs market incentives for private investment, for example), economic, social (investment in social infrastructure vs investment in productive infrastructure, for example) and environmental (impact on ecology vs economic benefit of the infrastructure, for example). The economic optics alone, therefore, is not sufficient to capture the interplay of factors that dictates the decision making on public investment in infrastructure. Economic measures, however, are most efficient and most widely used tools to make investment decisions and their effectiveness can be further increased by expanding the tools to incorporate impact of other factors in the decision making process. One such factor that has raised significant concern over long-term sustained infrastructure growth is the impact of disaster risks on infrastructure.

Three factors make the disaster risks a major concern for infrastructure investment.

- Climate change has resulted in increasing severity of disasters. Accordingly, the infrastructure is exposed to increased hazards.
- Aging infrastructure and lack of investment in upgrading the existing infrastructure have increased the stock of vulnerable structures.

- World urban population has increased from 33.6% (70% in North America) in 1960 to 54.8% (82% in North America) in 2017 (Data source - United Nations Population Division, 2018) which has resulted in increased pressure on infrastructure system in the urban areas. The capacity of the existing system is already overburdened to such an extent that even localized and small disasters may trigger cascading effects with large economic losses.

The existing infrastructure requires reinvestment for the maintenance and upgrading to function optimally and to negate the effects of aging. However, a study on the status of infrastructure in Canada reports that current reinvestment ratio for maintenance is lower than the target reinvestment ratio for all infrastructure (Canadian Infrastructure 2016). The same study also reports that one third of the municipal infrastructure in Canada is in fair, poor or very poor condition requiring immediate reinvestment. The status of existing infrastructure is of real concern in the United States too where the assessment of the current state of the infrastructure on a scale of A to F "has earned persistent D averages" since 1998 (Economic Development Research Group 2016). This underinvestment in maintenance and upgrading of the existing infrastructure has resulted in continuous degradation and sub-optimal performance of the infrastructure. Although there may be continuous flow of fund for investment in the infrastructure, this does not necessarily translates into increased funding for reinvestment in the existing infrastructure. Investment in new infrastructure is more attractive than investment in upgrading and maintenance of the existing infrastructure as new infrastructure has more visibility and political significance. Furthermore, increased exposure of infrastructure to disaster risks may result in directing the available resources to restoration of damaged infrastructure. As majority the infrastructure is owned by local governments, cities and municipalities need to make informed decisions on allocating resources for maintenance of existing infrastructure vs adding new infrastructure. This is more so now as the infrastructure is exposed to increase frequency and severity of disasters.

This paper analyzes sharing of funding between investment in new infrastructure and reinvestment in the maintenance and upgrading of the infrastructure with and without disaster risks. System dynamics model is used to analyze the interaction and forecast the long-term scenarios. The results of this paper provide answers to the question of the extent to which disaster risks increase pressure on available resources for reinvestment in the infrastructure.

2 INFRASTRUCTURE FOR ECONOMIC GROWTH

In his seminal papers, Aschauer (1989, 1990) advanced the idea that pubic spending on infrastructure increases rate of return in private capital and stimulates private investment in the economy. Mullen (1992) argues that investment in public capital can expand the economic output from two channels – first, the public investment has effect to increase resources and second, it also enhances productivity of the resources. Aschauer (1989) and Munnell (1990) both estimate the output elasticity of public capital larger than 0.3 which implies that one percent increase in the stock of public capital increases economic output by more than 30 percent. Although infrastructure is essential for economic growth, the actual contribution in terms of return from public investment in infrastructure has been a contentious issue as other studies suggest a much lower output elasticity in the range of 0.07-0.10 as in Calderón, Moral-Benito, & Servén (2015), for example.

Despite of the agreement on positive correlation of investment in the public infrastructure and the economic growth, there is no consensus on the optimal infrastructure stock. As the investment in public infrastructure comes from taxation and public money, the cost of funding additional infrastructure may outweigh its marginal contribution to the economic growth resulting in net harm to the economy (Leeper et al. 2010; Lammam and MacIntyre 2017). From an empirical study of large US cities, Haughwout (2002) concludes that "while public capital provides significant productivity and consumption benefits, an ambitious program of locally funded infrastructure provision would likely generate negative net benefits for these cities." Overinvestment in new infrastructure also diverts resources from much needed reinvestment in the existing infrastructure. Therefore, municipalities and local governments need to make informed decisions on allocation of the resources with a perspective of the long-term growth.

3 MUNICIPAL INFRASTRUCTURE, THEIR STATUS AND DISASTER RISKS

3.1 Municipal Infrastructure by Sector in Canada

According to Canadian Infrastructure (2016) report, the share of the net stock of core public infrastructure in Canada among Municipalities, Provinces and Federal Government is 56.8%, 41.4% and 1.8%, respectively. Therefore, municipalities are responsible to maintain more than 55% of the public infrastructure. The report classifies infrastructure stock into roads and bridges, potable water production, storage and distribution system, wastewater and storm-water collection, management and discharge system, Buildings and public transit system. The largest share of infrastructure stock in Canada is water and wastewater related network of infrastructure (51%) followed by roads and bridges (33%) (Canadian Infrastructure 2016). Depending on the types of infrastructure, required reinvestment for optimal performance of the infrastructure and rate of depreciation of the infrastructure are different.

3.2 Reinvestment in Existing Infrastructure and Depreciation

According to Canadian Infrastructure (2016) report, the current reinvestment ratio for maintenance of infrastructure (Table 1) is lower than the target reinvestment ratio for most of the infrastructure types. The average upper target of reinvestment is 2% but the current average level of spending in Canada is about 1% only (Canadian Infrastructure 2016). The report also shows that one third of the municipal infrastructure is in fair, poor or very poor condition requiring immediate attention. A lower level of reinvestment results in sub-optimal performance, faster depreciation and early phasing out of the infrastructure. Moreover, “deteriorating infrastructure, long known to be a public safety issue, has a cascading impact on our nation’s economy, impacting business productivity, gross domestic product (GDP), employment, personal income, and international competitiveness” (Economic and Development Research Group 2016, p.3).

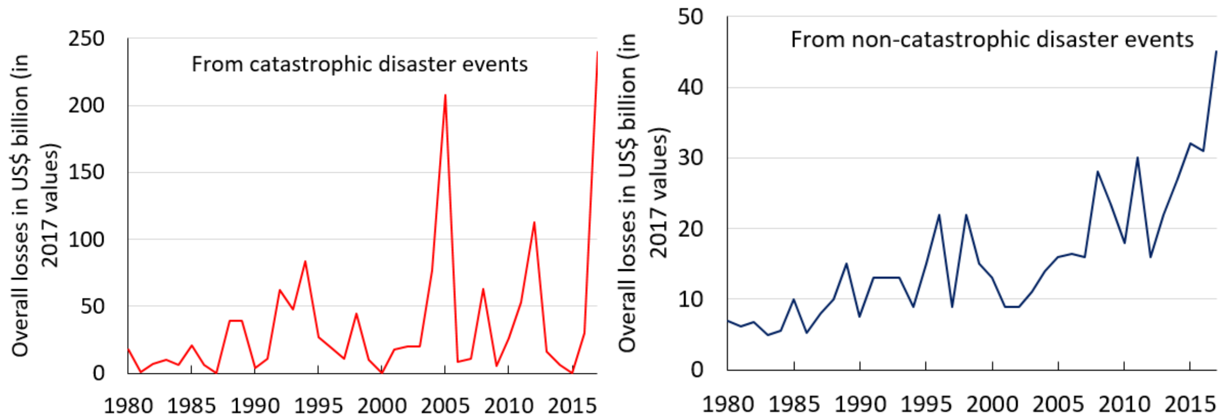
Table 1: Target reinvestment rates vs current reinvestment rates for infrastructure in Canada (Data source: Canadian infrastructure 2016)

Infrastructure	Lower target	Upper target	Current
Potable Water (linear)	1.00%	1.50%	0.90%
Potable Water (non-linear)	1.70%	2.50%	1.10%
Wastewater (linear)	1.00%	1.30%	0.70%
Wastewater (non-linear)	1.70%	2.50%	1.40%
Stormwater (linear)	1.00%	1.30%	0.30%
Stormwater (non-linear)	1.70%	2.00%	1.30%
Roads and Sidewalks	2.00%	3.00%	1.10%
Bridges	1.00%	1.50%	0.80%
Buildings	1.70%	2.50%	1.70%

3.3 Impact of Disasters

Infrastructure in urban areas is under pressure due to an increasing urban population and a lack of reinvestment in maintenance and upgrading. The adverse impacts from disasters further aggravates the situation as governments at all levels are under increasing pressure to divert significant amount of resources to restore the infrastructure damaged by disasters. A report on the costs associated with disasters in Canada states that (Public Safety Canada 2017, p.6):

> “Over the past 20 years, the DFAA [Disaster Financial Assistance Arrangement program] for weather events has been steadily increasing due to an increasing number of large weather events with greater intensity. The average annual federal share of response and recovery costs has increased from $10 million (1970-1995) to $110 million (1996-2010) to $360 million (2011-2016). Over the past six fiscal years, the DFAA provided more recovery funding than in its first 39 fiscal years combined”.



a. b.

Figure 1: Economic losses due to disaster events in North America from 1980 to 2017. a. Overall economic losses (in inflation adjusted US$ in 2017 values) from catastrophic events. b. Overall economic losses (in inflation adjusted US$ in 2017 values) from non-catastrophic events. Source: Graphs by the author from the data obtained from Munich Re, NatCatSERVICE (2019).

The trend of increasing loss from disasters has been observed in other countries too. Figure 1 shows trend of losses from catastrophic disaster events (major disaster events with fatality more than 1000 or economic loss more than US$ 3 billion, see NatCatService, 2019 for detailed definitions) and non-catastrophic disaster events during 1980-2017. The frequently occurring peaks indicate that catastrophic events are occurring frequently and their economic impact is increasing over the years (Figure 1a). The trend of economic losses from non-catastrophic events is also increasing at a significant rate. In average, the overall loss from these non-catastrophic disaster events has increased by 5% each year from 1980 to 2017. These smaller events of increasing severity are localized events that gradually erode economic resiliency of the communities and consume the resources much required for the investment in the infrastructure.

4 ANALYTICAL MODEL

4.1 System Dynamics model

System dynamics can be used to visualize the complex dynamics of real world operations in simple models and to understand the real world phenomena under different dynamic conditions. The application of system dynamics in economics has been explored and presented by many researchers. Weber (2007) and Kunte and Damani (2016) present system dynamic models for economic growth models and growth theories. Radzicki (2009) has summarized contributions of system dynamics to economic modeling where he argues that despite of mainstream economists being critical of the system dynamists' approach to economic modeling in the past, there is growing recognition of the potential of the system dynamics among economists from several schools of economic thought.

Dauelsberg and Outkin (2005) have used system dynamics framework to analyze economic effect of disruptions to critical infrastructures. Min et al. (2007) used the system dynamics framework to analyze interdependency of the components in the whole infrastructure system. This paper presents a system dynamics model using Vensim software to analyze allocation of funding for new infrastructure and for maintenance and upgrading of existing infrastructure and also to analyze the effect of disaster risks on investment in infrastructure. The system dynamics model used in this paper is shown in Figure 2. Economic output is modeled as growing at a fixed rate and a certain percentage of the economic output is invested in the infrastructure. Infrastructure stock is determined by infrastructure growth rate and depreciation and phasing out of the existing stock. Disasters occur at a certain frequency and may impact both the infrastructure and the economic output. In a disaster scenario, part of the infrastructure investment is diverted to restore the damaged infrastructure. The model is simulated for 100 years period to visualize the effect of different investment scenarios and impact of disasters on infrastructure in the long run.

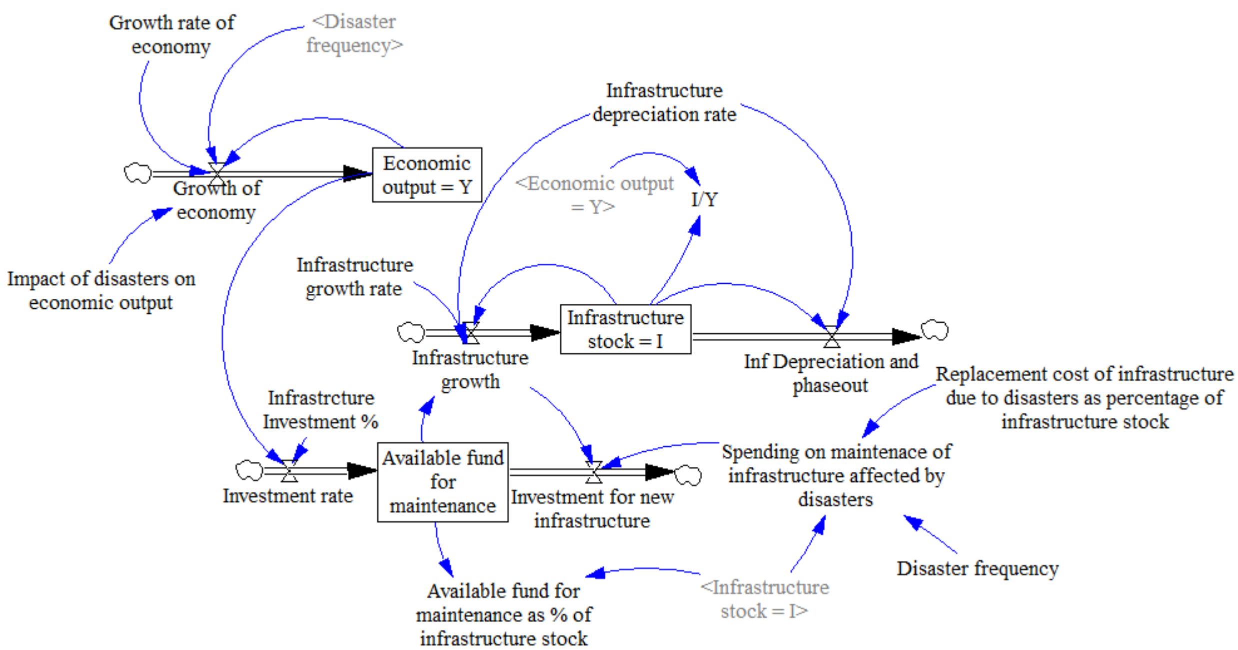


Figure 2: System dynamics representation of investment on infrastructure (Vensim Software)

4.2 Model Parameters

Economic output in the model is assumed to grow at a constant rate of 2%. The net stock of government infrastructure in Canada grew from about $325 billion in 1971 to about $750 billion in 2015 (tentative numbers read from the graph in Figure 1, p. 3 in Lammam and MacIntyre 2017) which can be calculated as an average growth of infrastructure stock by 2% per year. Therefore, a growth rate of 2% per year is assumed for infrastructure stock in the model. Data from Lammam and MacIntyre (2017) show that the government spending on infrastructure in Canada as a percentage of GDP between 1981 to 2015 ranges from a minimum of 1.4% to a peak of 3.1% but fluctuates between 1.5% and 2% in most of the years. Hence the model uses investment in infrastructure from 1.5% to 2% of the economic output.

The value of Canada's stock of infrastructure was $933 billion in 2017 with an average remaining useful life of about 57.7% (Infrastructure Economic Account, 2017). The GDP that year was about $ 2.1 trillion which gives the ratio of infrastructure stock to GDP as about 0.47 for that year. The model uses initial ratio of infrastructure stock to economic output (I/Y in the model shown in Figure 2) as about 0.3 (~0.57*0.47) which is derived from the remaining useful life of 57% and infrastructure stock to GDP ratio of 0.47.

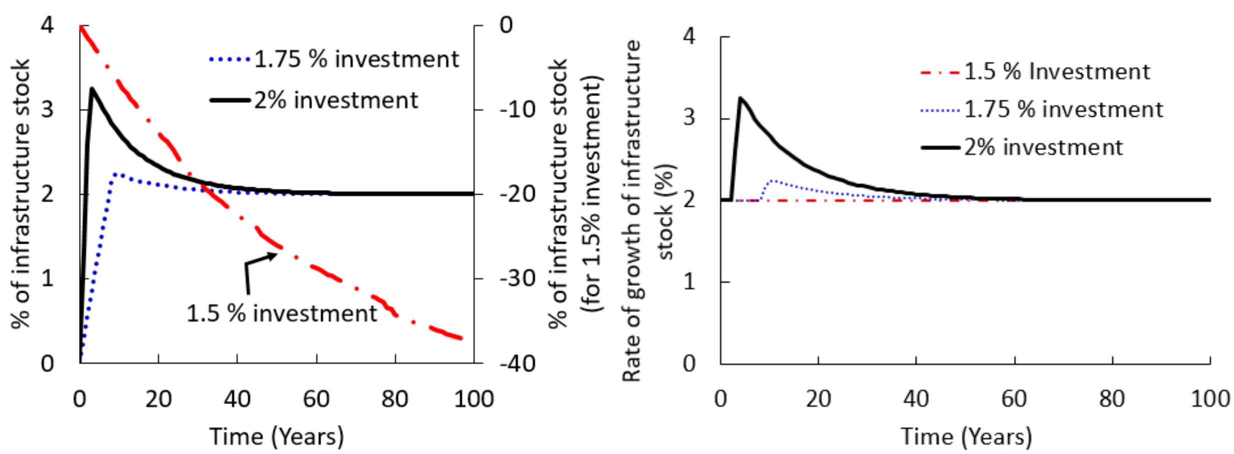
Existing infrastructure value depreciates and infrastructure phases out after few years. The rate of deprecation depends on the level of maintenance in such a way that a decrease in the infrastructure maintenance cost results in increase in the depreciation rate and vice versa. By increasing maintenance cost, however, the depreciation cannot be decreased below 4% per year (Stiff and Smetanin 2010). A depreciation rate of 5% is assumed in the model with a linear increment from 0 to 5% for the first 10 years. The model assumes that a minimum maintenance cost of 2% (average of upper reinvestment target in

Canada from Table 1) of the infrastructure stock needs to be maintained throughout the simulation period for the assumed 5% depreciation.

Disasters are simulated with random uniform function with a return period of 20 years. Although disaster events and loss database are available in many countries, there is lack of a comprehensive data for impact of disasters on infrastructure. Damage to infrastructure, critical infrastructure especially, not only results in direct economic loss but also leads to indirect loss to business and economic productivity. Furthermore, critical infrastructure failure has "repeatedly been a cause of triggering cascade effects of major disasters (OECD, 2018, p.22)." In the lack of data, damage to infrastructure by disasters is accounted as 0.5 percent of the infrastructure stock. Although restoration of damaged infrastructure takes many years, the model assumes that all the restoration funding is used in the year of occurrence of the disasters. Disasters also impact the economic output which is simulated in the model by three levels of losses: No impact, 10% loss and 20% loss.

4.3 Results and Discussion

The model uses three levels of investment in infrastructure: 1.5%, 1.75% and 2% of economic output. When the infrastructure stock growth rate is kept constant at 2%, 1.5% investment is just enough to meet for investment in new infrastructure and there is a sustained deficit of funding for maintenance of the existing infrastructure (1.5% investment curve with right vertical axis in Figure 3a). For the investment rates of 1.75% and 2%, the required maintenance funding of 2% is always available (Figure 3a). It takes few years to achieve 2% maintenance cost as the model initializes with zero maintenance cost. Once the available funding for maintenance exceeds 2% of the existing infrastructure stock (for 1.75% and 2% investment curves in Figure 3a), the additional budget is diverted to new infrastructure which results in more than 2% yearly increase of the infrastructure stock (Figure 3b). Under the given conditions, therefore, a minimum investment of 1.75% of the economic output is required to maintain 2% infrastructure growth and reinvestment of 2% for maintenance and upgrading of the existing infrastructure stock.



a. b.

Figure 3: Available investment for maintenance (as % of infrastructure stock) a. Cumulative available investment for maintenance and upgrading b. Growth of infrastructure stock under different investment scenario

The model is used to simulate impacts of disasters in investment on infrastructure. Disaster events are simulated using uniform random number generator with a return period of 20 years. The model simulates the impacts of disaster events in two ways. First, disasters damage the infrastructure directly which requires immediate diversion of resources from regular maintenance to the restoration of the damaged infrastructure. Second, disasters impact economic output directly and indirectly. The productive capital is impacted directly and the functioning of the economy is disrupted indirectly by domino effects of the service disruption and sub-optimal performance of the infrastructure. The model assumes that a disaster event (with 20 years return period) damages 0.5% of the existing infrastructure stock. The restoration expenses for a year in which disaster events occur, therefore, is 0.5% of infrastructure stock in addition to the regular maintenance cost of 2%.

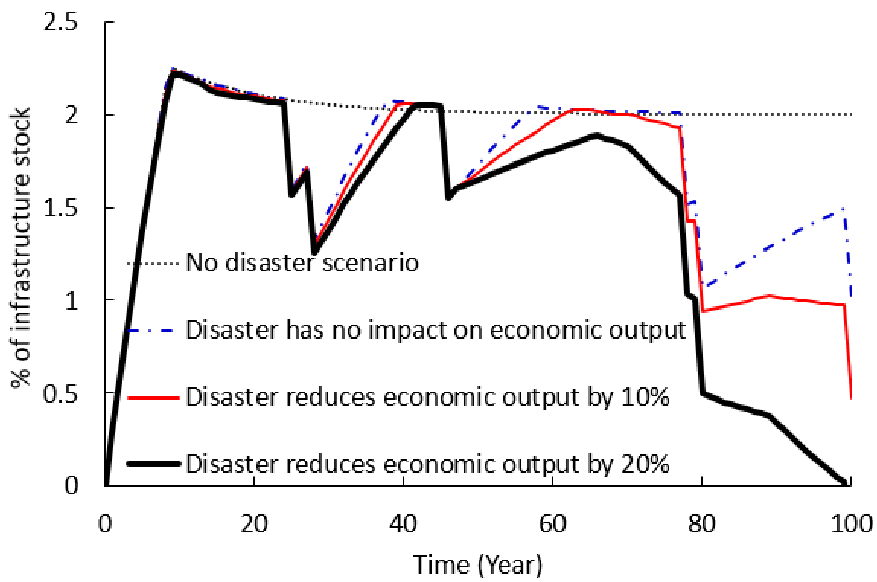


Figure 4: Available funding for maintenance (as% of infrastructure stock) at an investment of 1.75% of economic output for no disaster and disaster scenarios with different level of impacts on the economic output

The available maintenance budget for disaster and no-disaster scenarios for 1.75% investment in infrastructure are plotted in Figure 4. The results for disaster scenarios are shown for no effect on the economic output, 10% loss of economic output and 20% loss of economic output. Assuming that the funding required for 2% growth of infrastructure stock is already fixed, disasters impact available funding for reinvestment in infrastructure. A decrease in the economic output shows a long-term deficit in the available funding for maintenance and upgrading of the existing infrastructure. The results show that disasters deplete the funding which may result in long-term underinvestment in the maintenance and upgrading of the infrastructure which may lead to sub-optimal performance and early phasing out of the infrastructure.

4.4 Sensitivity Analysis

Sensitivity analysis is done to analyze the change in the available funding for reinvestment in the infrastructure. The parameters, their range and distribution functions for the parameters used in the model are shown in Table 3 below.

Table 3: Parameters for sensitivity analysis

Parameter	Range of values	Distribution type	Remarks
Disaster frequency	0.01– 0.1 Peak at 0.02	Triangular	From return period of 10 years to 100 years with peak at 50 years
Replacement cost of infrastructure due to disasters as percentage of infrastructure stock	0.001 – 0.01	Random uniform	Damage to infrastructure ranges from 0.1% to 1% of infrastructure stock
Impact of disasters on economic output	0.6 – 1.0	Random uniform	From 60 percent reduction to no effect

The results of sensitivity analysis for investment of 1.75% of economic output are presented in Figure 5. At a 50% confidence level, the available fund for maintenance is likely to remain below 2% level within 40-50 years. However, for an increased confidence level between 75% and 90%, the available funding for maintenance is most likely to be below 2% level most of the time after one or two decades.

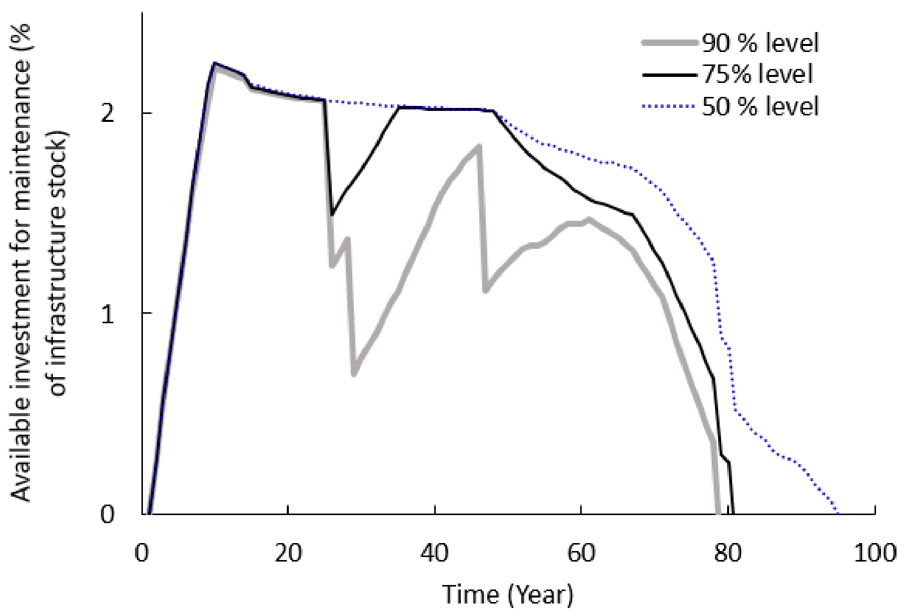


Figure 5: Output of sensitivity analysis from the system dynamics model (model parameters are shown in Table 3)

5 CONCLUSION

Although increasing infrastructure stock may be an obvious choice to sustain the economic growth and an apt choice for political reasons, there is a cost for adding infrastructure and more investment in new infrastructure is not necessarily a wise economic decision. Studies show that there is already a gap in the funding available for maintenance and upgrading of the existing infrastructure which has reduced the efficiency of the infrastructure and has rendered the infrastructure vulnerable to disaster risks. As the infrastructure stock piles up, so does the required maintenance and upgrading cost. Moreover, disasters damage the infrastructure and increasing frequency and severity of the disaster events mean more and more resources is required to restore the damaged infrastructure. This necessitates optimal allocation of resources for adding infrastructure stock and maintaining the existing infrastructure stock. In Canada, nearly 60% of the infrastructure is owned and maintained by the municipalities. Therefore, local governments require to make informed decisions such that there is enough funding for new infrastructure and also for maintaining the existing infrastructure in the long-run.

A system dynamic model is used to analyze the impact on available maintenance funding under different investment conditions. The model is also used to analyze the impact of disasters on infrastructure investment. The analysis shows that even under a condition where there is sufficient funding for maintenance, recurring disasters require the resources to be diverted to restore the damaged infrastructure which results in sustained deficit in available reinvestment funding. A sensitivity analysis under different disaster scenarios shows that governments need to take into account of disasters in planning for long-term growth. The system dynamics approach may be useful for all levels of governments to forecast long-term growth and investment scenarios and allocate resources accordingly.

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