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IMPLICATIONS OF CLIMATE CHANGE FOR ECONOMIC GROWTH AND DEVELOPMENT IN VIETNAM

NHÀ XUẤT BẢN THỐNG KÊ
HÀ NỘI - 2012

NXB THỐNG KÊ ★ TÁC ĐỘNG CỦA BIẾN ĐỔI KHÍ HẬU TỚI TĂNG TRƯỞNG VÀ PHÁT TRIỂN KINH TẾ Ở VIỆT NAM
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IMPLICATIONS OF CLIMATE CHANGE FOR ECONOMIC GROWTH AND DEVELOPMENT IN VIETNAM TO 2050

AUGUST 2012

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Acknowledgements

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Executive Summary

Introduction

Like many countries, Vietnam is concerned about the potential implications of climate change for economic growth and development. This paper presents a highly comprehensive analysis of climate change impacts for Vietnam. The paper focuses on implications for economic growth and development out to 2050. Three elements of the analysis merit special mention. First, a bottom-up structural approach is employed. The analysis relies upon a series of structural models that link climate outcomes to biophysical and eventually economic outcomes. Second, relative to most impact analyses, the approach is highly comprehensive incorporating six important impact channels: crop yields, irrigation water availability, hydropower production, road infrastructure, sea level rise, and cyclone strikes. Finally, the analysis incorporates climate projections from 56 General Circulation Model (GCM) runs employed for the Fourth Assessment Report of the IPCC. The combination of these three elements is unique and affords a very detailed examination of the implications of climate change for Vietnam. The use of multiple climate projections is particularly important because, as will be shown, the implications of climate change for Vietnam can vary strongly across projections. Consequently, choice of one limited set of GCM runs over another limited set can strongly influence conclusions. Here, the full range of outcomes across 56 future climates is presented.

A hotter and possibly drier future climate for Vietnam

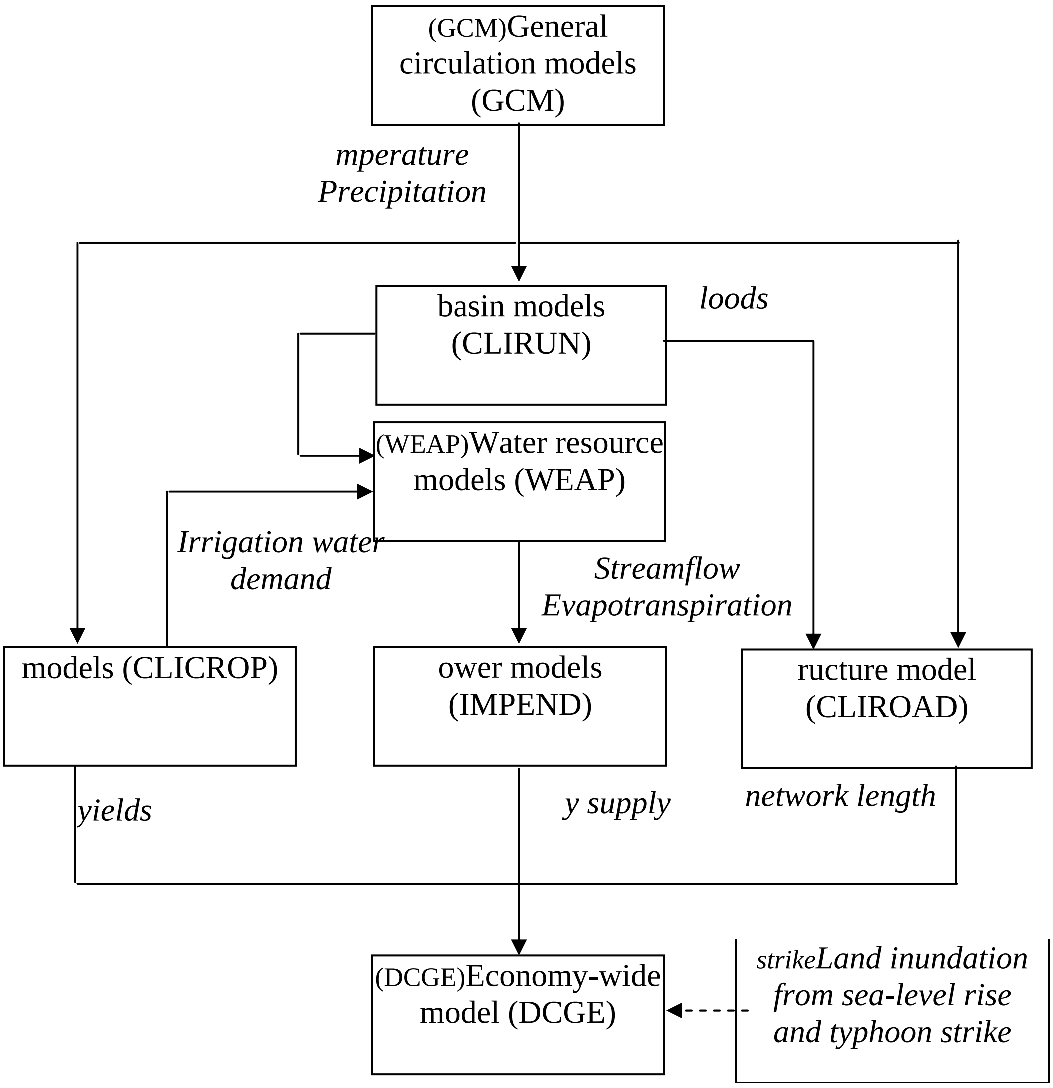
The median expected temperature increase for Vietnam is somewhat less than 1.5 degrees Celsius with most outcomes clustered near the median. For all regions of Vietnam, temperature increases range from a minimum of slightly less than one degree Celsius to a maximum slightly more than 2 degrees Celsius. Precipitation projections are considerably more uncertain than temperature projections. Vietnam is expected to experience a mild decrease in precipitation in that the median change is negative across all 56 climate futures. Nevertheless, wetter conditions are only somewhat less likely than dryer conditions at the national level. This uncertainty extends to all regions. For all provinces and climate projections, the inter-quartile range (between the 25th and 75th percentile of outcomes) includes both increases and decreases in precipitation. Maximum and minimum values are also broadly arrayed with increases in the 10-20 percent range and decreases in the 10-15 percent range. Overall, due to increased evapotranspiration and a mild decrease in median precipitation, climate conditions in Vietnam tend to become more arid, though the median change is not dramatic.

Linking climate change to biophysical and economic outcomes

The atmospheric projections for the baseline and climate change scenarios are translated into economic impacts via a series of specialized sector models. Figure 1 shows the flow of information through the integrated river basin and water resource models down to three sector models that estimate impacts on agriculture, energy and infrastructure. River basin models determine stream flows for water resource models, which then estimate water availability for hydropower models. The river basin model also predicts flood frequency and severity, which, together with precipitation and temperature, determines road damages in the infrastructure model.

Climate projections directly affect agricultural production in the crop models. Finally, biophysical results are passed down to a multi-sector economic model that estimates the economy-wide impacts of climate change. We also include a fourth sectoral impact channel that determines land losses from sea-level rise and cyclone strike.

Figure 1: Integrated modelling framework



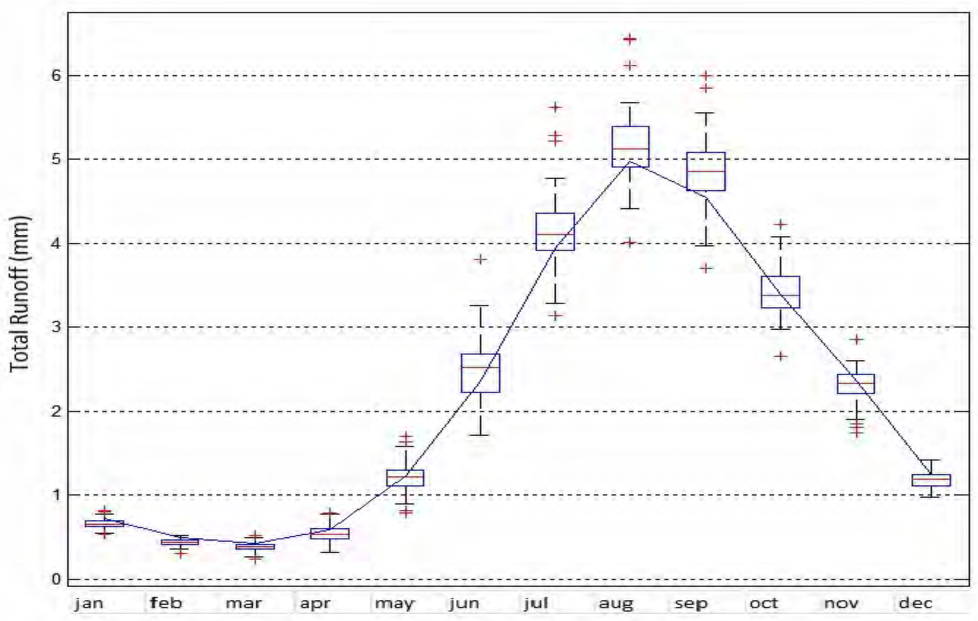
Source: Authors.

Water resources including hydropower

The ‘CLIRUN’ river basin model is an extension of a class of hydrologic models developed specifically to analyse the effects of climate change on runoff. Water enters CLIRUN via precipitation and leaves via evapotranspiration and runoff. The difference between inflow and outflow is the change in soil or groundwater storage. A total of 22 sub-basins, areas ranging from 1,500 to 45,000 km^2, were identified. Modelling trans-boundary river basins is crucial since all major rivers in Vietnam traverse other countries before entering Vietnam.

Figure 2 illustrates runoff by month in the 2040s for the historical baseline and for the 56 future climate projections considered. The latter are represented using a box and whisker plots. In these plots, the red line represents the median temperature change; the box illustrates the middle 25-75 percent of outcomes (the inter-quartile range); and the whiskers represent the maximum and minimum values with outliers discarded. Outliers are illustrated with a plus (+) sign. Overall, at the national level, the seasonality of runoff and the levels tend not to move dramatically by the 2040s.

Figure 2: Monthly average runoff comparison of base case and all the 56 GCM runoff output (2041-2050)

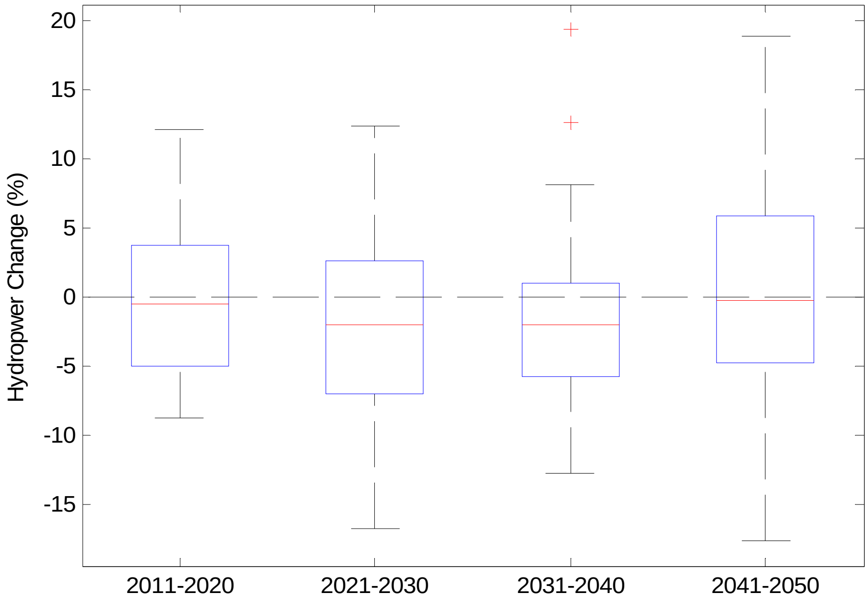


Being furthest downstream potentially makes Vietnam vulnerable changes in upstream reservoir policies. Therefore, the estimated stream flows from CLIRUN are passed down to a water resource model (WEAP) that simulates the management of all trans-boundary river basins within Vietnam and upstream. WEAP exogenously determines water allocation for industrial and domestic use, and then optimizes storage capacity and irrigation flows so as to maximize net benefits.

Hydropower generation relies on a combination of flow and elevation drop of water to generate electricity by turning turbines. There are 14 large-scale hydroelectric facilities in Vietnam. We use a hydropower planning model called 'IMPEND' that was originally developed for Ethiopia (Block and Strzepek 2010). IMPEND is a water accounting and optimization model that uses information on streamflow, evapo-transpiration and reservoir attributes to determine energy generation and associated project costs. In addition, 14 medium to large hydropower projects are under construction and are considered in this analysis. The total long term energy generation from these hydropower plants is estimated to be about 22,656 GWH. For the baseline scenario, IMPEND was calibrated to the existing capacity and expansion plan for 2010–2050, as well as to stream flow and evapotranspiration results from CLIRUN and WEAP. IMPEND was then rerun for the 56 climate change scenarios, initially assuming no change in the baseline's expansion plan (i.e., deviations in hydropower generation are solely attributable to climate change and not to changes in dam construction).

Figure 3 illustrates the changes in hydropower generation relative to the baseline by decade. At the median, hydropower generation is expected to decline very slightly in all decades. However, increases in hydropower production are also possible. The range of levels of hydropower production tends to expand with time (with the exception of the 2030s). By 2050, hydropower impacts range between approximately plus or minus 18 percent. However, about half of all outcomes fit in a much tighter range of about plus or minus five percent. In addition, while hydropower represents more than 35% of total energy production in the base, this share is expected to decline through time falling to about 8% by 2050. As a consequence, the implications of variation in hydropower production are less important in a macroeconomic sense through time.

Figure 3: Climate impacts on hydropower generation in percent difference from baseline



Infrastructure

Numerous studies confirm the importance of road infrastructure for economic growth. Both theory and evidence suggest that infrastructure investments are important determinants of economic growth and poverty reduction. In most developing countries, these investments represent commensurately large shares of public budgets and total investment. If the stock of public capital in general and the road stock in particular is material to growth and poverty reduction, then the rate of depreciation of that stock is also material. The implications of climate change can affect transportation infrastructure itself; its operation; and the demand for transportation services. Chinowsky et al. (2011a) document the potential costs of climate change on road infrastructure in ten geographically and economically diverse countries. They illustrate the opportunity costs of diverting infrastructure resources to climate change adaptation.

The relationships developed by Chinowsky et al. (2011a) are incorporated into a dynamic road network simulation model labelled “CliRoad”. The simulation model tracks the road stock broken by age since construction (or 20 year rehabilitation), road class (primary, secondary, tertiary), road type (paved, gravel, or unpaved), and region for each year over a simulation period from 2007-2050. While the stressor response functions are constant across regions, the climate inputs (precipitation, temperature, and flood events) are disaggregated by region. CliRoad is incorporated directly into the dynamic computable general equilibrium model used for economic analysis. Hence, results from CliRoad are described below together with other economywide impacts.

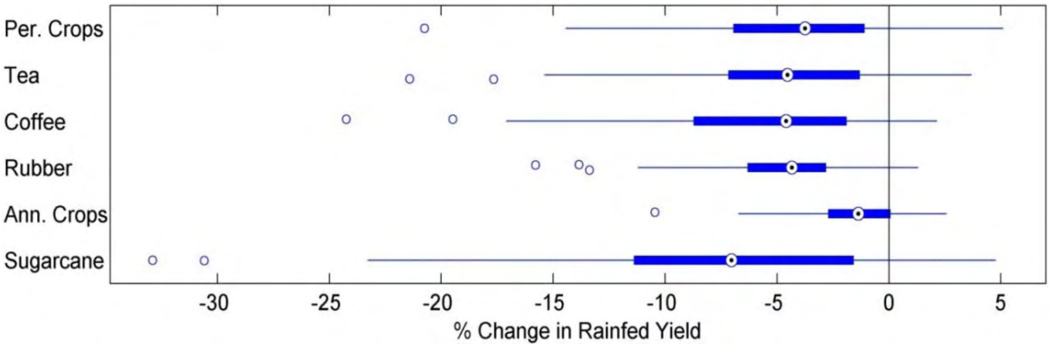
Agriculture

Agriculture is one of Vietnam’s most important sectors, accounting for about 16 percent of national income. We use a generic crop model called ‘CliCrop’ to simulate the impact of the baseline and climate change scenarios on rainfed and irrigated crop yields and on irrigation water demand. A special version of CliCrop for paddy rice is also developed. CliCrop was specifically designed to capture climate change impacts.

Figure 4 illustrates changes in yield for principal crops. These results presume that sufficient water is available to meet demand for water by irrigated crops. Under this assumption, climate change reduces yields by 2050 but not dramatically. For most crops, the median reduction in yield is less than five percent. Yield increases are possible but not likely for all crops considered. More dramatic declines of greater than ten percent are also possible for all crops considered but these outcomes tend to be confined to a relatively few GCM projections. The exception is sugarcane, which shows a median decline in yield of about seven percent with reductions greater than 20 percent possible.

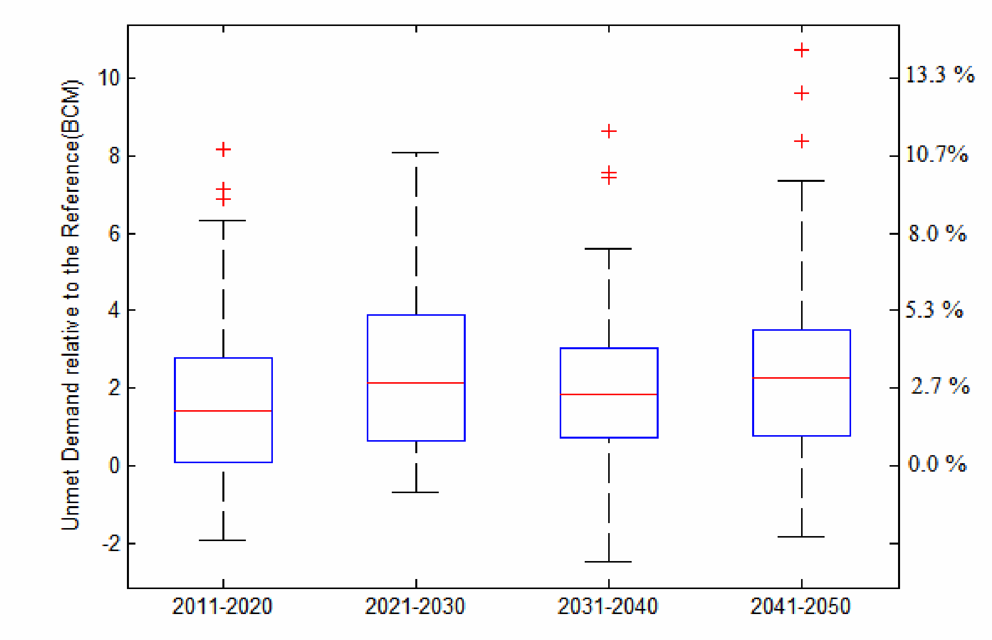
To assess the balance between irrigation water supply and demand, the water supply from the WEAP and water demand from CliCrop are compared. Under climate change, the analysis indicates that unsatisfied irrigation demand will generally increase. Box plots of unmet water supply for irrigation relative to the reference case for the 56 GCM runs are shown in Figure 5. The median value reaches about 2.1 billion cubic meters (BCM) for the year 2050. The Worst case scenario indicates a maximum deficit reaching seven BCM. In percentage terms, the median increase in unmet demand is about three percent. For paddy rice, production variation is principally determined by the variation in unmet irrigation demand.

Figure 4: Percent changes in yield from CliCrop for agriculture



Note: The abbreviations correspond to other perennial crops and other annual crops.

Figure 5: Unmet Irrigation demand with respect to Base case scenario



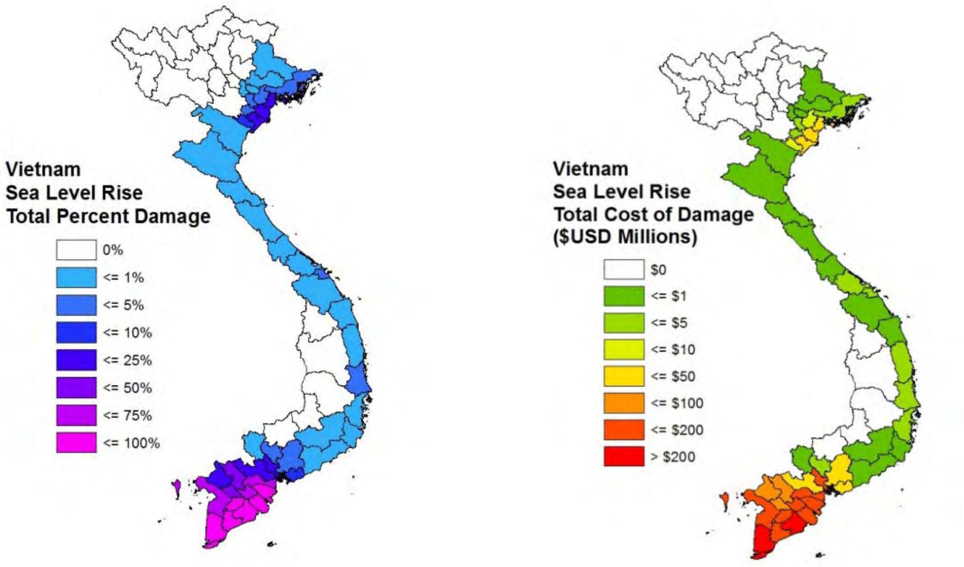
Coastal zones, sea-level rise and cyclones

Projections on the amount of sea level rise that will occur are uncertain and vary widely. Some recent studies have predicted a future sea level rise (SLR) higher than 1m by 2100 (Nichols and Cazenave, 2010). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) published in 2007 predicts an average of 60 cm by 2100 (IPCC 2007). By 2050, we expect 16 centimeters of SLR as a lower bound and 38 centimeters of SLR as an upper bound.

Analysis of SLR for Vietnam is constrained by the coarseness of elevation data. For low lying areas, the team was able to obtain information on elevations by one meter contour line. In order to consider the implications of these levels of SLR given the available data, additional assumptions are required. In particular, we assume a uniform distribution of farmland and road infrastructure through the administrative regions. Therefore, if half of a given area or “grid cell” is projected to be inundated by sea level rise, then half of the farmland and the road infrastructure in that area or cell is estimated to be destroyed.

Figure 6 illustrates, in the left hand panel, estimates of the share of area at less than one meter of elevation and, in the right hand panel, the value of current road infrastructure located at less than one meter of elevation. The Mekong river delta is of particular concern with very large shares of the region estimated to be at less than one meter of elevation. There are also concerns in the Red river delta though to a lesser extent.

Figure 6: Share of area inundated for one meter of sea level rise and value of road infrastructure estimated to lie at less than one meter of elevation



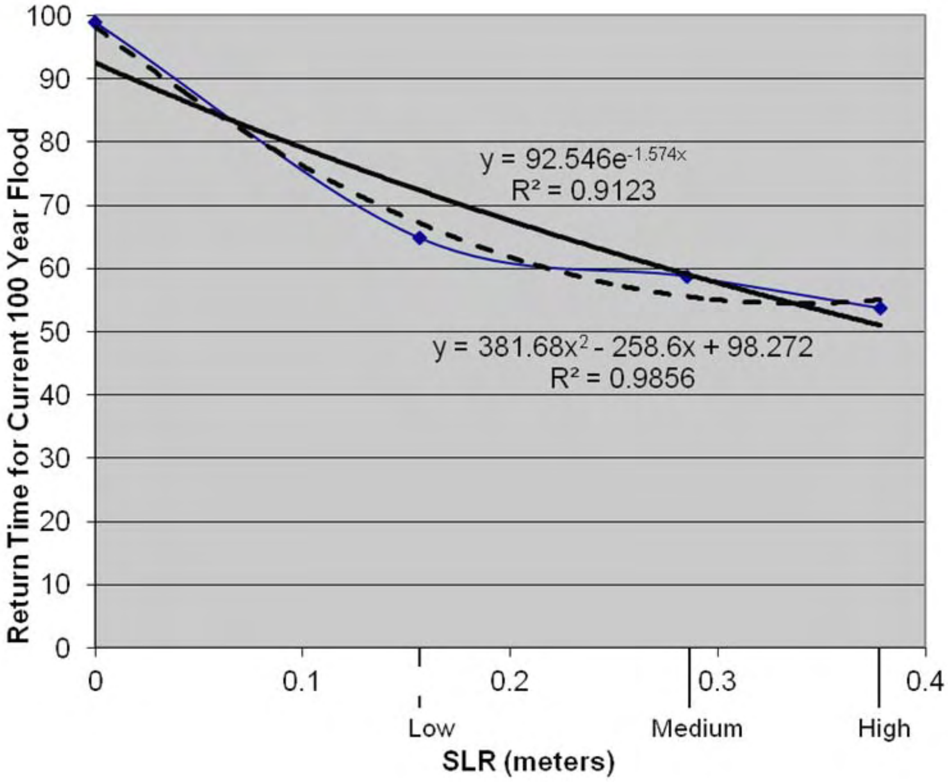
Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Detailed analysis of the combination of SLR and storm surge due to cyclones was undertaken for the Red river delta. The effects of climate change on cyclones can include changes in the intensity, frequency, and the track of individual storms. Changes in temperature are a potentially important factor in altering storm patterns, but, because cyclones are relatively rare events, differences in storm generation activity that might be experienced by 2050 are difficult to discern with current methods. As a result, we assume that cyclone frequency and intensity remains constant.

Sea-level-rise may have an important effect by magnifying the potential damage that may result from cyclones. Higher sea level provides storm surges with a higher "launch point" for the surge, which may increase both the real extent and the depth of the surge in areas already vulnerable to coastal storms. In addition, future sea-level rise, while uncertain, is more reliably forecast to 2050 than future storm activity. In general, the increase in sea level would make existing storms significantly more damaging.

The combination of storm surge and SLR is investigated for the Red river delta. Figure 7 provides estimates of the changes in effective return time for the current 100-year storm surge event as a result of SLR. The historical 100-year event at Ha Noi can be expected to occur more frequently with SLR. Rather than occurring every 100 years, by 2050, it can be expected to occur approximately every 65 years in the Low SLR scenario and every 54 years under the High SLR scenario. Similar reductions are seen in the return periods of other design storms as well. This drop in return period can have significant implications. The 100-year event exhibits a storm surge of approximately five meters. In the Red river delta, approximately 42.5% of GDP is estimated to be produced at elevations less than five meters. This amounts to about 9% of total GDP for Vietnam. This is very relevant to our analysis as Noy (2009) shows that damages from natural disasters are strongly correlated with subsequent economic growth.

Figure 7: Estimated change in effective return time for the 100-year storm as a result of SLR



Multi-sector macroeconomic model

The sector model results discussed above are passed down to a dynamic computable general equilibrium (DCGE) model of Vietnam, which estimates the economic impact of the baseline and climate change scenarios, including spillovers from the four focal sectors to the rest of economy (i.e., indirect or economy-wide linkages). Economic decision-making in the DCGE model is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. To adapt to climate changes, a variety of substitution mechanisms occur in response to variations in relative prices, including substitution between factors, between imports and domestic goods, and between exports and domestic sales. The Vietnam model contains 8 regions, 30 sectors, including electricity generation, transport services and 10 agricultural subsectors. Thirty seven factors of production are identified: three types of labour (by education level- primary, secondary, and tertiary and then further divided between rural and urban zones), capital, agricultural land, agricultural capital, livestock, and fish stocks. The agricultural capital, land, livestock and fish stocks are distributed across the eight subnational regions. This sectoral and regional detail captures Vietnam's economic structure and influences model results.

Climate change affects economic growth and welfare in the DCGE model via four principal mechanisms. First, productivity changes in rainfed agriculture are taken from CliCrop/WRM and the DCGE then determines how much resources should be devoted to each crop given their profitability relative to other activities (i.e., 'endogenous adaptation'). Second, the DCGE model directly incorporates fluctuations in hydropower production from IMPEND. Third, CliRoad is incorporated directly into the DCGE model. The length of regional road networks from CLIROAD is used in the DCGE model to help determine the rate of productivity growth. A shorter road network lowers transport productivity and increases the cost of moving goods between producers and consumers. Finally, the DCGE model incorporates the effects of SLR by reducing the total amount of cultivable land and road infrastructure in each region by the land inundation estimates presented above. In addition, the effects of cyclone strikes are magnified. Other potential impact channels are recognized but not explicitly considered, such as health and tourism.

The long timeframe over which climate change will unfold implies that dynamic processes are important. The recursive dynamic specification of our DCGE model allows it to capture annual changes in the rate of physical and human capital accumulation and technical change. So, for example, if climate change reduces agricultural or hydropower production in a given year, it also reduces income and hence savings. This reduction in savings displaces investment and lowers production potential. Similarly, higher road maintenance costs imply less infrastructure investment and shorter road networks both now and in the future. Extreme events, such as flooding due to cyclone strikes, also destroy infrastructure with lasting effects. Generally, even small differences in accumulation can cause large differences in economic outcomes over long time periods. Our DCGE model is well suited to capture these path dependent effects.

Climate change impacts on economic growth

In order to estimate the economic cost of climate change for Vietnam, it is necessary to first specify a baseline scenario that reflects development trends, policies and priorities in the absence of climate change. The baseline provides a reasonable trajectory for growth and structural change of the economy from 2007 to 2050 that can be used as a basis for comparison. Under baseline assumptions, Vietnam’s economy grows at about 5.4% per annum, with agriculture’s contribution to gross domestic product (GDP) falling from 16 percent to 7.6 percent during 2007–50. This strongly positive growth in per capita GDP leads to continued significant improvements in average household welfare.

In order to assess the implications of climate change for growth and economic development, the impact channels discussed in the earlier sections are introduced one by one. In all, six impact channels are considered. These are listed below with the name of the scenario at the beginning.

1. Agriculture. Impacts of temperature and precipitation changes for crop production by region combined with unmet irrigation demand.
2. Roads. Implications of climate change from CliRoad.
3. Hydropower. Percentage changes in hydropower production are imposed.
4. SLRlow. Sea level rise is assumed to reach 16 centimeters by 2050. This rise occurs linearly over the simulation period.
5. SLRhigh. Sea level rise is assumed to reach 38 centimeters by 2050 and is imposed in the same manner as SLRlow.
6. Cyclone. Probabilistic cyclone strikes across each of the 56 scenarios with only the marginal impact due to sea level rise imposed as a shock.

These scenarios are imposed in a cumulative fashion. So, the scenario Roads contains the shocks for Agriculture and for Roads. The last scenario, Cyclones, contains the shocks from the first three scenarios as well as SLRhigh. With low sea level rise, the marginal impact of cyclones due to elevated storm surge is small and is not presented.

Figure 8 shows the average level of real GDP for the period 2046-2050 across all scenarios. The average is presented in order to limit the implications of shocks in a particular year. Beginning with agriculture, we find the implication of climate change to be relatively mild *with impacts of sea level rise excluded.* In other words, only the implications of the yield shocks summarized in Figure 4 and unmet irrigation demands summarized in Figure 5 are imposed. The implications of these shocks for the national economy and for growth are relatively small for two reasons. First, the shocks themselves are not particularly large in most instances. Second and importantly, the agriculture share of GDP by 2046 to 2050 is, as indicated above, not very large. The agriculture share of GDP by 2046-50 varies strictly between seven and eight percent of GDP across all scenarios. Because the agriculture share of GDP tends to decline (a strong empirical regularity), variations or reductions in agricultural GDP have an increasingly muted effect on the national economy and overall economic growth rates.

For the roads scenario depicted in Figure 8, the implications of climate change become more pronounced and may be positive but are more likely to be negative at a national scale. These implications are driven by CliRoad (again, excluding infrastructure lost due to sea level rise). Figure 9 provides a summary of the distribution of road network length relative to the baseline no climate change scenario. As indicated earlier, CliRoad is incorporated directly into the CGE model. Road network length influences the rate of total factor productivity growth in the model. In addition, investment in roads is assumed to move proportionately with growth in government spending. As a result of these interactions, road network length differs in every scenario.

Figure 8: Level of Real GDP at Factor Cost (average from 2046-2050)

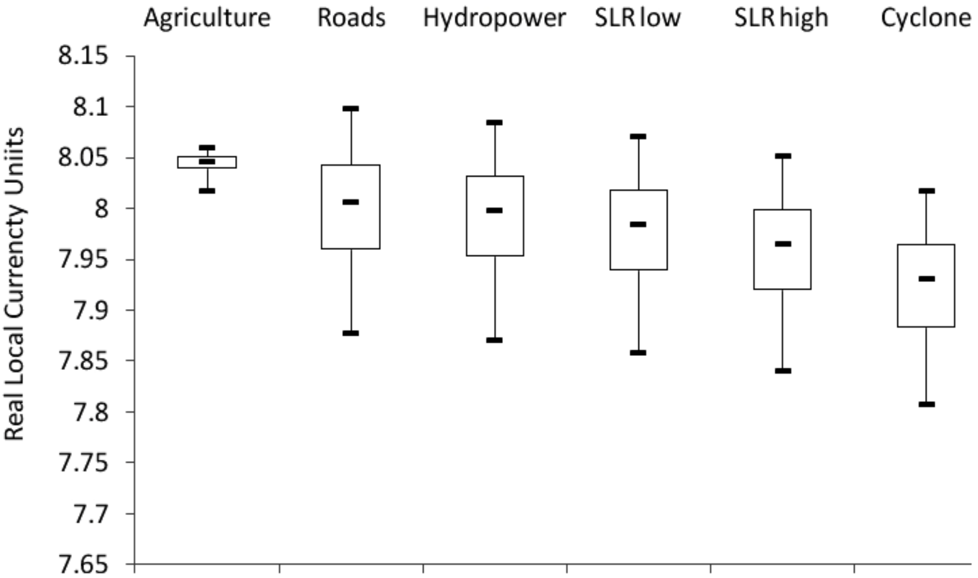
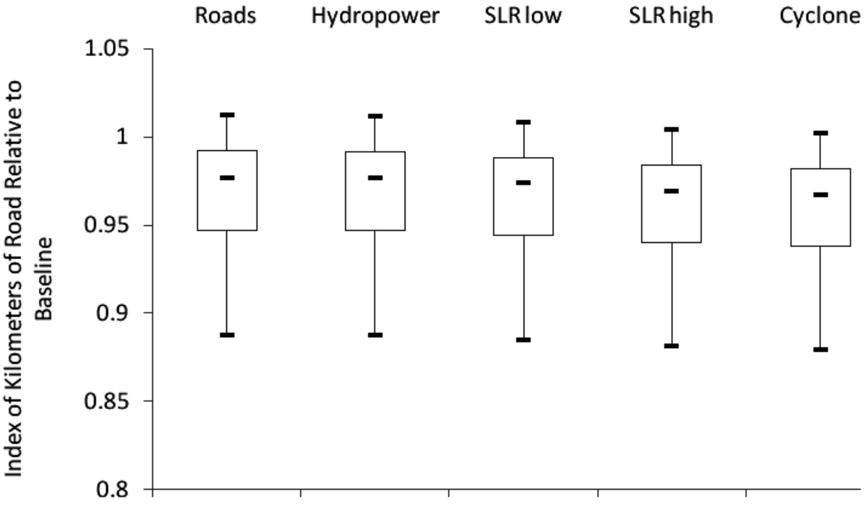


Figure 9: Index of road network length relative to the baseline (average of 2046-2050)



In some scenarios, road network length is greater under climate change than without climate change. Dryer scenarios tend to be more favorable to road network length due to reduced washouts from precipitation and flooding. Nevertheless, most scenarios generate reductions in road network length. This is due to three factors. First, all GCM scenarios produce increases in temperature. Higher maximum temperatures increase the rate of degradation of paved roads unless steps are taken to make roads more robust to higher temperatures. In the model, these adjustments are not undertaken and so rising temperature leads to higher maintenance costs, which in turn displace new road investment. Second, even though nationally precipitation declines slightly, the intensity of precipitation tends to increase leading to a higher rate of washouts particularly for unpaved roads. Third, the increase in precipitation intensity leads to, in most scenarios, a small rise in the frequency and intensity of flooding events. In a few GCM runs, large scale flooding events become much more frequent leading to important declines in the total road stock.

Degradation or destruction of infrastructure is different from agricultural impacts because the effects on infrastructure endure. Once a road is washed away, its negative effect remains until the road is rebuilt. However, with constant resources allocated to roads, reconstruction of a section of road that is washed away due to heavy rainfall or flooding implies fewer resources available for construction of new roads or regular rehabilitation of existing roads. Hence, for roads, climate change influences the rate of accumulation of the road stock, which in turn influences the rate of productivity growth in productive sectors. Because rates of accumulation are influenced, the effects can accumulate and become relatively large over time. In contrast, for agriculture, climate change (as modeled) influences production in a given year but not necessarily rates of growth in productive capacity through time. If growing conditions are poor, production declines; however, if growing conditions are favorable, production levels are favorable.

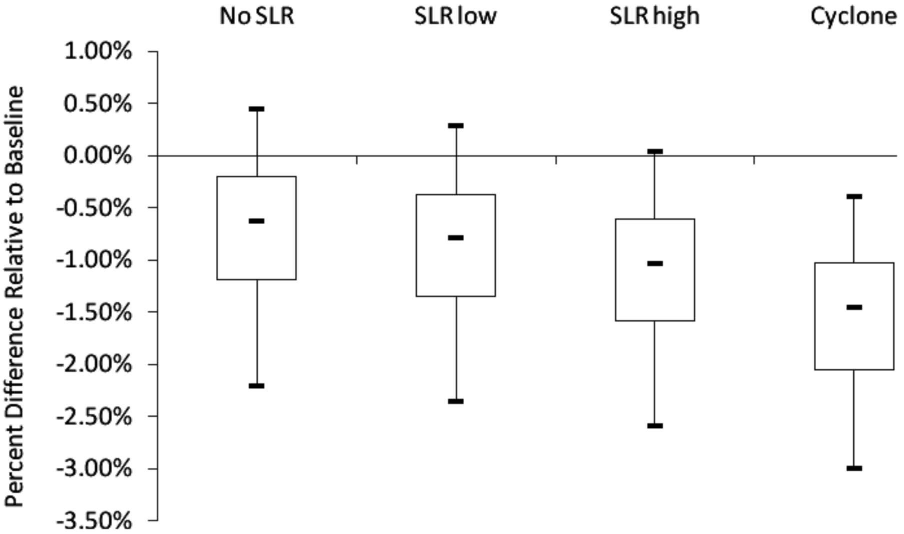
The third scenario depicted in Figure 8 adds the shocks with respect to hydropower. As shown in Figure 3, impacts on hydropower production are essentially centered about zero in the 2040s. However, in the 2020s and 2030s, when hydropower represents a larger share of total electricity supply, the impacts tend to be negative. The effect is to slightly reduce growth over the period resulting in a slight reduction in median GDP (across GCM runs) during the period 2046-2050.

The implications of sea level rise, as shown in Figure 8, are negative across all scenarios and basically shift the distribution of GDP outcomes downward. Sea level rise is uncorrelated with the particular GCM selected. Hence, the same sea level rise shocks are applied across all scenarios. The two principal drivers of losses from sea level rise are loss of agricultural land and loss of road infrastructure. As emphasized earlier, elevation data was obtained at one meter steps while climate change is expected to deliver at most 38 centimeters of sea level rise by 2050 (but potentially much more by 2100). It is, as a result, impossible to analyze the exact impacts of sea level rise to 2050 without additional assumptions. We assume that, with 38 centimeters of sea level rise, 38 percent of the area submerged by one meter of sea level would become unavailable. We also assume that this area constitutes principally agricultural land and road infrastructure. Other forms of capital, such as machines and significant permanent structures, are placed at risk in the cyclone scenario, to which we now turn.

The scenario Cyclone considers the marginal impact of the combination of cyclones and high sea level rise relative to the baseline. As discussed, we assume that there is no change in the frequency or intensity of cyclone strikes. Much of the damage from cyclone strikes is a function of wind velocity; however, this is held constant between the baselines and the climate change scenarios. As a result, the marginal impact of cyclones due to climate change is restricted to the interactions between storm surge and sea level rise. Thirty eight centimeters of sea level rise causes the storm surge to extend further inland and increases the depth of submersion in affected areas.

Nevertheless, the total effects on economic growth are not exceedingly large. Figure 10 illustrates the distribution of the percent reduction in the level of GDP during the period 2046-2050. The scenario labelled “No SLR” is the Hydropower scenario (e.g., the combination of Agriculture, Roads, and Hydropower). The SLRlow represents the least strong distribution of impacts considering all impact channels as well as low SLR. The level of GDP in that period ranges between +0.25 and -2.5 percent with the majority of outcomes between -0.5 and -1.5 percent. With high sea level rise and cyclones (scenario Cyclone), the level of GDP in the period 2046-2050 is between 0.5 and 3.0 percent lower.

Figure 10: Reduction in real GDP relative to the baseline (average 2046-2050)



Because growth is a cumulative process, these reductions in GDP levels translate into a small reduction in the average annual GDP growth rate over the simulation period (2007-2050). In the cyclone scenario, the average GDP growth rate is reduced by between 0.01 percentage points and 0.08 percentage points. In other words, if the expected average baseline growth rate without climate change is 5.4 percent per annum, then the growth rate would be expected to be between 5.32 and 5.39 percentage points.

While climate change is not expected to dramatically reduce the average economic growth rate over the next 40 years, the implications of climate change are not trivial. In addition, the analysis points to climate change as imposing an increasingly heavy drag on the economy with the implications becoming potentially large by the 2040s. The net present value of losses is illustrated by scenarios in Figure 11 and by decade for the scenario "Cyclone" in Figure 12. The net present value of losses is potentially substantial amounting to about 40 billion real 2007 USD in the worst case. The expected level of losses runs from about 8 to 21 billion USD. While positive outcomes are possible when SLR is excluded, the scenarios with all effects included (SLR low, SLR high, and Cyclone) all generate a negative net present value. Figure 12 further reveals that, despite the discount rate of five percent, the net present value of climate change impacts increases through time with the strongest impacts expected in the 2040s. This is principally due to the inexorable effects of sea level rise.

Figure 11: Net present value of losses by scenario (2008-2050)

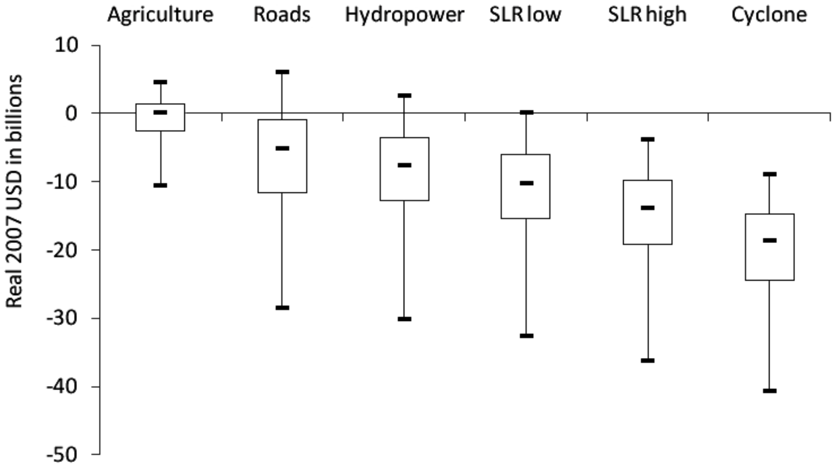
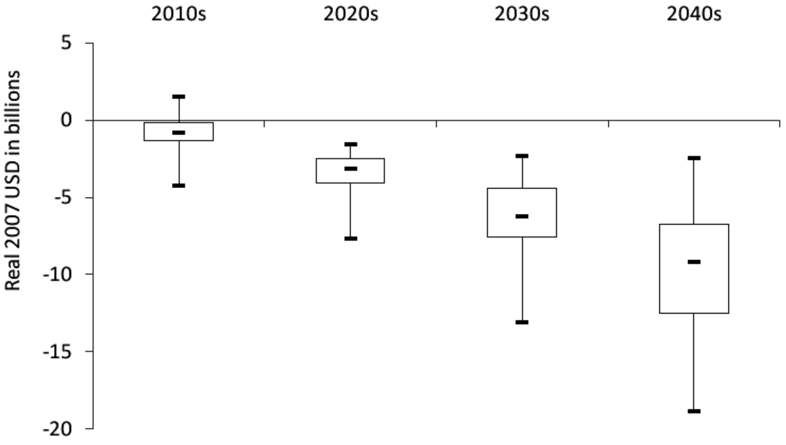


Figure 12: Net present value of losses by decade for the scenario "Cyclone"



Note: A discount rate of 5% is applied in both Figures 11 and 12.

Summary and Conclusion

Going out to 2050, the following effects on climate are observed: temperature rises by about 1-2 degrees centigrade; there are relatively mild effects on precipitation with a slight tendency towards a decrease and relatively mild effects on evapo-transpiration. The combination of a light decrease in rainfall and increase in evapo-transpiration leads to a mild "drying" of a wet climate. Changes in runoff are also mild and about as likely positive as negative (median slightly negative). These changes are typically not sufficient to generate large declines in agricultural production nor are they projected to generate (in most instances) very large increases in events, such as inland flooding, that would threaten infrastructure. In addition, hydropower production tends to be negatively affected but the effects are not so large as to serve as a major brake on economic growth.

Sea level rise delivers some of the largest effects, especially when the level is high and when sea level rise is combined with cyclone strike. The Mekong river delta is particularly vulnerable with significant shares submerged in 2050 under the high sea level rise scenario. Overall, climate change worsens the economic growth prospects of Vietnam out to 2050. Nevertheless, in a macroeconomic sense, the effects, *out to about 2040*, are not particularly large. Other factors are likely to be more important determinants of growth rates over at least the next few decades.

As the net present value numbers indicate, the effects of climate change are appreciable and adaptation policies are merited. This adaptation agenda includes:

- investment in information systems to monitor climate change impacts including improved geographic information systems with emphasis on elevation data for low lying provinces, river flow, and close following of global sea level rise projections;
- development of heat resistant crop varieties;
- improved efficiency of water use; and
- changes in design standards for infrastructure such as roads to handle a warmer and more variable climate.

The most serious policy choices concern the implications of sea level rise combined with cyclone strike. There are essentially two pro-active options. First, the government of Vietnam could channel economic activity in an evolutionary fashion towards higher ground. Second, the government could invest in protective infrastructure. These are not mutually exclusive options and decisions in response to climate change do not need to be made immediately. Nevertheless, while more study is required, the available evidence indicates that a gradual channelling of activity to higher ground is more likely to be economically efficient and is certainly less risky. A major detractor to protective infrastructure investments is that they raise the stakes. Both the costs of protective coastal infrastructure and the capital that will inevitably be placed in the shadow of that protection are vulnerable to cyclone strike of sufficient magnitude. Hence, with a protective strategy, there is always the possibility that one will lose a great deal alongside the certain costs of building the protective infrastructure. For the gradual evolution strategy to in fact be gradual and hence efficient, the channelling of economic activity to higher ground should probably begin soon, certainly within the next ten years or so, especially if the upper ends of sea level rise projections are being realized.

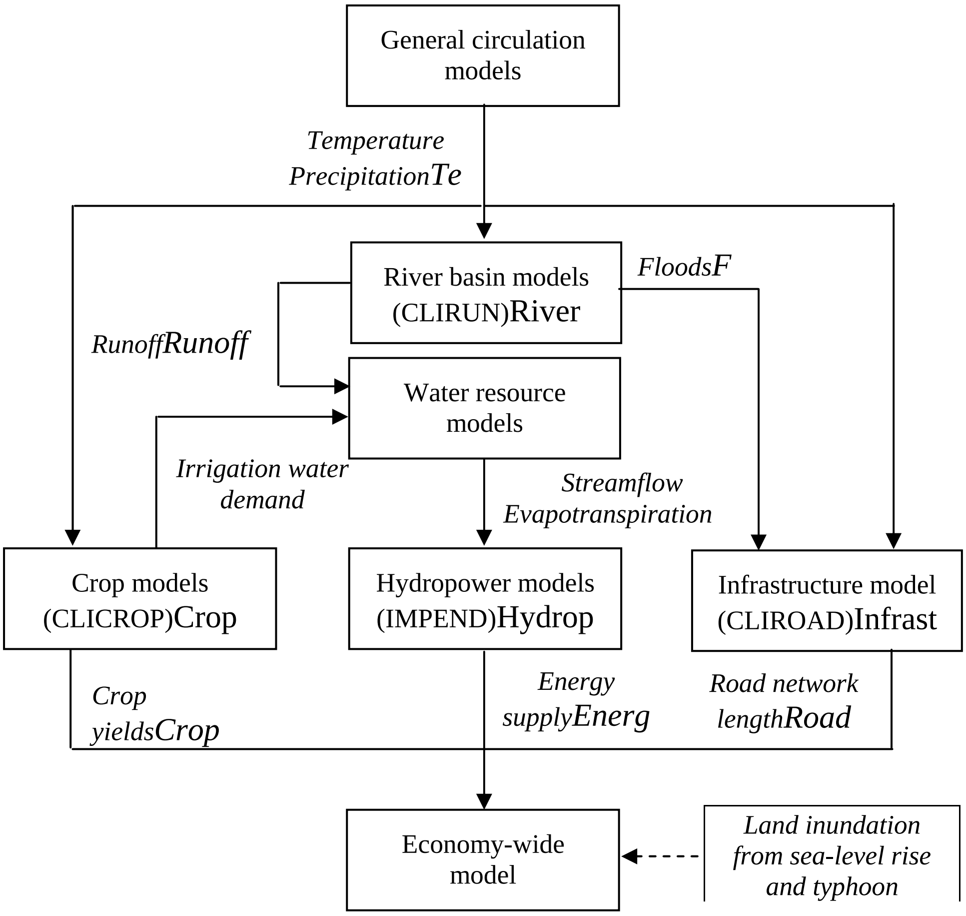
IMPLICATIONS OF CLIMATE CHANGE FOR ECONOMIC GROWTH AND DEVELOPMENT IN VIETNAM

1. Introduction

Like many countries, Vietnam is concerned about the potential implications of climate change for economic growth and development. This report presents a highly comprehensive analysis of climate change impacts for Vietnam. The paper focuses on implications for economic growth and development out to 2050. Three elements of the analysis merit special mention. First, a bottoms-up structural approach is employed. The analysis relies upon a series of structural models that link climate outcomes to biophysical and eventually economic outcomes. Second, relative to most impact analyses, the approach is highly comprehensive incorporating six important impact channels: crop yields, irrigation water availability, hydropower production, road infrastructure, sea level rise, and cyclone strike. Finally, the analysis incorporates climate projections from 56 General Circulation Model (GCM) runs employed for the Fourth Assessment Report of the IPCC. The combination of these three elements is unique and affords a very detailed examination of the implications of climate change for Vietnam. The use of multiple climate scenarios (GCMs) is particularly important. As will be illustrated, results can vary strongly by GCM. Consequently, choice of one limited set of GCM runs over another limited set can strongly influence conclusions. Here, the full range of outcomes across 56 future climates is presented.

The approach employed is illustrated in Figure 1-1. It shows the flow of information through the analytical system. As illustrated in the figure, climate projections for the baseline and climate change scenarios are translated into economic impacts via a series of specialized sector models. These include integrated river basin and water resource models and three sector models that estimate impacts of biophysical change on agriculture, energy, and infrastructure. The river basin models determine stream flows for the water resource models, which then estimate water availability for hydropower and irrigation. The river basin model also predicts flood frequency and severity, which, together with precipitation and temperature, determines road damages in the road infrastructure model. Climate projections directly affect agricultural production in the crop models. Finally, biophysical results are passed down to a multi-sector economic model that estimates the economy-wide impacts of climate change. We also include a fourth sectoral impact channel that determines land, infrastructure, and capital losses from sea level rise as well as the combination of sea level rise and cyclone strike.

Figure 1-1: Integrated modelling framework



Source: Authors.

The in-depth analysis presented in this report is motivated by serious concerns expressed in the literature. Dasgupta et al. (2007) point to vulnerability to sea level rise. Adger (1999) considers social vulnerability with an emphasis on the coastal regions of Vietnam. More recently, Yu et al. (2010) declared that "Vietnam is likely to be among the countries hardest hit by climate change" though their study focuses exclusively on the agricultural sector. The World Bank (2010c) presents a first attempt to aggregate a series of effects into an assessment for growth prospects. They find that climate change will have significant impacts on some regions and sector; nevertheless, the macroeconomic impacts are likely to be relatively modest, at least out to 2050 (p. xviii). They employ, however, only three climate change scenarios and consider a more limited number of impact channels.

This report is structured as follows: Section 2 summarizes climate change scenarios across the 56 GCM runs. Sections 3 to 6 summarize how the climate results are converted to biophysical and economic outcomes. Section 7 presents results with a focus on economic growth to 2050. Section 8 summarizes and concludes. We find that for the period 2046-2050, GDP is likely to be approximately 0.25 percent higher to 3.0 percent lower, with most outcomes concentrated between -0.5 and -2.0 percent. Because growth is a cumulative process, these reductions in GDP levels translate into small reduction in the average annual GDP growth rate over the simulation period

(2007-2050). In the cyclone scenario, the average GDP growth rate is reduced by between 0.01 percentage points and 0.08 percentage points.

While climate change is not expected to dramatically reduce the average economic growth rate over the next 40 years, the implications of climate change are not trivial. In addition, the analysis points to climate change as imposing an increasingly heavy drag on the economy with the implications becoming potentially large by the 2040s. The net present value of losses (discounted at five percent) is potentially substantial amounting to about 40 billion real 2007 USD in the worst case. The expected level of losses runs from about 8 to 21 billion USD. In addition, despite the discount rate of five percent, the net present value of climate change impacts increases through time with the strongest impacts expected in the 2040s. Consequently, especially in the absence of global mitigation policy, much stronger impacts can be anticipated in the second half of the 21st century, with the combination of sea level rise and cyclone strike presenting a particular menace.

2. Climate Change Scenarios

Future climate change is inherently difficult to predict due to the complexity of earth atmosphere system and to the human factors that influence it. Existing general circulation models (GCMs) produce a wide range of potential climate futures, especially when examined at the country level (see Solomon et al. 2007). These are due to differences in the science of modelling global climate systems and to uncertainty over how the global economy will evolve in coming decades. The latter uncertainty implies that GCMs have to be used to project climate change outcomes for a number of possible ‘emission scenarios’ based on different assumptions about future populations, technological advancements, and global agreements to reduce carbon emissions.

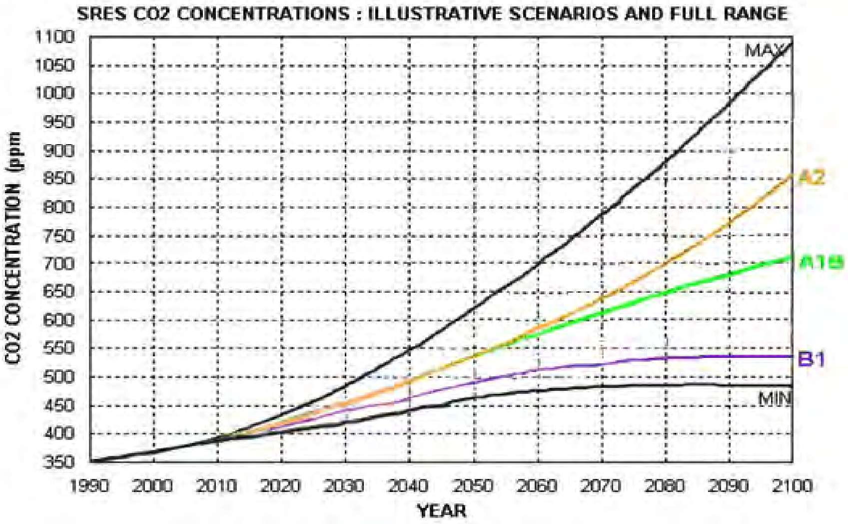
Initially presented in the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emissions Scenarios* (2000), the A2, A1B, and B1 emission scenarios represent three different possible 21st centuries in terms of the human factors which influence climate change. In the A2 scenario, globalization proceeds less rapidly. economic development and integration is primarily intraregional, population grows relatively rapidly, global GDP growth occurs at a rate similar to that in the baseline scenario, global energy use is relatively high, land use varies between maintaining its current rate and more rapid change, energy resource availability is relatively low, and technological change which increases energy efficiency is slow and not particularly focused on climate change-mitigating solutions.

The A1 scenario family represents a 21st century in which globalization proceeds more rapidly, integrating regional economies into a global economy and sharply reducing regional per capita GDP disparities. The A1B scenario represents a 21st century in which the globalized economy balances its technological pursuits between increasing the energy efficiency of fossil fuel-powered processes and developing renewable energy technologies. In this scenario, as less developed regions’ GDP per capita rises to parity with those of developed economies, birth rates decline to globally converge at a relatively low rate. The rapid growth of global GDP in this scenario leads to very high amounts of energy use, while the rapid pace of technological change and its focus on energy efficient technologies mitigates the resultant emission of greenhouse gases. Land use changes very little in this scenario, and fuel resources remain as obtainable as they were at the end of the 20th century.

The B2 scenario is the baseline scenario. ‘Business as usual’ population growth, GDP growth, energy use, land use change, energy-related resource availability, and energy-related technological change all maintain their late 20th century rates through the 21st century.

In this analysis, the A2, B1, and A1B scenarios were selected to represent the pessimistic, the optimistic, and the average cases, respectively. The total global cumulative CO_2 emissions (GtC) from 1990 to 2100 for these selected cases are compared in Figure 2-1.

Figure 2-1: Atmospheric Carbon Dioxide Concentrations Projected by the SRES Scenarios: (IPCC, 2007).

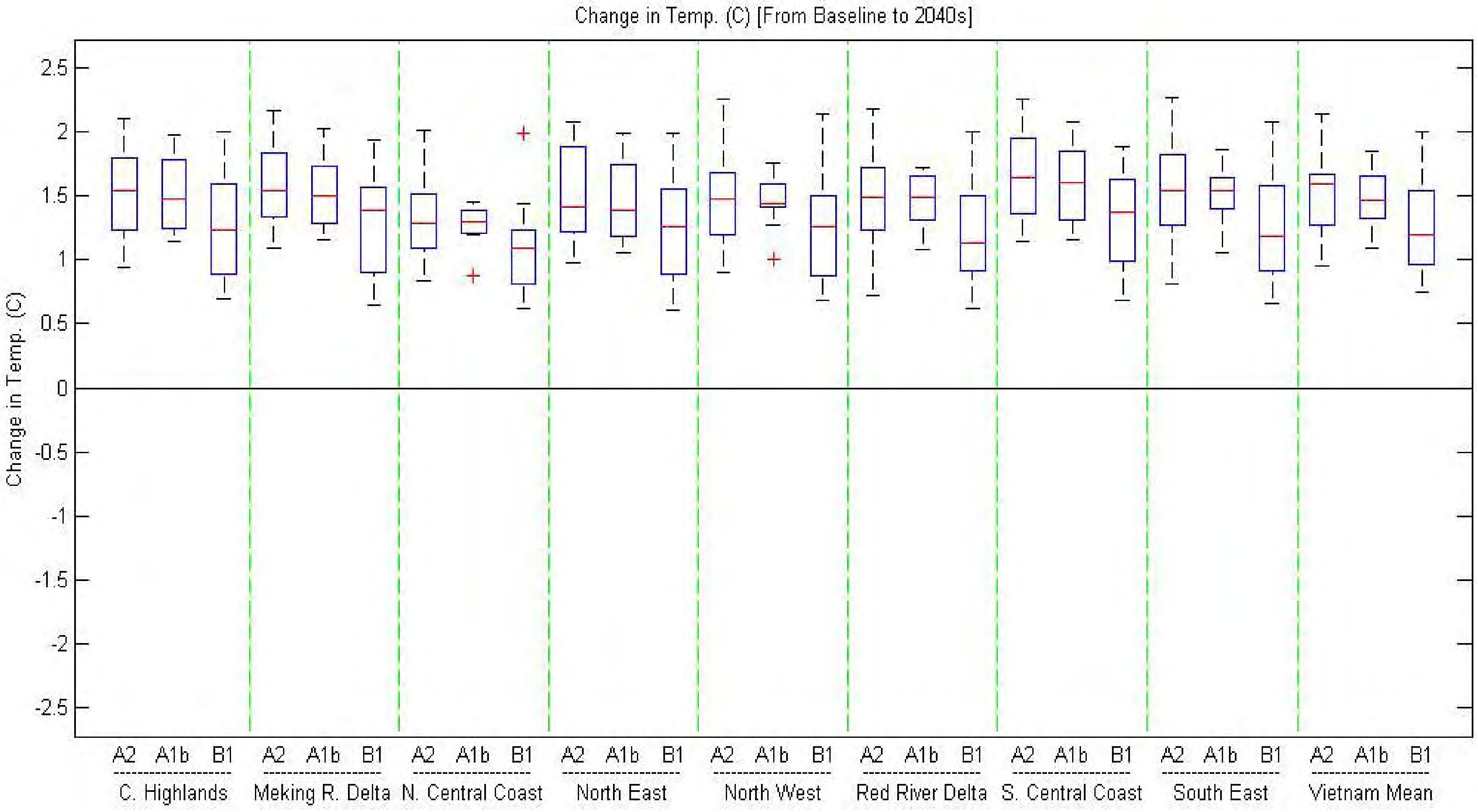


In order to capture the full range of possible climate change outcomes, this report employs results from 22 General Circulation Models (GCMs) across the three special report emissions scenarios (SRESs) in focus above. In all, the report employs 56 future climates, which represent the set of climate futures considered for the Fourth Assessment Report (AR4) of the IPCC (not all GCM-SRES combinations were included in AR4).

The outcomes of these models for Vietnam are summarized in Figure 2-2 to Figure 2-5 using box and whisker plots. Figure 2-2 illustrates temperature increase by the three SRESs considered (A2, A1B, and B1) and by region of Vietnam. Based on these models, median expected temperature increase by 2050 is somewhat less than 1.5 degrees Celsius, with most outcomes clustered near the median. For all regions of Vietnam, temperature increases range from a minimum of slightly less than one degree Celsius to a maximum of slightly more than two degrees Celsius.

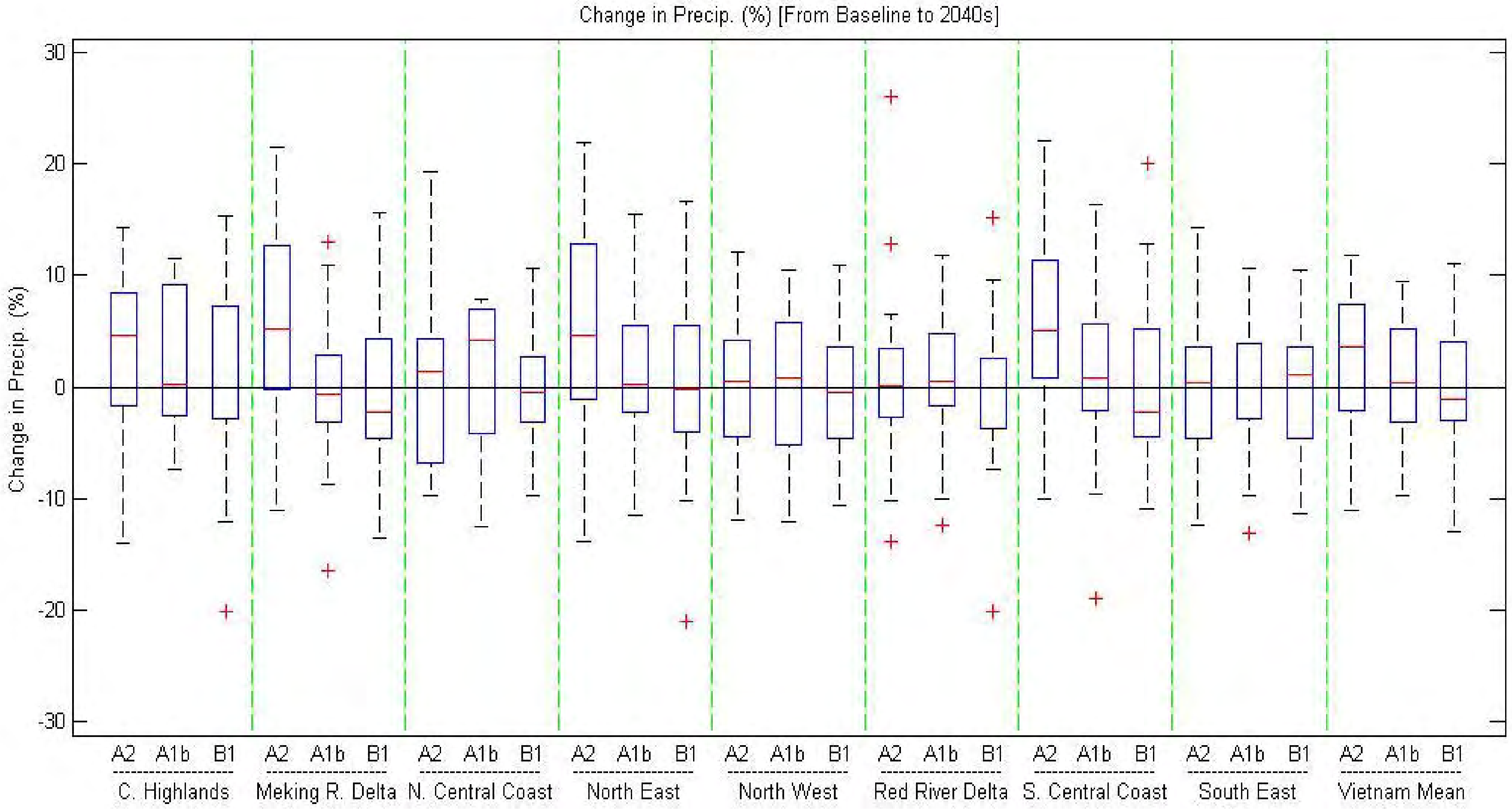
As Figure 2-3 illustrates, precipitation outcomes are considerably more uncertain than temperature outcomes. Overall, taking each GCM and SRES as equally unlikely, Vietnam is expected to receive a mild decrease in precipitation in that the median change is negative across all climate futures. Nevertheless, dryer conditions are only slightly more likely than wetter conditions at the national level. This uncertainty extends to all regions. For all provinces and SRES scenarios, the inter-quartile range (the "box" in box and whisker plots) includes both increases and decreases in precipitation. Maximum and minimum values are also broadly arrayed (even with outliers not considered), with increases in the 10-20 percent range and decreases in the 10-15 percent range. Consideration of results that are considered outliers (the + signs) extends this range even further.

Figure 2-2: Temperature anomalies during the 2040s relative to baseline climate



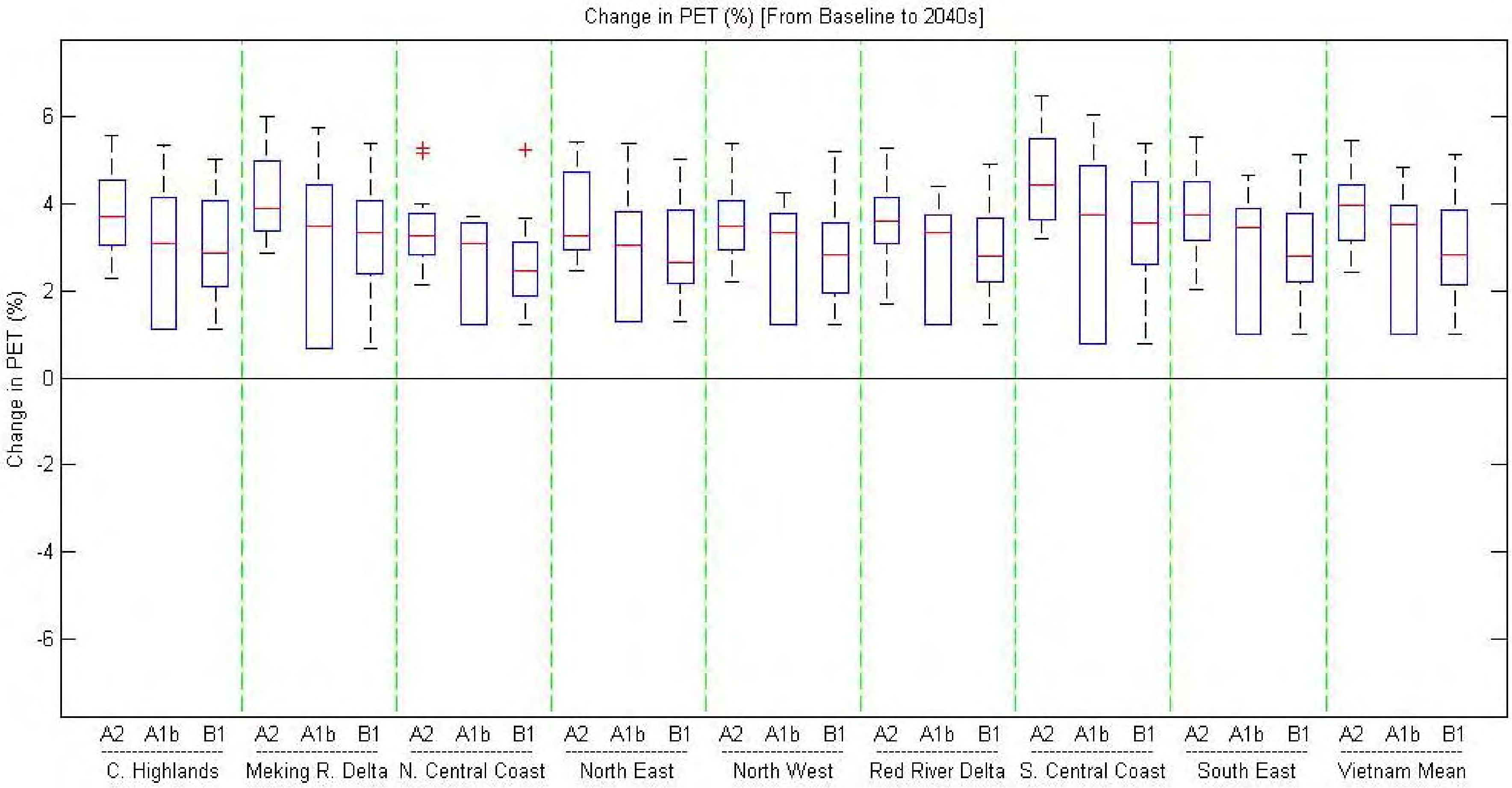
Notes: The red line represents the median temperature change. The box illustrates the middle 25-75 percent of outcomes (the inter-quartile range) and the whiskers represent the maximum and minimum values with outliers discarded. Outliers are illustrated with a plus (+) sign.

Figure 2-3: Precipitation anomalies in the 2040s relative to baseline climate



Notes: The red line represents the median precipitation change. The box illustrates the middle 25-75 percent of outcomes (the inter-quartile range) and the whiskers represent the maximum and minimum values with outliers discarded. Outliers are illustrated with a plus (+) sign.

Figure 2-4: Changes in potential evapotranspiration relative to baseline



Notes: The red line represents the median erapotranspiration change. The box illustrates the middle 25-75 percent of outcomes (the inter-quartile range) and the whiskers represent the maximum and minimum values with outliers discarded. Outliers are illustrated with a plus (+) sign.

Figure 2-5: Change in the climate moisture index relative to baseline

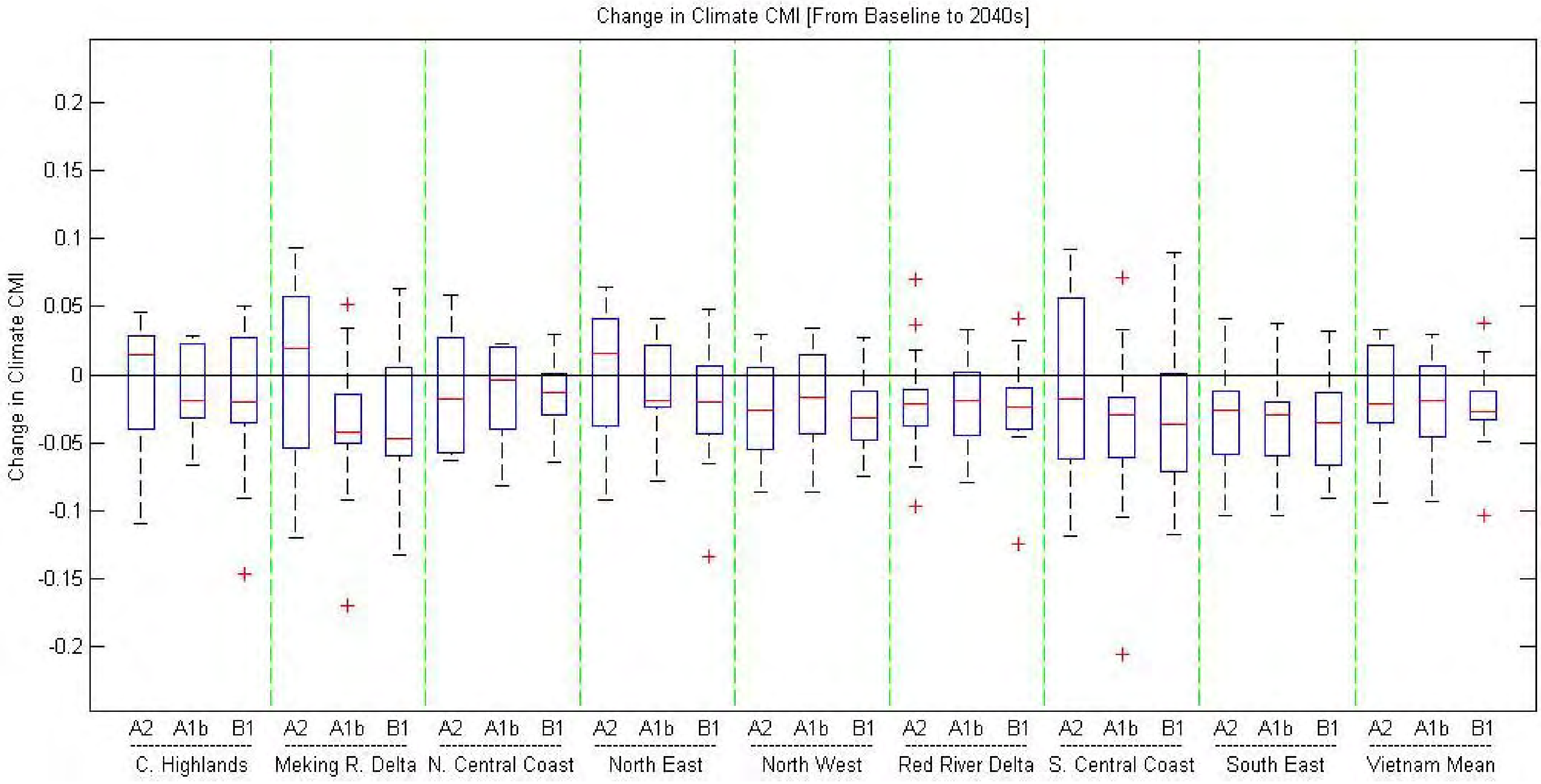


Figure 2-4 and Figure 2-5 illustrate changes in potential evapotranspiration (PET) and the climate moisture index (CMI). These two indicators combine measures of temperature and wetness to produce an indicator of net outcomes. PET illustrates changes in the rate of evaporation. PET is influenced by temperature and humidity. The climate moisture index (CMI) (Willmott and Feddema 1992) is an indicator of a region's aridity. The CMI depends on average annual precipitation (P) and potential evapotranspiration (PET). A climate is classified as semi-arid (semi-humid) and then arid (humid) as PET increases (decreases) relative to precipitation. The CMI is defined as:

CMI = -1 + P/PET when PET > P

CMI = 0 when PET = P

CMI = 1-(PET/P) when PET < P

A CMI of -1 is very arid and a CMI of +1 is very humid. In the case of Vietnam, the already high levels of humidity limit the change in PET. Nevertheless, PET tends to rise by more than precipitation in most regions. As a result, according the CMI, climate conditions in Vietnam tend to become more arid. There is, again, considerable uncertainty about Vietnam's future CMI value, especially at the sub-national level.

In terms of decadal trends, the average change in temperature, with respect to the base-case for all 56 GCMs, is illustrated in Figure 2-6. Decadal trends for precipitation by region are shown in Figure 2-7, Figure 2-8, and Figure 2-9.

Figure 2-6: Temperature changes from the reference (2011-2050)

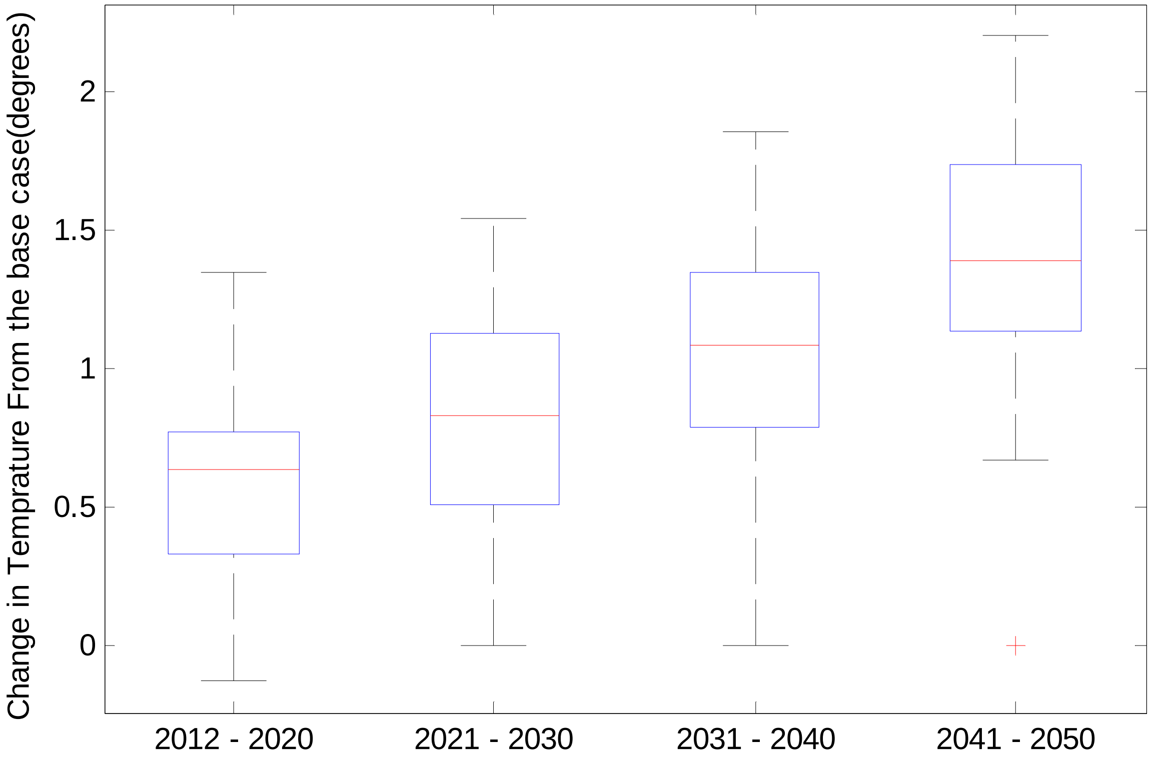


Figure 2-7: Average precipitation change for northern catchments

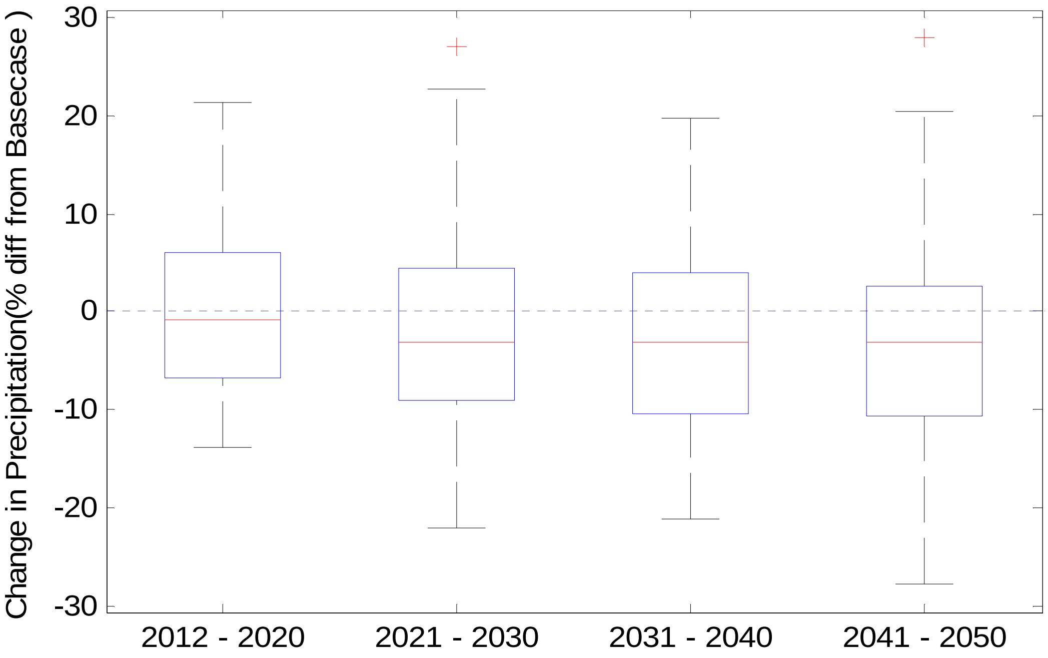


Figure 2-8: Average precipitation change for central catchments

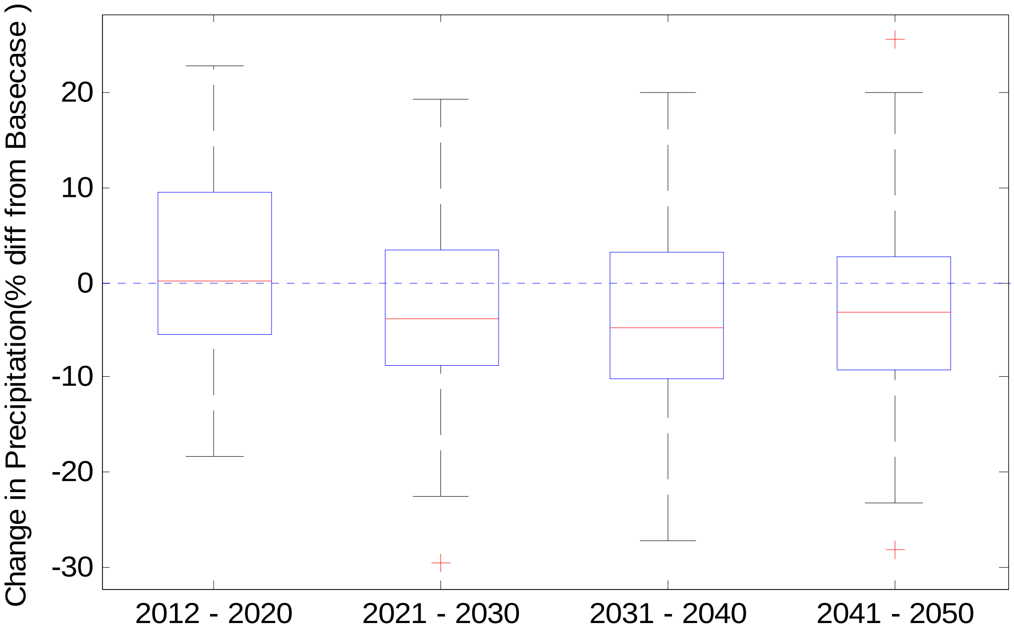
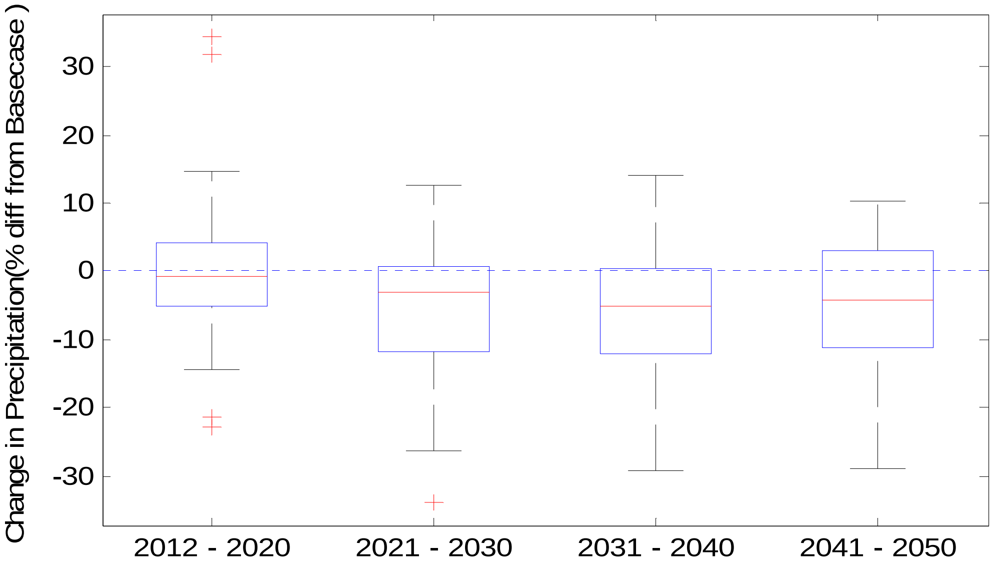


Figure 2-9: Average precipitation change for southern catchments



While GCMs are useful for forecasting trends in climate, they are less useful for predicting day to day weather variability. Following Yates and Strzepek (1998), Gleick (1991), Hulme (1989), and Arndt et al. (2011), this study make use of the 'delta' approach to derive future levels of precipitation and temperature. In this approach, GCM output of climatic variables, such as decadal anomalies for temperature and precipitation changes are imposed over historical observed meteorological data of the baseline period to construct climate change scenarios. This 'delta' approach is applied over the base case historical weather variables to generate future temperature and precipitation conditions.

Overall, the climate scenarios considered exhibit considerable variations across GCC/SRES scenario. This is particularly true for precipitation. Nevertheless, trends in temperature also vary by region and by decade. As the 56 future climates in focus here are all regarded as equally unlikely, the diversity in climate outcomes points to the desirability of considering all 56 possible climates rather than selecting only a few. This represents a step towards considering the more robust implications of climate change.

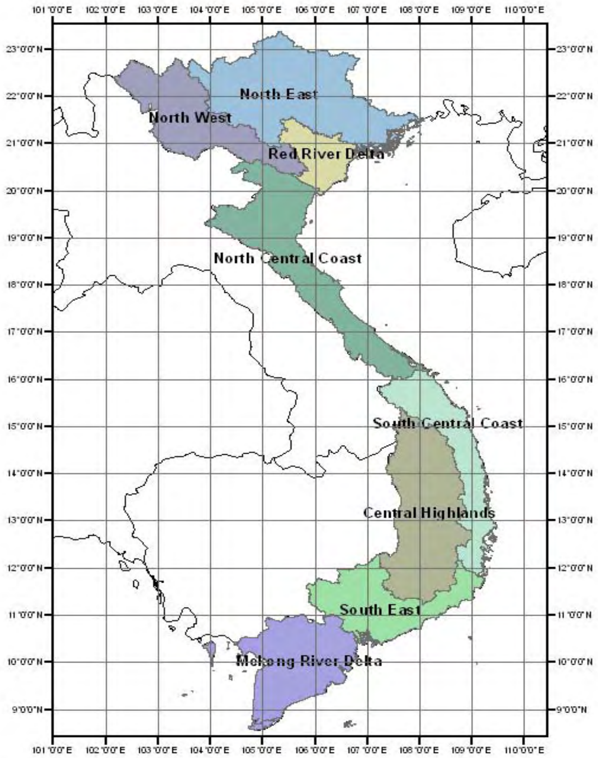
3. Agriculture: Impacts of Climate Change on Crop Yields and Irrigation Demand

In 2005, agriculture and forestry accounted for about 16% of gross domestic product (GDP). About 60% of the workforce was engaged in agriculture, forestry, and fishing related activities. Changes in mean temperature, precipitation, soil moisture, and salinity all impact crop production, which can in turn impact Vietnam's macroeconomy.

Vietnam's major cash crop is rice. Others include coffee, cotton, peanuts, rubber, sugarcane, and tea. For this study, paddy rice, coffee, rubber, sugarcane, tea, maize (to represent other annual crops), and cashews (to represent other perennial crops) were modelled to represent the agriculture sector. Vietnam was split into eight regions for the crop analysis: Central Highlands, Mekong River Delta, North Central Coast, North East, North West, Red River Delta, South Central Coast, and South East.[1] Annual yield and irrigation demand was calculated for each of these regions. These regions are shown in Figure 3-1 below.

Other studies have predicted a range of possible impacts to crops in Vietnam, although all have concluded that the impact will be harmful. Zhai and Zhuang (2009) found that climate change is likely to have non-negligible negative effects on Southeast Asia's economic output. This study used results from Cline (2007), who predicted that the effects of climate change would decrease crop production by two to 15 percent by the 2080s. Cline applied a combination of a Ricardian-statistical approach with crop models to the mean of 6 IPCC climate General Circulation Models (GCMs). Yu et al. (2010) comes to the conclusion that rice production will be "severely compromised" by the effects of climate change. This study uses the WOFOST crop model (Van Diepen et al. 1989; Boogaard et al. 1998) linked with an empirical hydro-crop model (Thurlow et al. 2009) to assess the effects of precipitation and temperature on crops. These results are then linked to a hydrological model and a river basin model. Paddy rice production in the Mekong Delta is predicted to decrease 13% by 2050 due principally to sea level rise (Yu, et al. 2010). The study assumes a 30 cm rise by 2050. The study used the climate predictions of 3 GCMs (a wet, medium, and dry projection), including the effects of a 30 cm sea level rise by 2050, causing inundation and salt water intrusion.

Figure 3-1: Regions of Vietnam



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

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[1] This corresponds to the regional disaggregation of agriculture in the dynamic computable general equilibrium model described in section 7.

3.1. Methods

For this study, the CliCrop model (Strzepek and Fant 2009) was used. This model is an attempt to balance accuracy and simplicity with an emphasis on estimating the effects of the changing climate on irrigation demand and rain-fed crop production. CliCrop is a generic crop water deficit model used to calculate the effect of changing daily precipitation patterns on crop yields and irrigation water demand. The model was developed in response to the available crop models, which use monthly average rainfall and temperature to produce crop outputs. These monthly models do not capture the effects of changes in precipitation patterns, which greatly impact crop production. In contrast to the existing models, CliCrop is able to produce predicted changes in crop yields due to climate change for both rain-fed and irrigated agriculture, as well as changes in irrigation demand.

CliCrop was also developed to require a minimal input set, since most of the studies suitable for the CliCrop model have limited data available. The inputs into CliCrop are weather (temperature and precipitation), soil parameters (field capacity, wilting point, saturated hydraulic conductivity, and saturation capacity), and crop-specific parameters that describe crop behaviour.

The effects of climate on the crop yield are modelled indirectly in the soil layers through the extraction of soil moisture caused by evaporation and transpiration and the infiltration from precipitation into the soil layers. The model uses the soil properties and precipitation amount to calculate the infiltration using a version of the USDA Curve Number method (Bureau of Reclamation, 1993). The model then calculates the soil moisture in each soil layer, calculates the amount of moisture allowed to percolate into the deep soil layers, and calculates a yield coefficient at the end of the growing season.

Yield calculations are based on the ratio of actual evapotranspiration (ET) and PET. Five yield values are calculated; one for each of the four development stages, and one for the whole season. The least of the five, considered the limiting yield, is reported as the estimated yield value. Each Yield value is calculated using the equation below (Allen, et al. 1998).

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y^d\cdot\left(1-\frac{ETC^d}{ETA^d}\right)$$

$$\%Yield^d=\frac{Y_a}{Y_m}$$

Where Y_a is the predicted actual yield, Y_m is the maximum yield; K_y^d is the yield coefficient for development stage d; ETC^d is the sum of daily ET crop demand for development stage d; ETA^d is the sum of daily actual ET for development stage d; $\%Yield^d$ is the ratio of actual yield over maximum yield, the ‘Yield Factor’ reported by CliCrop (Allen, et al. 1998). Each year, once the yield is calculated, the yield is reduced if any waterlogging occurred during the growing season based on a method developed by Sieben (1974).

Actual ET is calculated as a function of precipitation, temperature, PET, soil moisture, root depth, crop type, and atmospheric CO_2 concentration. This calculation is done each day, for each soil layer. CliCrop uses the Modified Hargreaves equation to calculate PET (Hargreaves et al, 2003). Soil moisture is calculated using a bucket-type scheme similar to the method used in the SWAT model (Neitsch et al, 2005), details are given in Strzepek and Fant (2009). Crop specific parameters similar to the ones used in CROPWAT (Allen, et al. 1998) are used in this calculation, as well as in the calculation of the daily ET crop demand. The atmospheric CO_2 concentration affects the daily ET crop demand, which follows the methods explained in Rosenzweig and Iglesias (1998). The crop parameters are adjusted from year to year using methods developed by Allen, et al (1998) – adjusting crop ET demand - and Wahaj, Maraux, and Munoz (2007) - adjusting crop stage durations, which estimate the local crop's reaction to deviations from 'average' climate conditions.

In order to model the rice paddies, which are significant for Vietnam, some modifications had to be made to the original CliCrop model. During the paddy crop stages, rice paddies are completely submerged in water (which typically requires irrigation). In order to model this using CliCrop, the code was adjusted so that the soil remains at complete saturation during these paddy stages, as well as a certain depth of ponding on top of the soil. If precipitation is not enough to satisfy this condition, the model assumes the farmer will irrigate. For all irrigated crops, the difference between the amount of water required by the plant and the amount received due to precipitation is termed the water deficit.

For the purposes of this section, CliCrop-PaddyRice assumes there is sufficient water available via irrigation. This assumption results in high yields and high levels of irrigation demand. In the water resources section, irrigation demand will be compared to irrigation supply. If demand exceeds supply, the farmer will need to leave some of the field fallow, partially irrigate, or leave some of the rice paddies rain-fed. Whatever the farmer decides in this case, paddy rice production will decrease. This type of production decrease is not shown in the Yield Factor produced by CliCrop shown in this section but is presented in section 4 captured in the economywide analysis presented in section 7.

The model was calibrated with daily weather data originally sourced from the Land Surface Hydrology Research Group at Princeton University (Sheffield, et al., 2006). This data is at a scale of 1-degree by 1-degree. For this reason, CliCrop was run for each 1-degree by 1-degree grid in Vietnam (See Figure 4-1 for grid size). All required soil parameters were derived from the FAO Soils Database (Batjes, 2002). Generic crop-specific parameters were used, which can be found in the CROPWAT and AquaCrop model input files, publicly available on the FAO website (fao.org). Future climate inputs are as described in section 2.

3.2. Results

3.2.1. Baseline Scenario

Table 3-1 shows the average yield factor for the baseline scenario for the regions and crops used in this study. These yield factors represent a fraction, where 1 is perfect yield (the plant reaches its full yield potential) and 0 is no yield. The reductions in yield (any value less than 1) are caused by water stresses predicted by the CliCrop model. As indicated, for paddy rice (PR), an irrigated version of the CliCrop model was used, meaning that water stresses on the crop are minimal (resulting in relatively high yield factors). Changes in water deficit and sea level rice will aslo affect rice production. Paddy rice was run for three growing seasons: main season, planting between May and August; summer-autumn, planting between April and June; and Winter-spring, planting between December and February (Maclean, et al., 2002).

The annual average water deficit is shown in Table 3-2. Each of the water deficit values is dependent on the length of the growing season cycle. For example, sugarcane is grown all year, so the total irrigation demand (in mm/year) represents the sum of the water deficit for the whole year. Alternatively, horticulture has an average growing cycle of 95 days, so these values for horticulture represent the sum over about 95 days. For maize (used as a proxy for Annual Crops), the length of the crop cycle is 135 days; for rubber, 190 days; for coffee, 190 days; for tea, 265 days; for pistachios (used for Perennial Crops) , full year; and for paddy rice (PR), 165 days.

Table 3-1: Average Yield Factor for the Base Scenario for Vietnam

Region	Sugarcane	Ann. Crops	Rubber	Coffee	Tea	Per. Crops	PR Main	PR Sum-Aut	PR Win-Spr
North East	0.43	0.76	0.84	0.64	0.71	0.72	0.96	0.95	0.96
North West	0.39	0.97	0.66	0.47	0.68	0.74	0.99	0.84	0.88
Red River Delta	0.41	0.79	0.68	0.52	0.68	0.63	0.98	0.85	0.95
North Central Coast	0.44	0.90	0.66	0.47	0.65	0.69	0.92	0.80	0.83
South Central Coast	0.38	0.71	0.74	0.56	0.68	0.65	0.99	0.90	0.96
Central Highlands	0.40	0.88	0.80	0.57	0.72	0.71	0.98	0.92	0.93
South East	0.37	0.91	0.62	0.47	0.67	0.64	0.99	0.82	0.90
Mekong River Delta	0.39	0.68	0.80	0.63	0.66	0.69	0.97	0.95	0.96

Table 3-2: Average Water Deficit (mm/cycle) for the Base Scenario for Vietnam

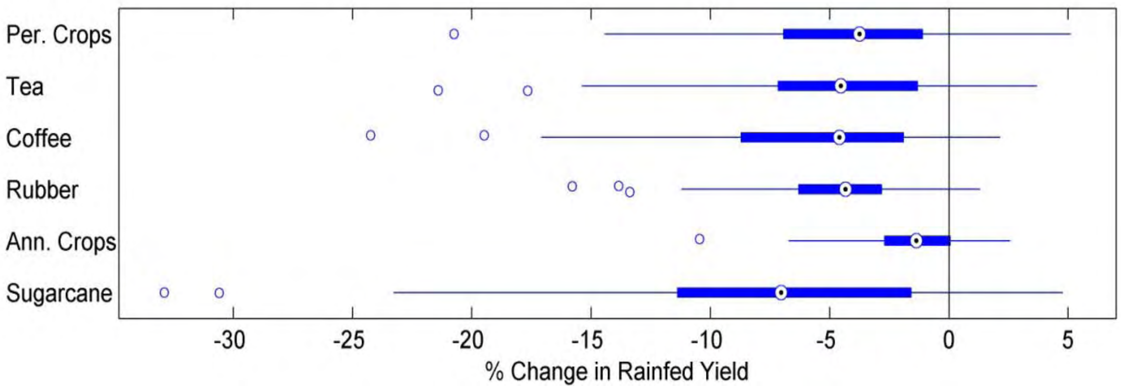
Region	Sugarcane	Ann. Crops	Rubber	Coffee	Tea	Per. Crops	PR Main	PR Sum-Aut	PR Win-Spr
North East	554	113	114	254	239	119	927	1016	984
North West	567	113	126	349	198	155	918	1102	1127
Red River Delta	465	84	85	217	178	99	862	950	884
North Central Coast	493	44	95	313	161	119	896	1042	1092
South Central Coast	534	64	162	395	234	173	877	1040	1058
Central Highlands	568	27	139	446	203	154	746	998	1107
South East	551	7	110	446	171	91	564	880	989
Mekong River Delta	447	3	87	392	137	81	451	723	834

3.2.2. Future Scenarios

3.2.2.1. Yield Factors

The changes in the yield factors for the 7 crops are illustrated using the box and whisker plot technique in a manner similar to the figures showing the predicted climate changes in section 2. Each box and whisker plot represents the PDF of the projections of the 56 GCM-scenario pairs. Figure 3-2 shows the changes in yield factor predicted by CliCrop averaged over Vietnam.

Figure 3-2: Changes in Yield Factor from Baseline to the 2041-2050 Mean for Vietnam



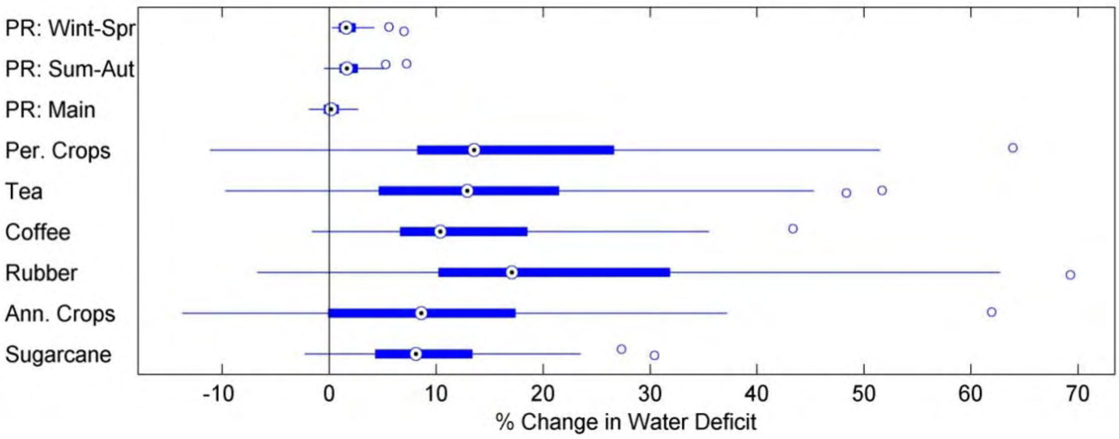
As this plot shows, the yield results tend to vary for the different crops, although most of the GCM-SRES climate projections predict a yield decrease for all crops. The variations shown across the different crops are likely based on two primary input categories. First, the weather affecting the crop is dependent on the length of the growing season and the months on which the growing season falls. The future climate projections used in this study predict climate changes that are seasonal. For example, some of the GCMs might predict that precipitation will increase in the winter months but decrease in the summer months. Second, each crop undergoes four growing seasons in CliCrop, which could be more or less important for the resulting yield, depending on the crop-specific parameters.

As discussed previously, the yield results for paddy rice are not an accurate indicator of the climate effects on yield, since CliCrop-PaddyRice is an ‘irrigated’ water deficit crop model. Alternatively, the changes in irrigation demand for paddy rice (described on the following pages) is a useful indicator of the effects of a changing climate.

3.2.2.2. Water Deficit

The following figure shows the changes in water deficit (an indicator for changes in irrigation demand) for the 7 crops using the box and whisker plot technique. Again, the box and whisker plot represents the PDF of the projections of the 56 GCM-scenario pairs. Figure 3-3 shows the predicted changes in irrigation demand from the baseline scenario to the 2041-2050 mean from the CliCrop results averaged over Vietnam.

Figure 3-3: Changes in Irrigation Demand from Baseline to the 2041-2050 Mean for Vietnam



Like the changes in yield, the irrigation demand changes are dependent on a number of parameters. As an indicator, irrigation demand tends to have a stronger correlation to changes in climate because the yields are calculated using the ‘limiting yield’ approach. In the limiting yield approach (described briefly in Section 2.1) the stage with the least yield factor is output as the actual yield factor. This means that the yield factor is only directly dependent on the crop stage that results in the least yield. On the other hand, the water deficit values are the sum of crop water demand (the amount of water the crop needs to yield the theoretical maximum) subtracted by the actual ET (the amount of water the crop received) on a daily basis. So the irrigation demand indicator is sensitive to the climate during the entire crop cycle, while the yield factor could be showing a seasonal change in climate.

As shown, the results from this study suggest that irrigation demand will mostly increase over Vietnam, with only a few exceptions. This is caused by the predicted decrease in soil moisture (decrease in CMI and increase in PET), which causes an increase in water deficit.

3.2.2.3. Sea Level Rise and Other Impacts on Crop Production

Since CliCrop is a 1-dimensional crop water stress model, the impacts of sea level rise, increased floods, and other phenomena that are not related to changes in on-site precipitation and temperature are not taken into account in this section. Sea level rise and more frequent storm surge caused by climate change would significantly increase salinization in low lying farms along the coast. If this occurs, many crops will experience reduced yields. Since paddy rice is typically grown in these areas, rice production is particularly vulnerable to salinization caused by sea level rise and storm surge.

3.3. Conclusions

With the GCMs predicting temperatures rising, small changes in precipitation (for most future climates), and decreases in soil moisture, the people of Vietnam should be prepared for more unfavourable climate conditions for crop production. Furthermore, the results of this study seem to suggest that agricultural yields will likely decrease by 2050 for all of the crops considered. These results also indicate that irrigation demand will increase more dramatically than the predicted yield decrease, causing a greater need for readily available irrigation water. As this study is a general study for the country using global datasets, and agricultural production is a highly complex process, a more detailed crop impact study is suggested before specific adaptation decisions are made.

Considering the fairly large variation in predicted future climates for Vietnam (causing the large variation in the yield and irrigation demand results), planners should be prepared for more severe extremes. Options for developing more water efficiency and storage capacity should be considered. Also, in terms of crop production, traditional agricultural methods should be reconsidered. The possibility of a shift in seasonal precipitation and temperature might be cause for encouraging farmers to adapt by changing the planting and harvest seasons accordingly. Crop genotypes more resistant to higher temperatures, water deficit stresses, and excess water stresses should also be considered.

4. Water Resources Including Hydropower

Future climate change and variability will cause changes in temperature, precipitation patterns, and snowmelt thus altering the hydrologic cycle, global circulation patterns, and local weather patterns. As these alterations change water availability, quality, and stream flow, it will have a direct impact on water resources and freshwater ecosystems. This, in turn, will affect the function and operation of existing water infrastructure as well as water management practices.

Due to the complex interactions of climatic variables with the hydrologic cycle, together with the uncertainty involved in regional projections of how precipitation may change, assessment of the impact of climate change on water availability and stream flow remains a challenging issue. Assessing potential climatic change impacts on stream flow has been attempted in different studies applied to global sub-basins (Yates and Strzepek, 1998; Gleick 1991; Hulme 1989). For this analysis, the CLIRUN-II model is used to simulate the hydrologic process and predict corresponding runoff from the catchments for each scenario generated. The analysis also considers irrigation water availability and hydropower generating capacity. Water resource assessment is conducted using the WEAP model to analyze impacts on irrigation water availability and hydropower energy generation for the time span of 2011 to 2050. The assessment includes current hydropower in the sub-basins and future planned hydropower development.

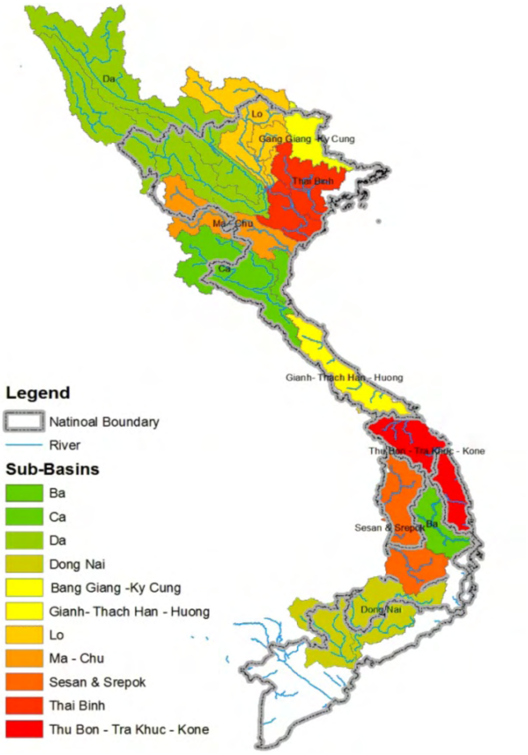
4.1. Hydrology and Catchment Overview

4.1.1. Sub-Basin Classification

A Shuttle Radar Topography Mission (SRTM) global Digital Elevation Model (DEM) of 90 meters resolution was used to delineate the catchment boundaries and derive drainage networks. A total of 22 sub-basins, areas ranging from 1,500 to 45,000 km^2, were identified based on United States Geologic Survey (USGS) Level 4 classification. Figure 4-1 shows the sub-basin classification used in this analysis. Some of the catchments are trans-boundary, for example the Da and Low river basins. For these sub-basins, the upstream portion of area that extends into China is also included in the analysis.

Northern Vietnam belongs to the Red River System Basin containing the Da, Thai Binh, Lo, and Cu sub-basins, with a total area of 210,380 square km. This basin contains some of the existing large reservoirs, as well as those under construction, such as Hoa Binh and Son La. The central catchment is the coastal sub region, a very narrow land strip between mountains and sea. It is composed of many small, separate basins which are aggregated into larger catchments for this analysis. The lower part includes the Dong Nai and Sesan sub-basins, but excludes the lower part of the Mekong's river basin and the Cuu Long sub-basin due to Lack of data. The areas of sub-basins included in this analysis are summarized in Table 4-1.

Figure 4-1: Level 4 sub-basin classification delineated from STRM global DEM data 90 meter resolution



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

4.1.2. Precipitation

Temperature and precipitation data are obtained from the Climatic Research Unit's[2] CRU Global Climate Dataset, available through the IPCC DDC. A historical monthly precipitation data set for global land areas from 1901 to 2000 gridded at two different resolutions (2.5 degrees latitude by 3.75 degrees longitude and 5 degrees latitude/longitude) has been constructed and is available for use in scientific research (Hulme 1994, Hulme, Osborn, and Johns 1998). The 5 degree dataset was downloaded and aggregated over the 22 sub-basins to derive a precipitation time series for each sub-basin selected for this analysis for the base case historical precipitation scenario.

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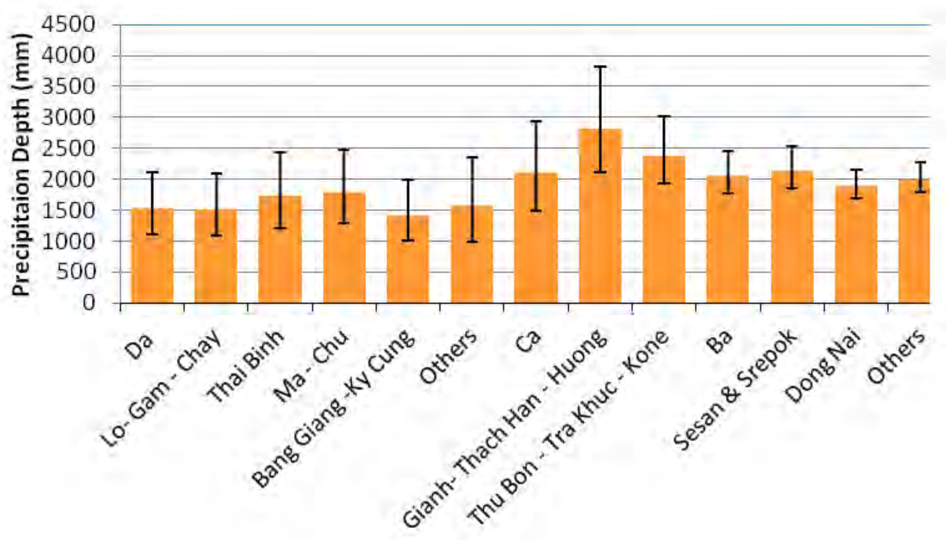
[2] gu23wld0098.dat' (Version 1.0) constructed and supplied by Dr Mike Hulme at the Climatic Research Unit, University of East Anglia, Norwich, UK. This work has been supported by the UK Department of the Environment, Transport and the Regions (Contract EPG 1/1/48)."

Table 4-1: Sub-basin classification and areas

Location	Sub-basin	Area (Square Km)	Total (Square Km)
Northern Catchments	Da	104,568	
	Lo - Gam - Chay	34,423	
	Thai Binh	27,323	
	Ma - Chu	24,184	
	Bang Giang -Ky Cung	11,849	
	Others	8,034	210,380
Central Catchments	Ca	37,718	
	Gianh - Thach Han - Huong	20,101	
	Thu Bon - Tra Khuc - Kone	26,233	84,053
Southern Catchments	Ba	13,469	
	Sesan & Serepok	30,143	
	Dong Nai	42,215	
	Others	19,474	105,302
Total			**399,735**

The average annual precipitation for the northern sub-basins is about 1588 mm, where the highest is in the Ma Chu sub-basin, with a value of 1785 mm. The Central and the southern sub-basins have relatively higher rainfall, with average annual values of 2431 mm and 2019 mm, respectively. The spatial distribution of annual rainfall is shown in Figure 4-2.

Figure 4-2: Annual Rainfall for Major Sub-basin



The average, minimum, and maximum monthly rainfall patterns over the historical years 1901 to 2000 for representative catchments in the north, central, and southern Vietnam are provided in Figure 4-3, Figure 4-4, and Figure 4-5 respectively.

Figure 4-3: Monthly rainfall pattern for northern sub-basins

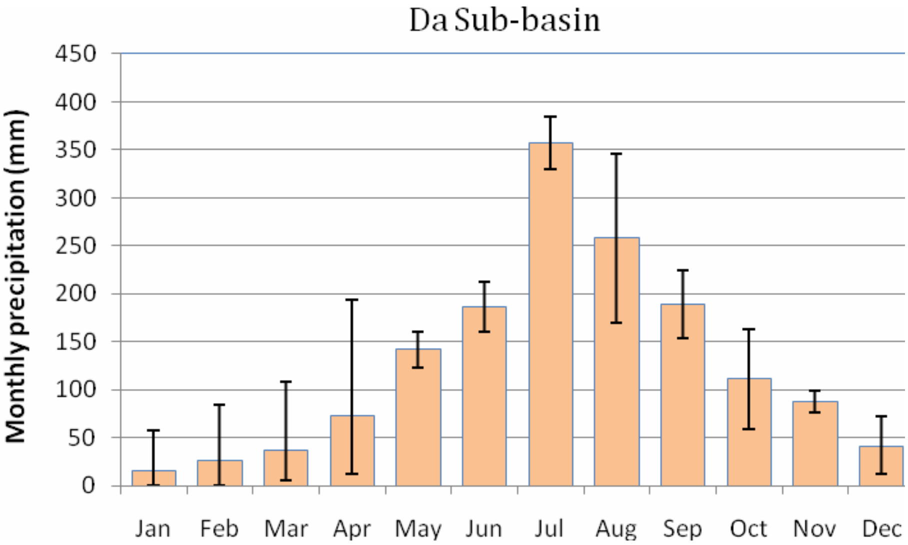


Figure 4-4: Monthly rainfall pattern for central sub-basins

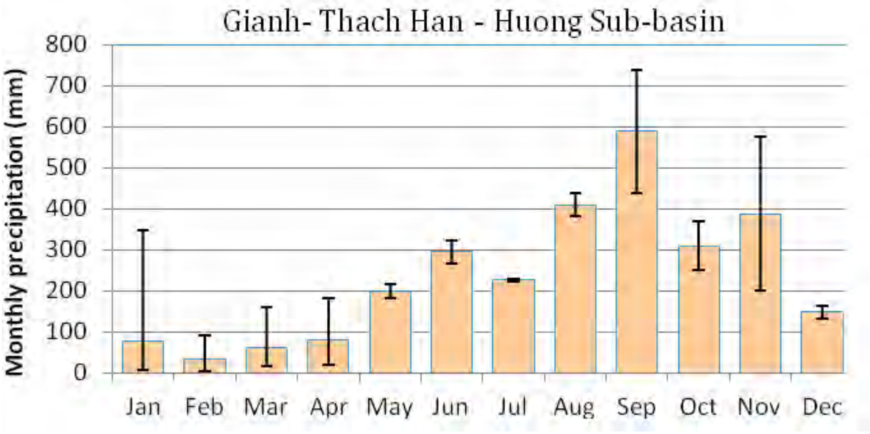
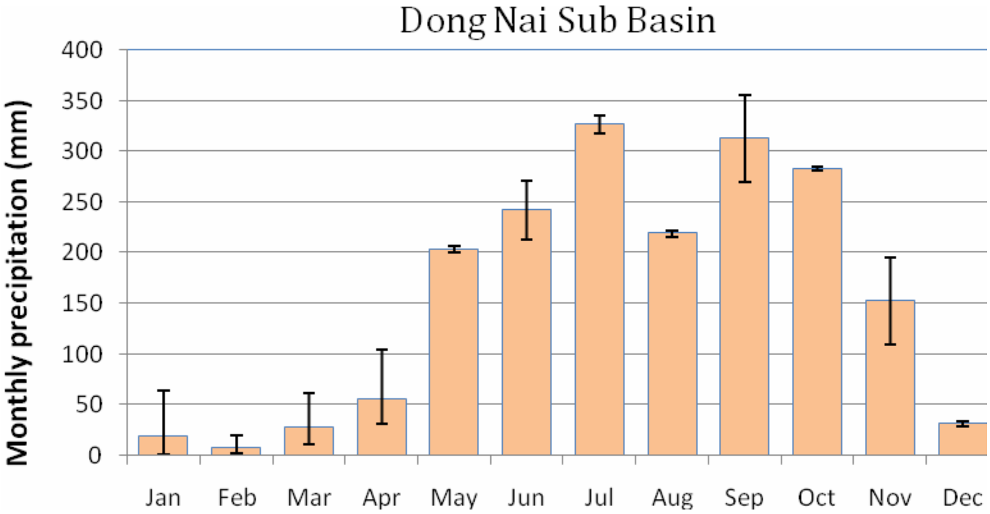


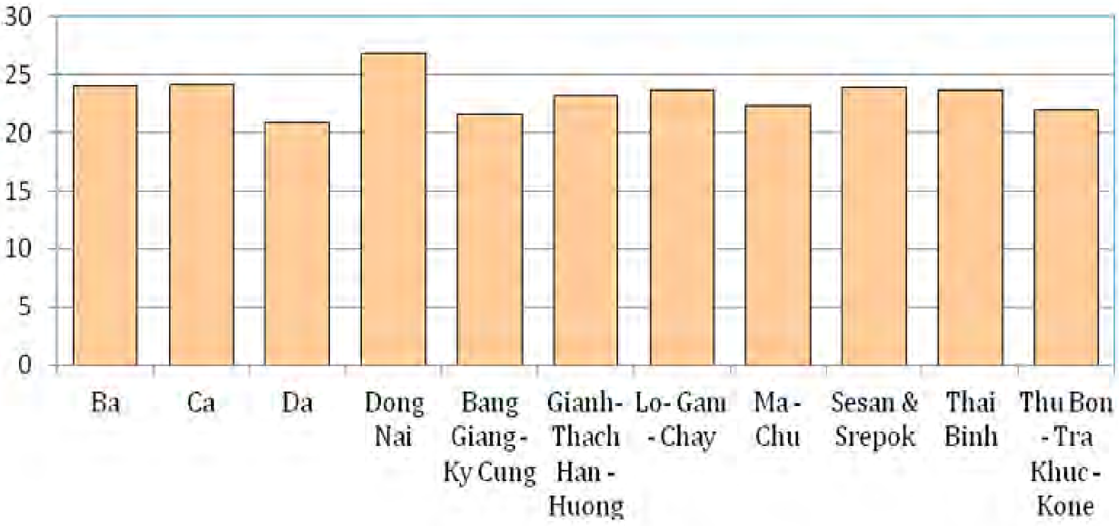
Figure 4-5: Monthly rainfall pattern for southern sub-basins



4.1.3. Temperature

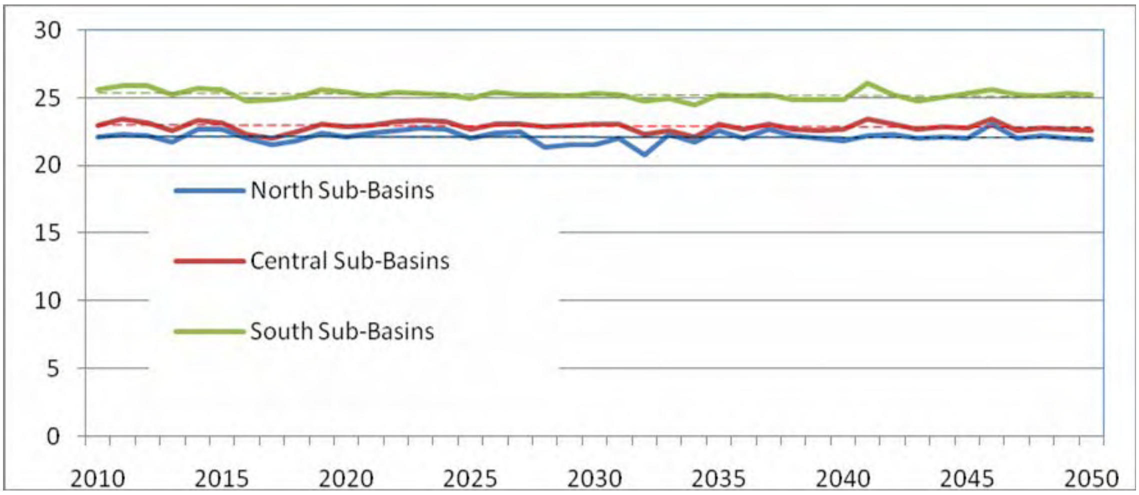
Temperature data is also obtained from the Climatic Research Unit for the historical time period of 1901 to 2000. The gridded dataset is aggregated for the sub-basins. The annual temperature distribution is fairly uniform across the sub-basins (see Figure 4-6), with an average temperature value of 23.3 degrees Celsius. Although there is a slight trend in the rise of temperature, it can be assumed to have stayed uniform. According to the data, temperature has only risen about 0.3 degrees in the past 100 years in Vietnam.

Figure 4-6: Spatial distribution of temperature in degrees Celsius



The historical temperature pattern used for the base case scenario - “No climate change”, for the years 2011 - 2050 is shown in Figure 4-7.

Figure 4-7: Historical temperature pattern projected forward to 2050



4.1.4. Historical Runoff

Runoff data was obtained from the Vietnam Institute of Hydrology, Meteorology, and Environment for the Red River, Thai Binh, and Dong Nai sub-basins. This monthly runoff dataset for the northern sub-basins was obtained for 19 locations covering the time from 1971 to 2005. For the Dong Nai sub-basin, data was obtained for 23 small catchments covering the same time span. In addition to that, gridded monthly average runoff data of 0.5 degrees by 0.5 degrees was obtained from a global runoff database generated by the Global Runoff Data Centre (GRDC). This gridded dataset was aggregated to the 22 sub-basins identified.

4.2. Modelling Surface Runoff - CLIRUN

4.2.1. Methodology

Surface water runoff was modelled with the rainfall-runoff model CLIRUN-II, the latest model in a family of hydrologic models developed specifically for the analysis of the impact of climate change on runoff (Strzepek et al. 2008). CLIRUN-II models runoff as a lumped watershed with climate inputs and soil characteristics averaged over the watershed, simulating runoff at a gauged location at the mouth of the catchment. For this analysis, monthly time step is used to simulate the runoff from weather variables.

CLIRUN-II has simulation and calibration modules. A calibration procedure is used to determine the coefficient values that are specific to the catchment under consideration. Table 4-2 illustrates these calibrated coefficients. Based on observed historical data, the model was first calibrated using 100 years of data covering 1900 to 2000 for each of the selected 22 basins. The calibration procedure gave rise to best estimated values of coefficients for each sub-basin under the preset calibration goal.

Table 4-2: CLIRUN-II model parameters

Model Parameters
Intercept Coefficient
High Temperature Threshold
Low Temperature Threshold
Saturation Value
Lower Layer Thickness
Upper Layer Runoff Coefficient
Lower Layer Runoff Coefficient
Percolation Coefficient
Excess Precipitation Runoff Coefficient

In this analysis, two calibration steps were used based on the two sources of stream flow data available. For the Red River basin and Dong Nai sub-basin, observed stream flow data was available from the Vietnam Institute of Hydrology, Meteorology, and Environment. For the remaining sub-basins, however, GRDC runoff data was the only available source of historical runoff data. Consequently, the Red River basin and Dong Nai sub-basin were calibrated using both datasets. However, the remaining catchments were only calibrated using the monthly average runoff data from GRDC.

After the calibration procedure was finished, the resulting modelled runoff was also checked for any unrealistic runoff by looking at minimum and maximum values. The coefficients obtained as a result of this calibration procedure are then fed to the simulation module to generate runoff corresponding to the climate change scenarios.

4.2.2. Calibration from Observed Stream flow Data and GRDC Runoffs

Out of the 22 level-4 sub-basins, it was possible to obtain reliable runoff data from The Vietnam Institute of Meteorology, Hydrology, and Environment (IMHEN) for eight of these sub-basins. The data spans the years 1971 through 2005 for the northern Vietnamese basins Nam Na, Da, Thaom, Gam, and Pho Day. Within the Red River and Thai Binh River basins at sub-basin outlets, data for two more runoff stations were available in the southern sub-basins in the Dang Nai catchment. In total, we were able to obtain observed runoff data for 10 out of the 22 sub-basins. These 10 sub-basins were calibrated both on observed stream flow data and GRDC global runoff data; the best parameters were selected based on R^2 and model error (the difference between observed and simulated outcomes). Results of the calibration are indicated in Table 4-3.

Table 4-3: Calibration result of catchments with observed stream flow stations

Catchment	**Model Error**	**R-squared**
NamNa - 6	-0.012	65.21%
Da- 7	-0.027	83.01%
Da- 8	-0.027	57.01%
Thao - 9	-0.024	76.07%
Thao -10	0.001	79.55%
Gam- 11	-0.012	80.01%
Pho Day - 21	-0.377	9.48%
Lo- 22	-0.034	79.36%

4.2.3. Calibration from GRDC datasets

The majority of the catchments exhibited a good fit between the observed and simulated runoffs. The observed and simulated monthly average runoffs are shown for the Da, Lo, and Dong Nai Sub-basin catchments shown in Figure 4-8. Table 4-4 presents the outputs obtained from calibration based on the GRDC datasets.

Figure 4-8: Historical observed and Clirun-II simulation results

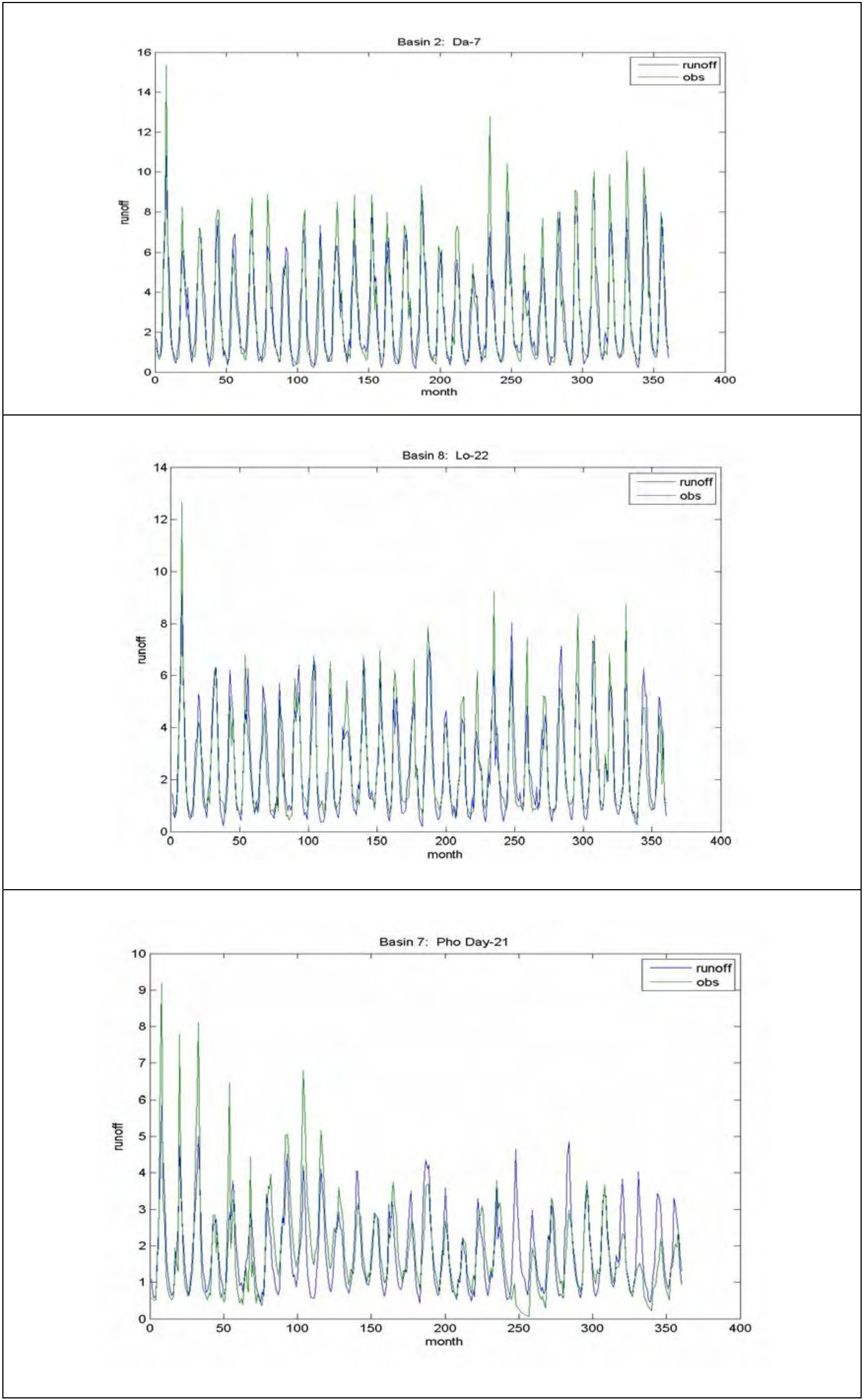


Table 4-4: Runoff model calibration based on GRDC datasets

Catchment Id	Model Error	R2	Catchment Id	Model Error	R2
1	-0.037	94.69%	12	0.000	87.88%
Thai Binh- 2	-0.175	76.24%	Thu Bon	0.083	66.27%
Bang Giang	0.065	91.98%	Dong Nai-14	0.069	89.60%
Sesan & Serepok	0.006	75.20%	Dong Nai- 15	-0.002	93.55%
Thai Binh- 5	-0.105	83.67%	Ma -Chu	-0.015	92.67%
Da (NamNa)	-0.108	82.07%	Ca-17	-0.154	63.46%
Da- 7	-0.009	94.79%	Ca-18	-0.093	82.81%
Da- 8	0.094	88.36%	Gianh- Thach Han - 19	-0.046	86.21%
Thao - 9	-0.047	92.94%	Ba-20	0.022	49.64%
Thao -10	0.003	95.03%	Pho Day - 21	-0.103	76.43%
Gam- 11	-0.012	94.63%	Lo- 22	-0.039	95.18%

4.2.4. Climate change impacts on runoff

Monthly national average runoff for the baseline (1950 - 2000) was used to calculate a percent change in runoff for each basin and each of the 56 climate projections. Box plots of the runoff from all the climate change scenarios are shown in Figure 4-9. Results indicated that the dry season national runoff will generally be reduced, and the wet season peak will be higher than in the base case scenario.

The highest annual runoff, with 20% higher than the base case, and the lowest national annual runoff, 16% lower than the base case, are obtained for GISS GCM eh A1 and UKOM HADGEM B1 scenarios, respectively. Comparison of the results, averaged over 2041 through 2050, is provided in Figure 4-10. Overall, at the national level, the seasonality of runoff and the levels tend not to move dramatically by the 2040s.

Figure 4-9: Monthly average runoff comparison of base case and all the 56 GCM runoff output (2041-2050)

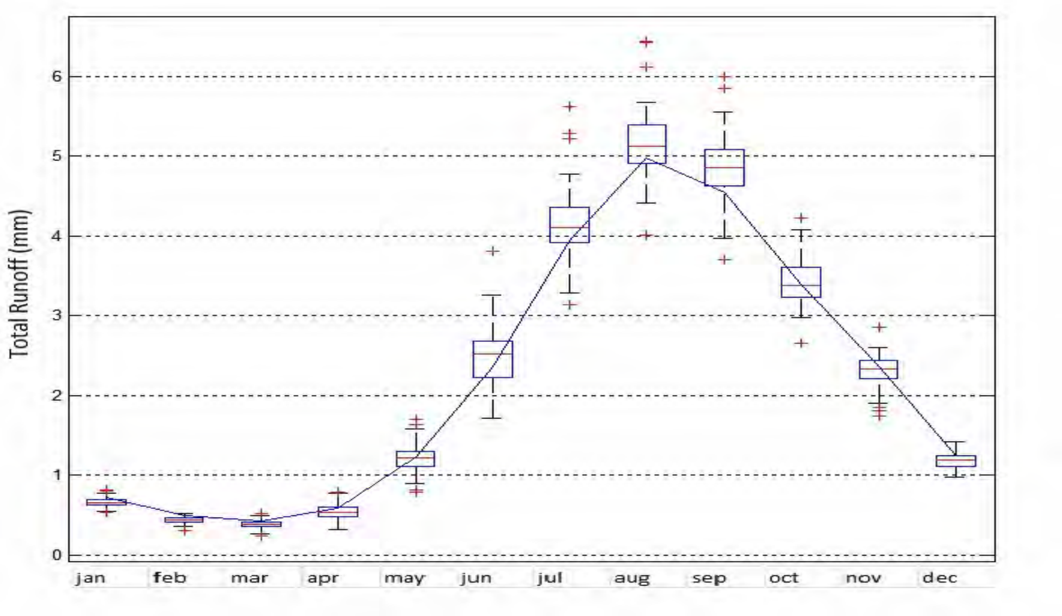
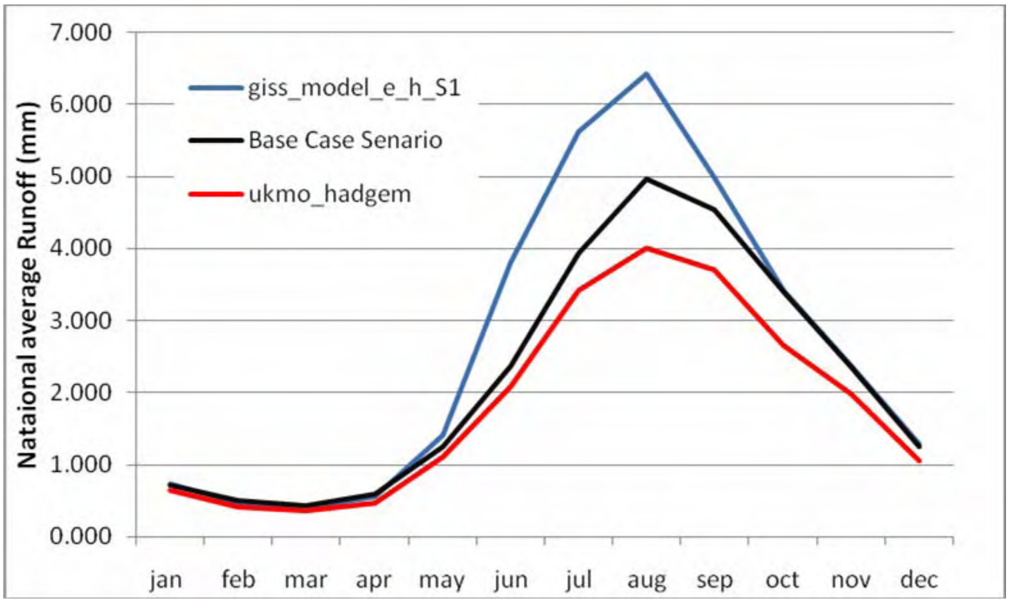
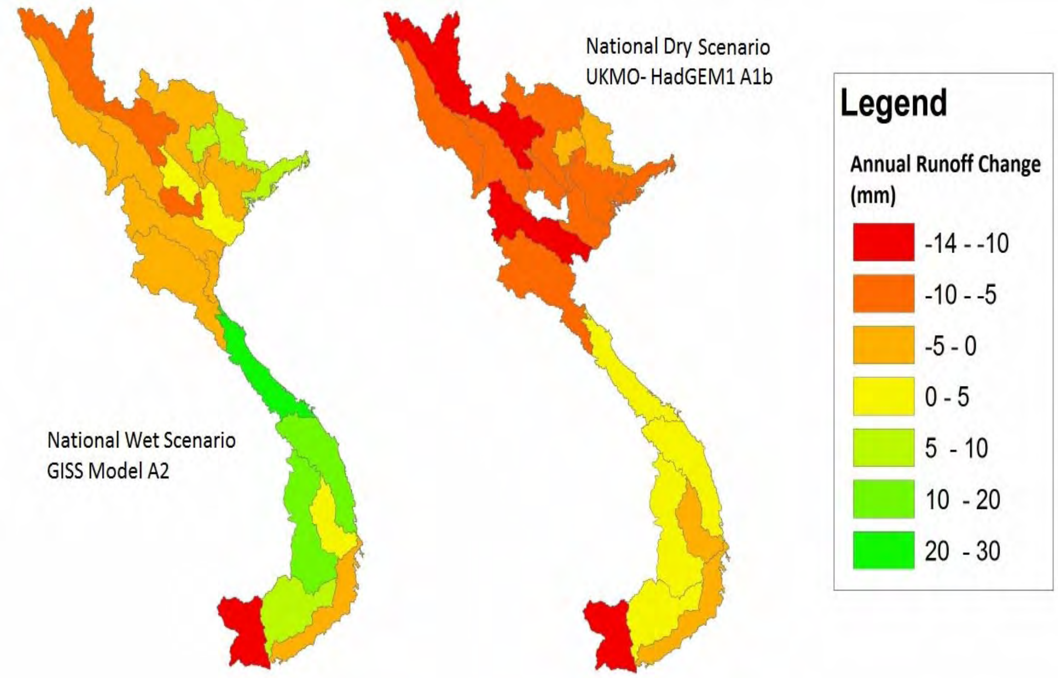


Figure 4-10: Monthly runoff comparison of base case against highest and lowest national annual runoff results of CLIRUN



Even though some of the models have shown higher national average runoff than in the baseline scenario, not all sub-basins are affected equally. On the contrary, the runoff from most of the GCMs shows a decrease in runoff for the sub-basins in the northern part of Vietnam, mainly the Red River basin. For the central and some of the southern sub-basins, however, the runoff has shown to increase in most of the cases. Figure 4-11 shows the spatial distribution of change of runoff for GCMs resulting in national highest and lowest runoffs, and in both cases it shows a pattern of decreasing runoff in the northern sub-basins.

Figure 4-11: Spatial comparison of runoff result for dry and wet scenarios



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

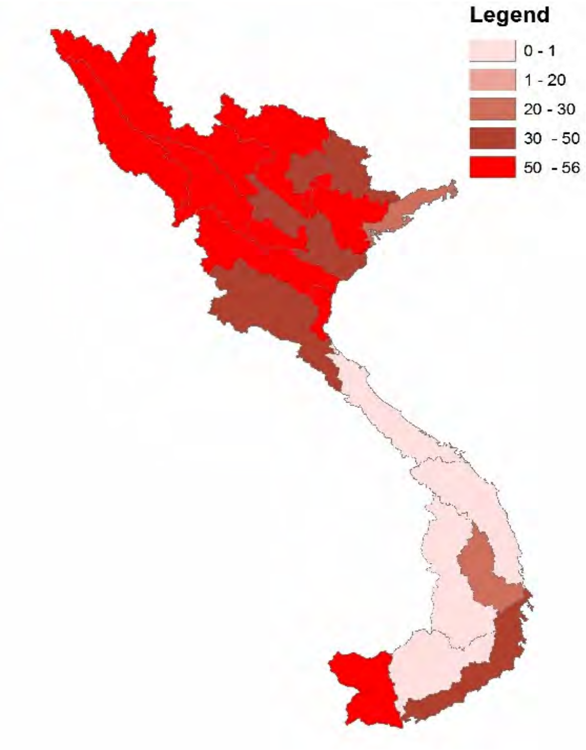
For comparison purpose, the top three CGM models resulting in the highest runoff and the bottom three GCMs giving the lowest runoff by region are shown in Table 4-5. Ukmo_hadgem1 A1B shows a decrease in runoff in all the sub-basins. On the other hand, Cccma cgcm31 A1B shows increases in central and southern sub-basins, but a decrease in the Red River sub-basin.

Table 4-5: Top three GCM model for highest and lowest runoff by region

GCM	Sub-Basins		
	Northern	Central	Southern
Ukmo_hadgem1 A1B	-15%	-14%	-16%
Ipsl cm4 A1B	-10%	8%	6%
Cnrm cm3_A1B	-9%	3%	6%
Giss model er A1	-2%	5%	8%
Giss model er A1B.	-5%	16%	9%
Cccma cgcm31 A1B	-6%	21%	15%

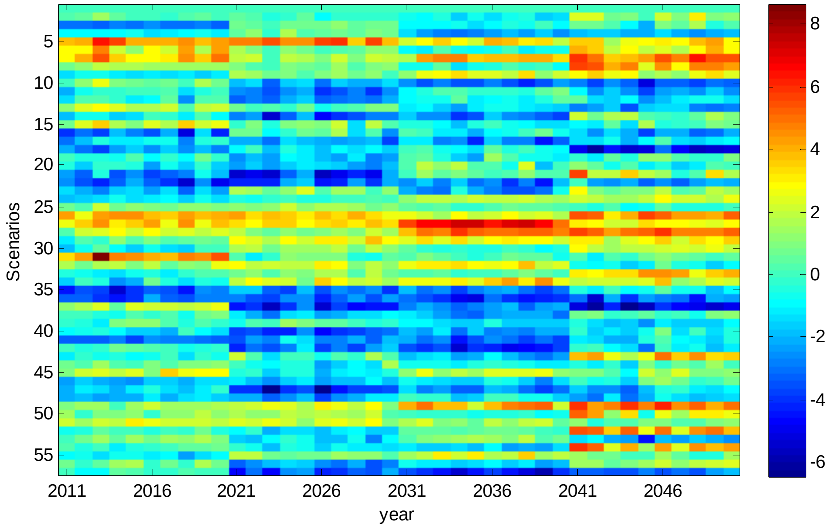
Figure 4-12 reports the number of times less runoff than the Base case is obtained during the 2040s. This figure strongly reinforces the picture of drying in the north. Figure 4-13 is complicated figure that provides an indication of the change in runoff relative to the base case by year and by GCM.

Figure 4-12: Number of times less runoff than the Base case is obtained



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Figure 4-13: Annual Average Runoff Difference from the base case (millimeters)



4.3. Water Resources Analysis: WEAP Model

4.3.1. Methodology and System Modelling

The Water Evaluation And Planning (WEAP) system is a Windows-based decision support system for integrated water resources management and policy analysis. WEAP is a model-building tool, used to create simulations of water demand, supply, runoff, evapotranspiration, infiltration, crop irrigation requirements, instream flow requirements, ecosystem services, groundwater and surface storage, reservoir operations, and pollution generation, treatment, discharge, and in-stream water quality, all under scenarios of varying policy, hydrology, climate, land use, technology, and socio-economic factors.

In this analysis, this model is employed to evaluate the impact of changing runoff and irrigation water demand on the competing demands of water management; growing municipal and industrial (M&I), hydropower, and irrigation water use. Hydropower energy generation and the percentage of unmet consumptive demand are two of the main indicators used for impact assessment on resource utilization.

Normally, the WEAP model is applied by configuring the system to simulate a base-case scenario (i.e., no climate change) for which the resource availability and demands are already determined. The model is then used to simulate plausible futures scenarios. Historical monthly runoff data spanning 40 years (1951 -1991) (described in section 3.5) with no climate change is used for the base case scenario. The alternative scenarios are based on the runoff generated corresponding to the 56 GCMs modelled using CLIRUN-II, as described in section3, and irrigation water requirement outputs computed using CLICROP for the corresponding GCM models.

Schematics of existing and planned water resource development options for the northern catchments, the Red and Thai Binh River basins, and the southern sub-basin, mainly Dong Nai, are provided by the Vietnam Institute of Hydrology, Meteorology, and Environment.

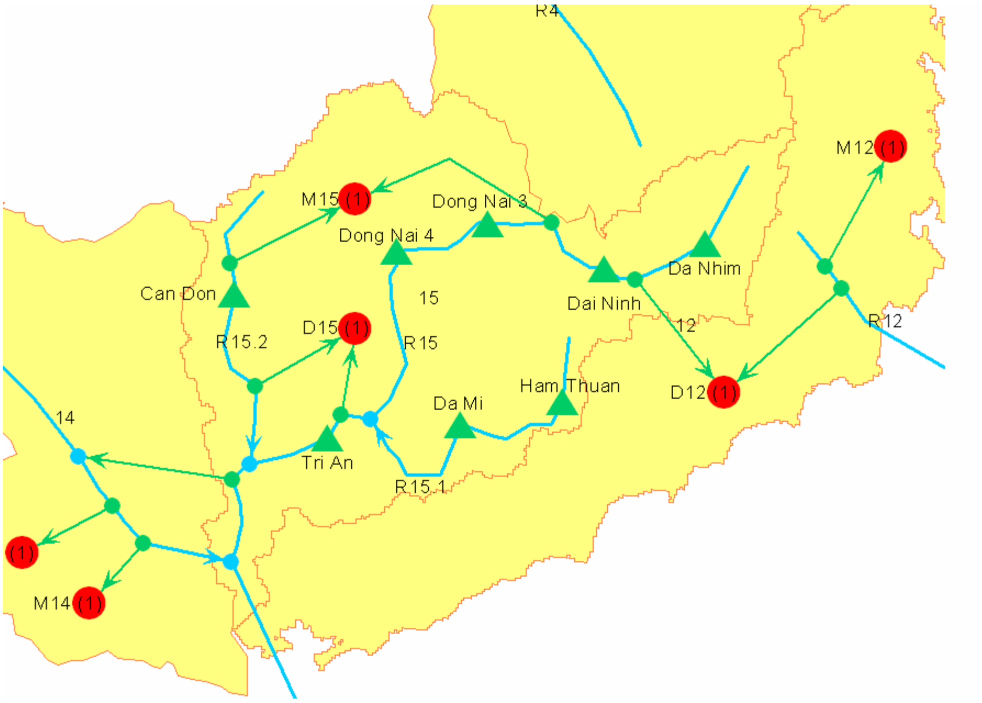
4.3.2. Assumptions and Simplifications

Irrigation Demand: The simplification involved in representing water supply points for irrigation demand is that water transmission links only connect demand sites and rivers within the same sub-basin. This configuration doesn’t consider transfers between sub-basins, and thus special consideration is made for the following cases:

- The link between the Hong and Thai Binh sub-basins, transferring approximately 1/3 of the flow from the Red River before Hanoi.
- Duong River: Transfer from Dong Nai sub-basin to the Dong Thap Muoi catchment.

Since irrigated area could to be distributed over the sub-basin, multiple locations of demand nodes of water extraction for irrigation demand are considered within the same sub-basin. This would simulate the effect of water extraction at different locations in a single sub-basin. This allows the model to allocate the available water in the best possible combination of water extraction. For, illustration schematization of the Dong Nai sub-basin is shown in Figure 4-14.

Figure 4-14: Dong Nai Sub-basin WEAP schematization



With respect to hydropower calculations, WEAP computes hydropower generation from the flow passing through the turbine, based on the reservoir release constrained by the turbine's maximum flow capacity. For river reservoirs, WEAP assumes all water released downstream is sent through the turbines, but water pumped from the reservoir to satisfy direct reservoir withdrawals is not sent through the turbines.

$$Release_H = DownstreamOutflow_H$$

The volume of water that passes through the turbines is bounded by the maximum turbine flow, and if there is too much water, extra water is assumed to be released through spillways that do not generate electricity.

$$VolumeThroughTurbine_H = Min(\ Release_H\ ,\ MaxTurbineFlow_H\ )$$

The gigajoules (GJ) of energy produced in a month,

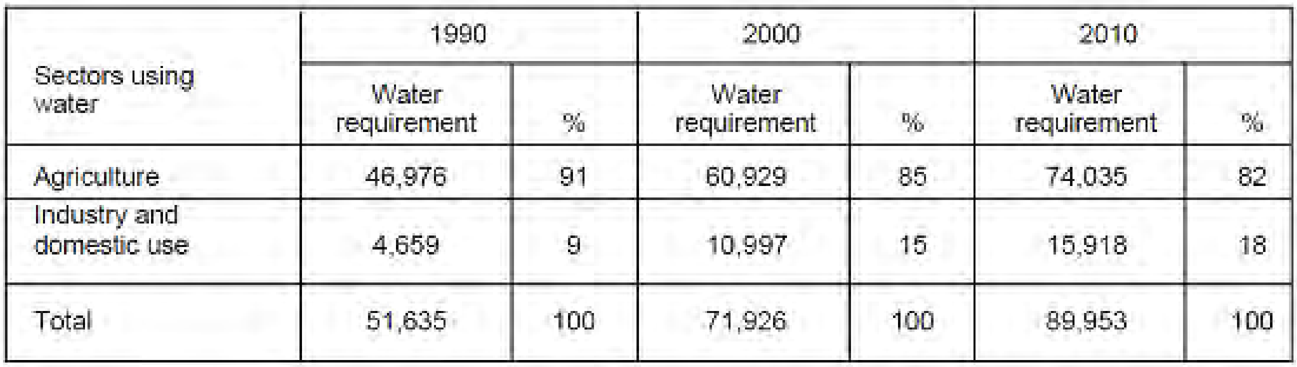
$$EnergyFullMonthGJ_H = VolumeThroughTurbine_H \ x\ HydroGenerationFactor$$

4.4. Water Demands

4.4.1. Irrigation Demand

In Vietnam, irrigation places the largest burden on water resources. The amount of water allocated for irrigation development has risen from 47 BCM to 74 BCM in the last 20 years. Although the percentage of water allocated for irrigation has decreased due to the increased water demand as a result of industrial development and domestic consumption, irrigation is still estimated to account for over 82% of Vietnam’s total water utilization, as illustrated in Table 4-6.

Table 4-6: Trend in water requirement for agriculture and other economic industries (1990- 2010)



Sectors using water	1990		2000		2010	
	Water requirement	%	Water requirement	%	Water requirement	%
Agriculture	46,976	91	60,929	85	74,035	82
Industry and domestic use	4,659	9	10,997	15	15,918	18
Total	51,635	100	71,926	100	89,953	100

Source: The strategy of management and protection of water resource in Vietnam - The Water Resource and Hydraulic Works Department 6/96.

The extent of the area under cultivation was obtained from the Spatial Production Allocation Model (SPAM) dataset developed by HarvestChoice[3]. SPAM provides global estimates of spatial data for crop production, area, and yield for 20 major crops at 5 arc-minute resolutions. SPAM made four spatial products available for public use: harvested area, physical area, production, and yield.

The physical area dataset from SPAM 2000 version 3.0.2[4] was used in this analysis. It was used to obtain distribution of area for each crop. Physical area refers to where a specific crop in a given input system is being cultivated in the year 2000. In this dataset, multiple harvesting seasons in one year are not taken into account. However, the CLICROP output of water deficit accounts for multiple growing seasons.

Data was aggregated by sub-basin to produce annual irrigated area by crop for each sub-basin. Annual irrigated area is about around 7.94 million hectares, in which rice crop accounts for about 46 percent of the total area. The density of paddy rice cultivation obtained from SPAM dataset is shown in Figure 4-15. Figure 4-16 shows the distribution of irrigated area by crop as obtained from the SPAM 2000 dataset.

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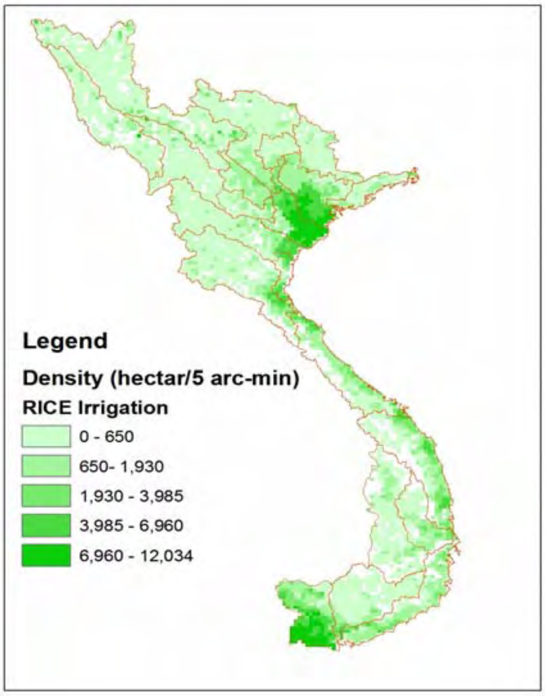
[3] A joint research initiative managed by IFPRI’s Global Food Systems research program and the International Science and Technology Practice and Policy (InSTePP). HarvestChoice generates information to help guide strategic investments in agriculture aimed at improving the well[7] being of poor people in Sub-Saharan Africa through more productive and profitable farming.

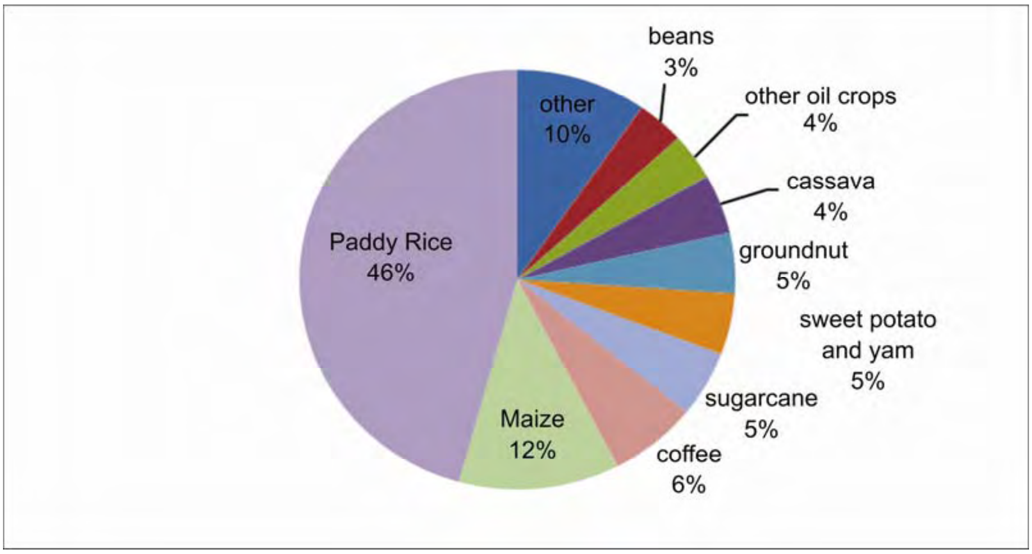
[4] Version 3.0.2 (Version 3 Release 2; April 5, 2010)

Figure 4-15: Density of rice cultivation obtained from SPAM dataset



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Figure 4-16: Irrigation area distribution by crop obtained from SPAM database



The total irrigated area expanded at a rate of 2.9% annually in the period 1980-87, 4.58% between 1988 and 1994, and the latest reports indicate that it has increased by roughly 3.4% on average since 1998 - 2011. However, it was not possible to obtain reliable data regarding future plans for expansion of irrigated area, so this analysis assumed that the maximum irrigation potential of Vietnam, 9.4 Million hectares (FAO 2000), will be achieved by the year 2050. Therefore, the current irrigation area is projected linearly. This gave rise to 0.6% expansion of irrigated area per year.

The CliCrop model was used to predict future irrigation crop water requirements under climate change (see section 3). This model was run for all the 56 climate change scenarios, providing the monthly water deficit for the different kind of crops. This water deficit was multiplied by the irrigation area in each sub-basin to get the total volume of water required for irrigation. Annual water use per hectare was provided by AQUASTAT (FAO 2000), which indicated that irrigation withdraws 77.75 billion cubic meters of water per year. Total water deficit values obtained from CliCrop model indicated an annual irrigation demand of 54 BCM, indicating an irrigation supply efficiency of 70%. Although there is a possibility of enhancing efficiency of irrigation systems in the future, in this analysis, a value of 70% efficiency was adopted uniformly across all scenarios. Box plots for supply requirements are indicated in Figure 4-17 and Figure 4-18.

Figure 4-17: Absolute annual irrigation water requirement and the base case (red line)

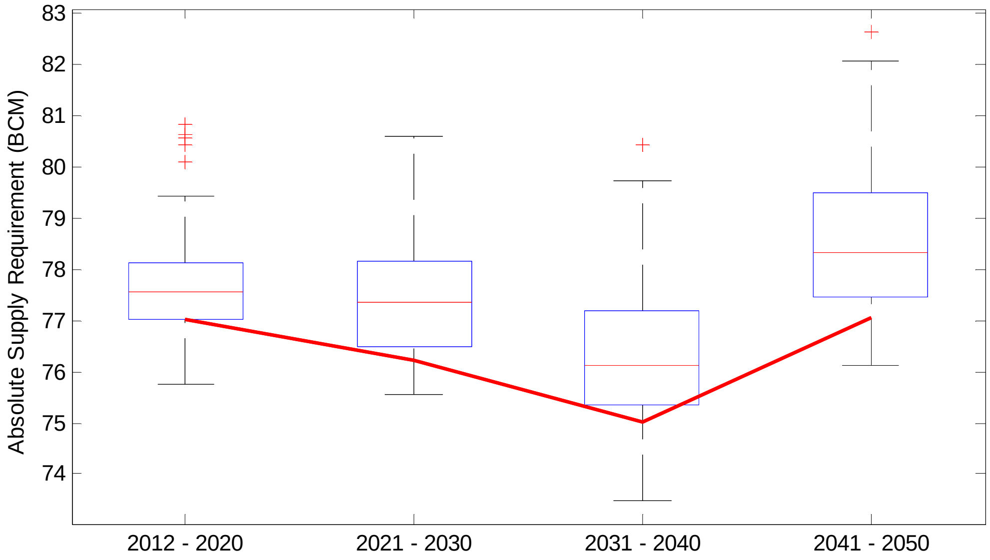
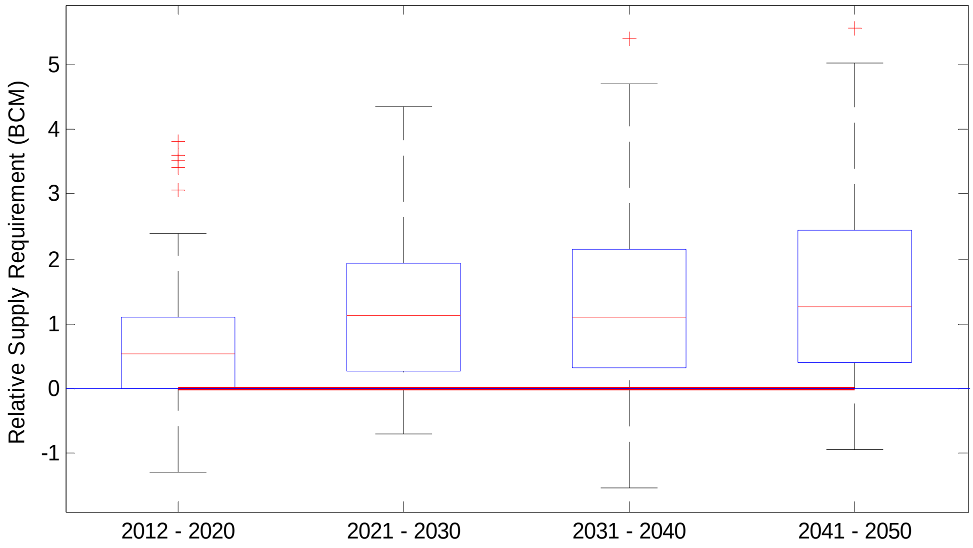


Figure 4-18: Annual irrigation supply requirement relative to the base case



4.4.2. Hydropower

Hydropower is one of the major sources of electricity in Vietnam. The total hydropower generating capacity of existing and under-construction hydropower plants in Vietnam is 10,320 MW. According to Electricity of Vietnam (EVN), this number is expected to grow by 4,760 MW by the end of 2020, increasing the total installed capacity to 14,670 MW.

There are over 14 hydropower power plants operating in Vietnam currently, with 4,577 MW of installed capacity providing, long term, 20,112 GWH of energy per year. This number is about 30% of the total energy potential of Vietnam. The hydropower generating capacity in the sub-basins considered in this analysis is shown in Table 4-7.

Table 4-7: Existing hydropower generating capacity in operation as of 2011

River Basin	Power (MW)	Long term Energy (GWH)
Lo Gam	108	430
Da	1,920	8,160
Ba	70	360
Se San	1,188	5,791
Dong Nai	1,263	5,177
Serepok	28	194
Total	4,577	20,112

The highest generating capacity is in the Da River basin; Hoa Binh Dam accounts for 40% of the total electricity generated in Vietnam. Two more plants are being constructed upstream in the Da River. These are expected to be completed by 2012, increasing the total generation capacity in the Da River basin to nearly double the existing capacity. Table 4-8 summarizes the major hydropower reservoirs considered in the analysis.

Fourteen medium to large hydropower projects invested by EVN and under construction are considered in this analysis. The total long-term energy generation from this hydropower plan is estimated to be about 22,656 GWH. The biggest plant is Son La Hydropower Plant, projected to generate 2400 MW and be completed by late 2012. Table 4-9 and Table 4-10 identify major hydropower projects under construction considered in this analysis by river basin and individually. In addition, EVN has identified 408 potential sites for hydropower plants in the National Master Plan for Small Hydropower Development. These sites range from one to 30 MW of generating capacity, and are capable of generating 13500 GWH for a total capacity of 2,887 MW (PECC1, 2004). This, combined with the existing hydropower and that under construction, will bring Vietnam to 86% of its generating potential.

Table 4-8: Existing hydropower plants: location and generating capacity

Dam	Location	Annual Energy (GWH)
Thac Ba	Lo-Gam	430
Hoa Binh	Da	8160
Song Hinh	Ba	360
Yali	Se San	3650
Se San 3	Se San	1224
Se San 3a	Se San	475
Pleikrong	Se San	442
Thac Mo	Dong Nai	589
Can Do	Dong Nai	290
Hàm Thuận	Dong Nai	957
Đa Mi	Dong Nai	590
Da Nhim	Dong Nai	1025
Tri An	Dong Nai	1726
Dray Hling	Serepok	194

Table 4-9: Hydropower plants under construction by sub-basin

River Basin	Power (MW)	Total Energy (GWH)
Lo-Gam	562	2488
Da	2920	12150
Ba	220	825
Se San	381	1596
Dong Nai	820	2894
Serepok	840	2703
Total	5,743	22,656

Table 4-10: Hydropower plants currently under construction

Dam	Location	ENERGY (GWH)
Tuyen Quang	Lo-Gam	1329.6
Ban Chat	Lo-Gam	1158.1
Son La	Da	10246
Huoi Quang	Da	1904.2
Song Ba Ha	Ba	825
Se San 4	Se San	1401
Se San 4a	Se San	195
Dong Nai 3	Dong Nai	607.1
Dong Nai 4	Dong Nai	1103.8
Dai Ninh	Dong Nai	1,183
Tou Srach	Serepok	347
Buon Kuop	Serepok	1346
Serepok 3	Serepok	815
Serepok 4	Serepok	195

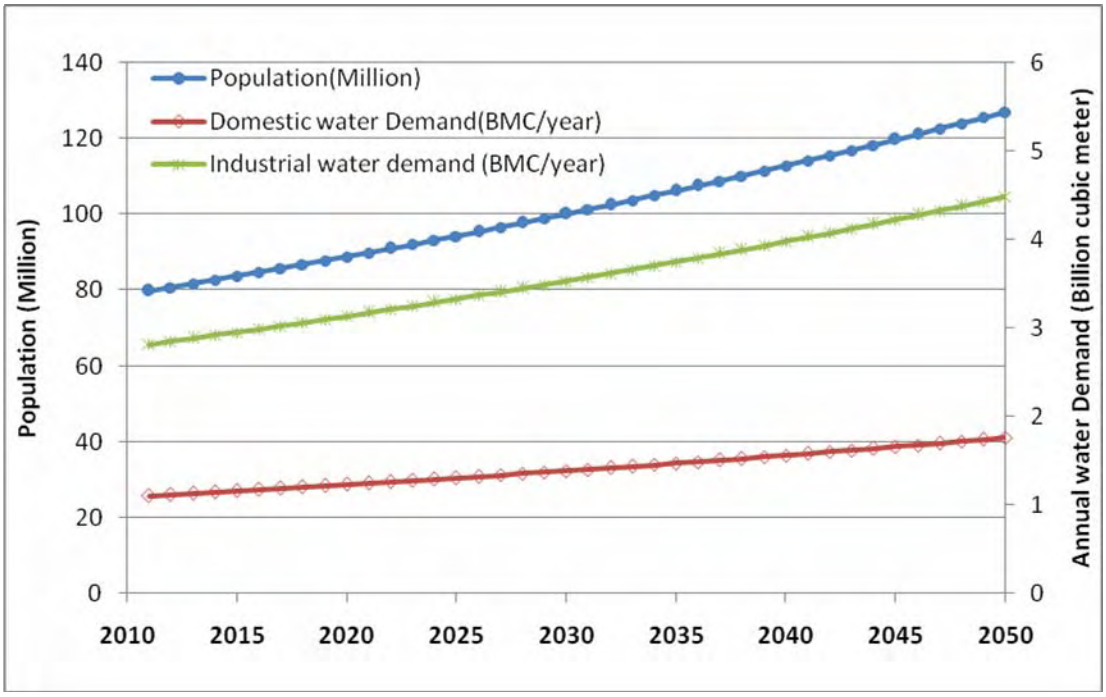
4.4.3. Municipal and Industrial Water Demand

Domestic and industrial water demand data is obtained from AQUASTAT, FAO's global water and agriculture database [http://www.fao.org/nr/water/aquastat/dbase/index.stm, updated in 2011]. Municipal water demand is the annual quantity of water withdrawn primarily for the direct use by the population. It includes renewable freshwater resources as well as potential over-abstraction of renewable groundwater or withdrawal of fossil groundwater and the potential use of desalinated water or treated wastewater. The industrial demand refers to self-supplied industries not connected to the public distribution network, including water for the cooling of thermoelectric plants.

Values of 3.074 BCM/year and 1.206 BCM/year are converted to per capita per year 13.84 and 35.3 cubic meters for domestic and industrial water demand, respectively. These water demands are assumed to be directly proportional to population, and therefore water demand calculation was carried out for each sub-basin according to its total population. These demands are also projected to 2050 following the population growth rate estimate.

Population estimates for each sub-basin are extracted from the 2010 gridded population densities data distributed by the Center for International Earth Science Information Network (CIESIN), Columbia University [http://sedac.ciesin.columbia.edu]. Original raster data is at 2.5 arc-minutes resolution adjusted to match UN totals in persons per square km. This data is aggregated by the 22 sub-basins used in the WEAP model.

Figure 4-19: Population growth and annual industrial and domestic water demand forecast



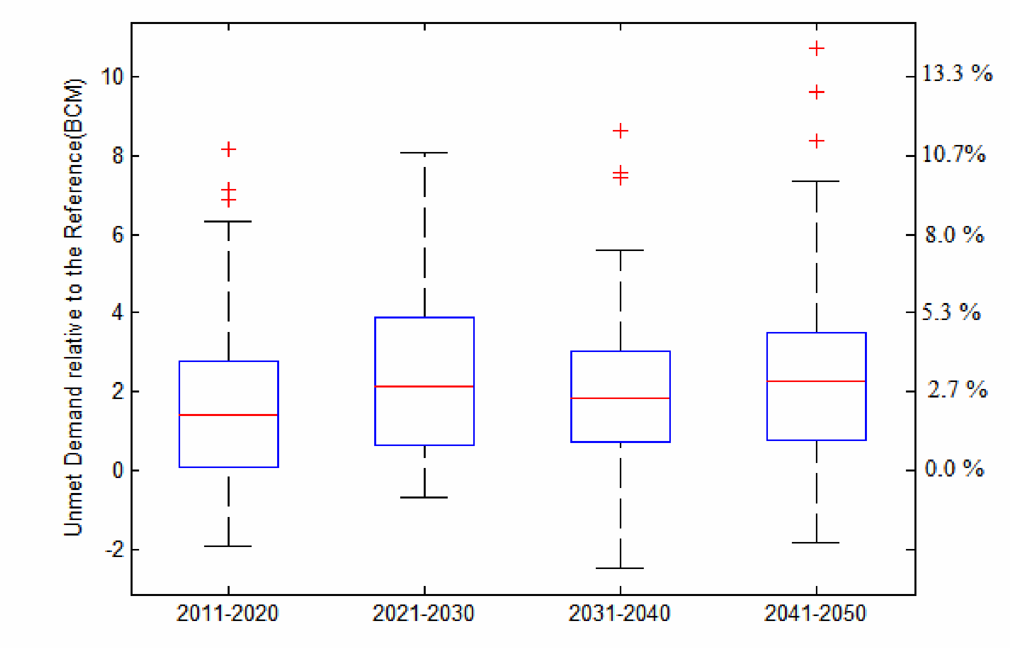
4.5. Results of Water Resource Analysis

4.5.1. Impact on Irrigation

The relative unmet demand result from WEAP analysis was the main indicator used to assess the impact of climate change on irrigation water supply. Under the base case scenario, results indicated that there is already a stress in the system. In the Da and Pho Day sub-basins, a long-term average of 200 million cubic meters annual unmet demand is observed. For the remaining scenarios with climate change, the analysis indicates that the unsatisfied irrigation demand will generally increase in the coming years.

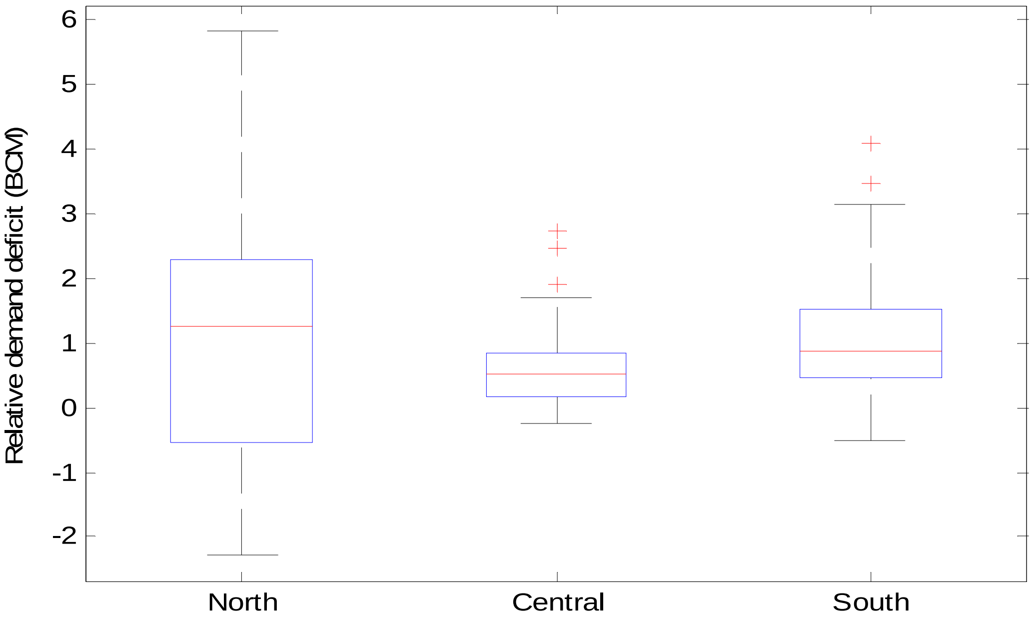
Box plots of unmet water supply for irrigation relative to the reference case for the 56 GCMs is shown in Figure 4-20. The median value reaches about 2.1 BCM for the year 2050. The Worst case scenario indicates a maximum deficit reaching 7 BCM.

Figure 4-20: Unmet Irrigation demand with respect to Base case scenario



As described in the previous sections, climate change will affect the runoff more in the northern sub-basins, mainly in the Red River basin. This is also reflected in the spatial distribution of unmet demand, in which the majority of the deficit is occurring in the Red River basin, mainly as a result of lower runoff in this region, as indicated in the runoff analysis. Furthermore, the range of results is also wider for northern sub-basins, ranging from 6 BCM deficits to 2 BCM excesses with respect to the base case scenario. Figure 4-21 shows relative unmet demand in the three regions for the year 2050.

Figure 4-21: Relative unmet demand in the three regions for the year 2050



Three scenarios corresponding to GCMs that gave rise to maximum, median, and minimum runoffs are compared for relative unmet demand on decadal average in Table 4-11. It can be inferred that even in the case of increased runoff (e.g., the Cccma cgcm31 A1B model) the extra amount of water available during the 2020s will be depleted by the year 2050 due to the gradual increase of irrigation water demand.

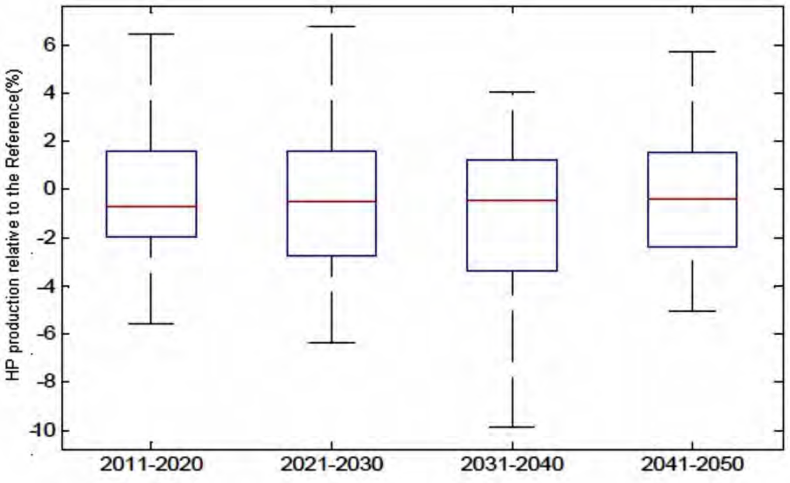
Table 4-11: Ten years average unmet irrigation demand in million meter cubed for selected climate change scenarios

GCM scenario	Location	2011-2020	2021-2030	2031-2040	2041-2050
Minimum runoff - Ukmo_hadgem1 A1B	Northern Catchments	1906	3750	4461	5285
	Central Catchments	1049	1213	1754	1903
	Southern Catchments	1242	794	1424	1516
Median runoff - Inmcm3_0 B1	Northern Catchments	594	715	1498	2341
	Central Catchments	427	397	868	932
	Southern Catchments	684	363	1400	1503
Maximum runoff - Cccma cgcm31 A1B	Northern Catchments	-1900	-1435	-2211	-918
	Central Catchments	-255	78	-457	223
	Southern Catchments	325	574	456	741

4.5.2. Impact on Hydropower

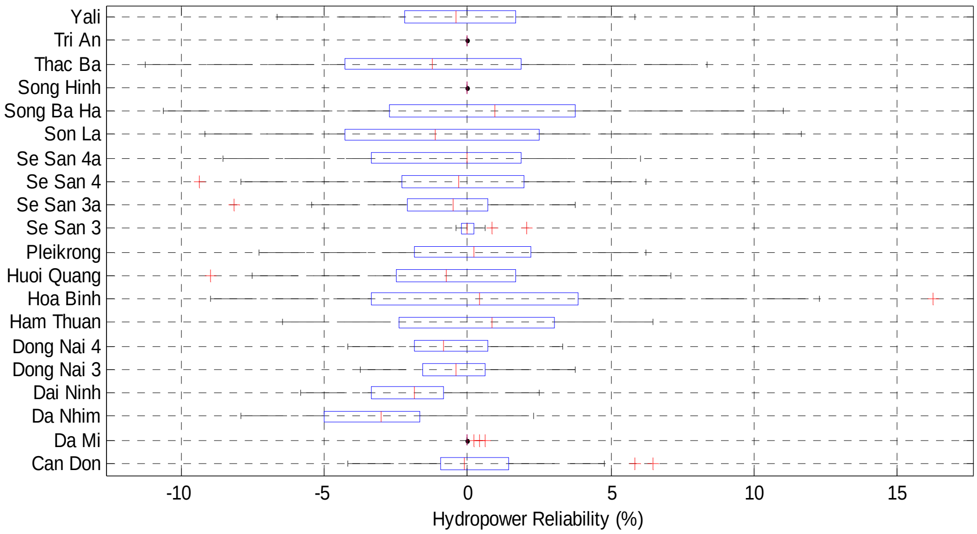
Median hydropower generation shows a slight overall decrease over the climate change scenarios. Overall, hydropower plants' generating capacities will be affected by a maximum of a 14% reduction by the years 2041 to 2050. Percentage of reduction for the 10 year average generating capacity of reservoirs is shown in Figure 4-22.

Figure 4-22: Hydropower generating capacity with respect to the base case scenario (%)



The current existing energy generating capacity after the implementation of all hydropower plants which are currently under construction is about 42.76 TWH. The reliability of hydropower generation to meet this annual demand will also shows high range of variability. Figure 4-23 shows reliability of hydropower for selected Hydropower plants under the 56 climate change scenarios used in this analysis. There is a high uncertainty in the reliability of the big HP plants such as Son La and Hoa Bini ranging within +/- 5 % over the 40 years.

Figure 4-23: Hydropower reliability for selected Hydropower Dams



4.6. Adaptation Mechanism

4.6.1. Northern Sub-basin

The main impacts on water resource in the northern sub-basins are reduced runoff and increased irrigation water requirements. Consequently, the combined effect of reduced runoff and increased irrigation water requirements will results in severe water shortage for irrigation development and failure to meet irrigation demand. Furthermore, hydropower generating capacity in the region will also significantly be reduced.

Agricultural water accounts for a huge share of the water utilization in northern sub-basins, thus implementing efficient utilization of water is essential to reduce future impact of climate change on irrigation demand. Minimization of water loss in the canals and implementation of better water application techniques could significantly reduce the irrigation supply requirement.

EVN has identified several multipurpose reservoirs within this region. The implementation of these reservoirs may serve as storage for the dry season, catering to the reduced hydropower generating capacity and enabling optimized allocation of resources for irrigation demand.

4.6.2. Central and Southern Sub-basins

As mentioned above, most of the GCM runoff results indicated increased runoff for the central and southern sub-basins. In addition, the wet season runoff will be higher, but the dry season flow will be reduced. The combined effect of increased peak flow and higher runoff will intensify natural disasters, creating more frequent floods and more severe flood damage.

Furthermore, reduced dry season flow will also decrease hydropower generation and cause water shortage for irrigation.

Construction of additional multipurpose reservoirs and increasing the system's storage capacity will enable Vietnam's water infrastructure to provide for dry season flow and significantly reduce the risk of flooding. Although impact on irrigation as a result of reduced dry season flow is minimal, efficient utilization of water is essential; increasing irrigation efficiency plays a major role in reducing the future impact of climate change.

Currently, the total water demand for industry and domestic use is 18% (See Table 4-6). In the near future, this water demand will account for a significant portion of resource allocation due to population growth and rapid industrialization. Recycling and usage of an efficient water distribution system will be essential in minimizing the impact of climate change.

5. Road Infrastructure

5.1. Road Infrastructure and Economic Growth

Numerous studies confirm the importance of road infrastructure for economic growth. In a seminal paper, Fernald (1999) examined data for the United States for the period 1953-1989 and concluded that road investments had a significant causal impact on productivity growth during 1953-1973 - the period when the interstate highway system was constructed. The author estimated that public investment, principally in roads, "contributed about one percentage point to total factor productivity growth" (p. 620). To achieve this gain, net road investment exceeded "a quarter of the value of net non-residential private investment" (p. 619). Public road investments therefore contributed to the United States' strong economic performance during the 1950s and 1960s. After 1973, Fernald asserts that the marginal product of road investments declined (i.e., a second interstate highway system is less beneficial than the first).

Developing countries are less likely to face a declining marginal product of road infrastructure investment due to excess supply since road stocks in these countries are often low. Of course, the marginal (and average) product of infrastructure investment can be low for other reasons. Governments can, for example, waste resources constructing poor quality or unnecessary infrastructure. Nevertheless, the empirical evidence is generally favourable to the proposition that public road investments generate reasonable returns. For example, Esfahani and Ramírez (2003) use cross-country panel regressions and find that infrastructure services' contribution to gross domestic product (GDP) is substantial and exceeds the cost of their provision (p. 443). Similarly, Calderón and Servén (2004) find that growth in Latin America is positively related to infrastructure stocks and that income inequality declines with higher infrastructure quantity and quality. More recently, these authors applied the same techniques to Africa (Calderón and Servén 2008) and reached similar conclusions.

A litany of methodological problems haunts the cross-country regression literature (see, for example, Roodman 2009). However, country-level studies are also generally positive. For Vietnam, Mu and van de Walle (2007) find that investment in rural roads has significant average impacts on the development of local markets. Furthermore, they find that, while impacts are heterogeneous across income levels, they tend to be pro-poor. In a study of Nepal, Jacoby (2000) finds that “providing extensive road access to markets would confer substantial benefits on average, much of these going to poor households” (p. 713). Dillon, Sharma, and Zhang (2011) also conclude in their study of Nepal that rural roads are one of the most productive public expenditures. Fan and his co-authors conduct detailed studies to estimate the returns to public investment in China, India, and Uganda (Fan et al. 2004; Fan and Chan-Kang 2008; Fan and Hazell 2001; Fan and Zhang 2008). They consistently find positive returns to road investments, particularly rural roads.

Both theory and evidence therefore suggests that infrastructure investments are important determinants of economic growth and poverty reduction. In most developing countries, these investments represent commensurately large shares of public budgets and total investment. If the stock of public capital in general and the road stock in particular is material to growth and poverty reduction, then the rate of depreciation of that stock is also material. We next review the literature on the implications of climate change for the stock of roads.

5.2. Road Infrastructure and Climate Change

The literature on climate change impacts and adaptation in the infrastructure sector is primarily qualitative, emphasizing broad recommendations and warnings based on general weather studies. Research by the Transportation Research Board in the United States, the Scottish Executives, and Austroads in Australia are notable examples (TRB 2008; Galbraith et al. 2005; AUSTROADS 2004). The authors compare weather-related disasters and their perceived severity with predicted climate change impacts. More focused studies estimate specific impacts of temperature, rain, snow, ice, wind, fog, and coastal flooding on roads (CCSP 2006). Further studies address areas where climate change may threaten infrastructure unique to that locale. For example, Canadian roads are particularly vulnerable to rising temperatures (Industrial Economics 2010). Similarly, northern climates may face greater infrastructure degradation due to increased freeze-thaw cycles (Jackson and Puccinelli 2006).

Mills and Andrey (2002) provide a general framework for considering climate impacts on transportation. They enumerate baseline weather conditions and episodic weather-influenced hazards that determine the environment in which infrastructure is built, maintained and used. The authors note that climate change will alter the weather-related context, affecting the frequency, duration, and severity of hazards. These hazards can affect transportation infrastructure itself, its operation, and the demand for transportation services. The latter might include climate effects on agriculture that alter the location of production and, thus, the need and mode for shipping agricultural products.

A limitation of the above studies is their focus on a narrow potential impact of climate change, and their lack of specific estimates of costs or damages that may result from climate change. In response to this limitation, Chinowsky et al. (2011a) document the potential costs of climate change on road infrastructure in ten geographically and economically diverse countries. They illustrate the opportunity costs of diverting infrastructure resources to climate change adaptation. This response methodology has been extended to estimate climate change impacts on bridges (Stratus Consulting 2010) and roads in northern climates (Industrial Economics 2010).

The relationships mentioned above are incorporated into a dynamic road network simulation model labelled CliRoad. This simulation model tracks the road stock broken by age since construction (or 20 year rehabilitation), road class (primary, secondary, tertiary), road type (paved, gravel, or unpaved), and region for each year over a simulation period from 2007-2050. While the stressor response functions are constant across regions, the climate inputs (precipitation, temperature, and flood events) are disaggregated by region. Because CliRoad is incorporated directly into the dynamic computable general equilibrium model discussed below, some results from CliRoad are left for discussion in section 7.

Vietnam is in the process of improving and expanding all facets of the country's infrastructure. From ports to roads and power, Vietnam recognizes the long-term benefits and the short-term need to enhance the overall infrastructure within the country. Combinations of public and private funds are being pursued to implement these improvements. However, in contrast to traditional approaches to infrastructure development, Vietnam is expanding its concern for construction costs to include mitigating the potential effects of climate change on infrastructure. While these costs are a concern for all countries, these costs are of particular concern in developing countries, where the additional funds needed to address climate change concerns are limited. The limitations on these available funds are challenging developing countries to identify the threats that are posed by climate change, develop adaptation approaches to the predicted changes, incorporate changes into mid-range and long-term development plans, and secure funding for the proposed and necessary adaptations at the commencement of the construction process.

Earlier work by the UNFCCC, IPCC, World Bank and others, have attempted to quantify the impact of climate change on physical assets that will be affected in the coming decades. The current study extends these efforts by addressing the effect of climate change on the road infrastructure within Vietnam as part of the UNU-WIDER Development Under Climate Change (DUCC) research effort. Paved, gravel and unpaved road inventories were selected as the single infrastructure type to evaluate because of their economic, social, and development importance to Vietnam. The infrastructure study examines the extent to which climate change from global and country-specific climate scenarios will divert resources from the further development of road infrastructure to the maintenance and adaptation of the existing infrastructure. The analysis incorporates impacts from climate stressors (precipitation and temperature changes) and projected sea level rise impact of one meter. Because of its significant coastal zones, both types of analyses are important when considering climate change impacts.

The study is designed to create a broader understanding of the effect that climate change may have on facets of development including social, economic, and transport issues by analyzing the road infrastructure. This study expands upon the methodology established in the Economics of Adaptation to Climate Change study conducted by the World Bank that introduced an engineering-based, stressor-response methodology to quantify the impact of climate change on specific physical assets (World Bank 2010a).

The concept of 'Opportunity Cost' is utilized in the study to identify the benefits of adaptation for the country for the projected climatic changes. From this concept, the study provides a context for policy and decision makers to further understand the impacts of future climate change on Vietnam at multiple scales through 2050. In summary, the study is designed to provide a larger context for policy makers to address, in part, the question of "adapt now or later?" Should Vietnam postpone adaptation to potential climate change effects on critical infrastructure?

5.3. Methodology

The analysis of the impacts of climate change on Vietnam road infrastructure requires a combination of Global Climate Model (GCM) future climate projection scenarios, stressor-response degradation analysis, GIS analysis, sea level rise predictions, and cost information within the context of Vietnam and its geography and infrastructure. At the core of this analysis is the use of a stressor-response methodology. The stressor-response methodology is based on the concept that exogenous factors, or stressors, have a direct affect on and subsequent response by, focal elements. In the context of climate change and infrastructure, the exogenous factors are the individual results of climate change including changes to sea level, precipitation levels, temperatures, storm frequency, and wind speeds. The focal elements are the individual infrastructure types including roads, railroads, water and power distribution, and public buildings among others. Therefore, a stressor-response value is the quantitative impact that a specific stressor has on a specific infrastructure element. In this case, the impact on road infrastructure is analyzed as it relates to the overall development effort. The analysis takes a two-phase approach that first determines the appropriate climate effects on the given infrastructure inventory in the selected locations and then determines the cost impacts on this infrastructure based on a set of stressor-response functions.

The first phase of this methodology emphasizes the use of foresight to anticipate potential climate effects that may impact specific infrastructure components in specific regions. The use of this approach is adopted based on the concept that proactive design policies will have greater economic benefit than a reactive approach emphasizing the repair of damages after an event. Using a proactive approach, potential impacts can be identified and adaptations can be put in place at appropriate times and locations. Through the use of multiple climate scenarios, comparisons can be made as to what may be the appropriate level of proactive action based on likelihood of climate events occurring in a given location. Given the uncertainty associated with climate, there is the potential that a proactive approach will result in an overbuilding of infrastructure elements. This "regret" potential is partially offset by the maintenance savings and expanded lifespan that is obtained by enhancing the design policy. This savings is reflected by the Maintenance Savings calculations provided in the current analysis.

The second phase of the methodology emphasizes the use of response functions to determine specific impacts and costs. The response functions are utilized in conjunction with climate stressors to examine response requirements. Specifically, stressors are examined in the context of paved, gravel, and dirt road infrastructure components to illustrate the impact of each stressor on the road infrastructure component based on the intensity of the stressor. The stressors of interest in the study are sea level rise, precipitation, temperature, and flooding. For example, the potential increase in precipitation levels is examined as a specific quantitative impact on unpaved roads in terms of the impact of lifespan based on the degree of increase in the precipitation.

In this manner, the research diverges from a focus on qualitative summaries to an emphasis on quantitative estimates. Flooding, precipitation, and temperature are analyzed on a time-series basis with cost adjustments calculated on a yearly basis through 2050. Sea level rise impacts are analyzed in a uniform one-meter sea level rise due to data limitations. The inundation projection assumes that all roadstock in the area will be completely destroyed. Therefore, costing for sea level rise impacts are determined as the replacement cost for the inundated roadstock.

5.3.1. Parameters of Analysis for Current Study

Within this overall methodology, several parameters have been set in the current study to create an approach that is consistent and comparable when looking at different assets and time periods. First, a consistent and uniform roadstock inventory is used for analysis in all time periods. The existing roadstock is allocated (described below) and utilized for all future analysis. This eliminates uncertainty surrounding planned and actual future construction of new inventory. Second, all figures are shown based on a discount factor of 5% relative to a base of 2010. Third, “Adaptation” options are presented in tandem with “No Adapt” options. These refer to policy choices surrounding climate change and infrastructure investments. The Adaptation option assumes that the future climate is predicted and all new roads being re-surfaced are adequately upgraded to the changes in climate projected during their lifespan. The upgraded roads are then considered ‘climate proof’ against the new impacts of degradation due to increases in precipitation or temperature due to climate change. Normal maintenance schedules are assumed and not counted in the costing, as they would have been performed under non-climate change conditions.

In addition to these base parameters, a consistent set of adaptations are used for each road type and in each scenario. For paved road inventory, the ‘adaptation’ upgrades include a new binder, which is more resilient to increased pavement temperatures. For gravel roads, adaptation upgrades are focused on precipitation and flooding impacts. An upgraded road is resurfaced with crushed gravel mix and a deeper road base is laid. Increased culvert size and capacity is included in the costing mix. Unpaved roads are also analyzed based on the projected flooding and precipitation increases. For unpaved roads, the adaptation option is to upgrade the unpaved (dirt) road to an ‘adapted’ gravel road. The upgrading of an unpaved road to a gravel road provides a maintenance savings, since annual maintenance assumed on the unpaved road is no longer needed. Additional benefits to transport time and cost are not included in the costing analysis.

5.3.2. Climate and Inventory Determination

The analysis for SLR and other climate stressors differ in their climate change impact data source, method of impact determination, and time series application, but the same roadstock allocation methods are used.

5.3.2.1. Division of Road Inventory

The division and allocation of existing road inventory into specific geographical areas is important for analyzing climate variations and impacts on roads in specific administrative areas. Provincial estimates of road inventory were determined based on an allocation process that combined the relative population and area of each province as a percentage of the national total. These relative ratios were then used to determine proportional amounts of road inventory that should be allocated for each province. Due to the lack of GIS spatial data on exact location of roads within provinces and the scale of climate data available, once roadstock is allocated to provincial administrative regions, it is assumed that the roadstock is uniformly distributed throughout the administrative region. This process is summarized in the following equation, where:

$$\mathbf{RA = RN * [((PopA / PopN) + (TA / TN)) / 2]}$$

A = Administrative Region (Province)

PopN = Population, National

PopA = Population, Administrative Region

TN = Total KM2 Land Area, National

TA = Total KM2 Land Area, Administrative Region

RN = Roadstock, National

RA = Roadstock, Administrative Region

The allocation is done for each type of the nine types of road analyzed: Paved, Gravel, Unpaved and Primary, Secondary, Tertiary.

5.3.2.2. Climate Impact Projection Data

Climate change data for the current study was performed with data from two sources: a selection of the IPCC-approved Global Circulation Models (GCMs) for the Climate Stressor analysis, and the *Center for Remote Sensing of Ice Sheets* from the University of Kansas SLR Projections for the SLR analysis. In terms of the GCM data, the GCMs provide climatological data for future climate change scenarios through 2100. The data used in this analysis include the available A2, A1B and B1 scenarios, which represent different scenarios of future development based on the accepted definitions of the Intergovernmental Panels Fourth Assessment Report (IPCC 2007). Further details are provided in section 2.

To provide a robust analysis of possible climate change projections, all GCM data sets approved by the IPCC containing complete data projections for climate and flood data for Vietnam were used in the Climate Stressor analysis on the Vietnam roadstock. In total, 25 GCMs were used for analysis. Each of these climate models contains annual predicted precipitation and maximum temperatures. In an effort to get a broad picture of the potential effects of climate change, the range and likelihood of the low-impact, medium-impact, and higher-impact scenarios were developed in relation to other projections.

To analyze the impact of sea level rise, a data set is used from the *Center for Remote Sensing of Ice Sheets* from the University of Kansas. This data set provides information for a 1 meter or greater projected sea level rise throughout the context of the Vietnam study. The data is provided in a publicly available Geographic Information System (GIS) format. The sea level rise information was used to estimate the percent of each grid cell that would be ‘inundated’ – land completely covered by more than 1 meter of sea level rise. Where inundation was projected, it was assumed that all nine types of roadstock located in an inundated area would be destroyed. The impact function methodology is described in Section 5-4 below.

To ensure that the application of the data was completed accurately, both the sea level rise and provincial mapping of Vietnam were translated into a standard grid system based on latitude and longitude. Climate Research Unit (CRU) grid cells of .5 degree latitude by .5 degree longitudinal (approximately 250km square area) were the basis of this data translation (Climate Research Unit Time Series Version 2.1). The basis of this translation is through an overlay process that translates the geographic information for each province into grid cells. Specifically, the provinces are allocated to grid cells by percentage of geographic area that corresponds to specific CRU grid cells. For example, Administrative Area 1 may be allocated geographically between grid cells A and B at 30% and 70%, respectively. In this case, the province is recorded as having proportional area allocations in each grid location. In a region where detailed road location is not available, the roadstock is then uniformly distributed at the same ratio of 30% and 70%, respectively as the basis for the impact analysis. The result of this allocation process is that the kilometres of road in each province are allocated proportionally on a grid cell level.

5.4. Impact Functions

5.4.1. GCM Climate Impact Analysis: Flooding, Precipitation and Temperature

Utilizing the climate data projected by the GCMs described above and a baseline no-climate change scenario, it is possible to determine the costs and impacts on the individual infrastructure elements based on the stress-response methodology. The authors used an established methodology based on stressor-response functions for precipitation, temperature and flooding in the context of road infrastructure in Africa (Chinowsky et al 2011b).

The stressor-response factors are divided into two general categories; impacts on new construction costs and impacts on maintenance costs. New construction cost factors focus on the additional cost required to adapt the design and construction when rehabilitating an asset to changes in climate expected to occur over the asset's lifespan. Maintenance cost effects are those maintenance costs, either increases or decreases that are anticipated to be incurred due to climate change to achieve the design lifespan. In each of these categories, the underlying concept is to retain the design life span for the structure. This premise was established due to the preference for retaining infrastructure rather than replacing the infrastructure on a frequent basis.

5.4.2. Sea Level Rise Impact Methodology

For this study, the analyses for climate impacts and sea level rise are analyzed separately and on different time scales. The climate stressor impacts of precipitation and temperature is done on a daily basis and results are aggregated to provide decadal numbers to give an overall look at climate impact over the medium-term. Because of lack of available time-scaled data on sea level rise projections, the SLR analysis is done at an instant in time utilizing one impact scenario: a uniform SLR of 1 meter. There are limitations to the robustness of this approach as discussed below. However, utilizing both impacts of climate give a projection and understanding of the potentially diverse impacts of climate change, particularly in coastal areas.

Projections on the amount of sea level rise that will occur in a specific region are uncertain and vary widely. Some recent studies have predicted a future SLR higher than one meter by 2100 (Nichols and Cazenave, 2010). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) published in 2007 predicts an average of 60 cm by 2100 (IPCC 2007). The effects of SLR will not be uniform throughout the world and certain areas will be affected at much greater levels than others (Dasgupta et al, 2008 and Neumann et al, 2000). As has been discussed, Vietnam is particularly vulnerable to SLR.

The SLR impact methodology in this study is based on several assumptions: a uniform distribution of roadstock through the administrative regions; a uniform one meter SLR estimate applied to land at or below one meter elevation; and that all inundated land will require permanent relocation of the roadstock in the area. Costing is applied to the inundated roadstock at the amount required to rebuild the existing roadstock. For example, if 50 percent of a CRU grid cell is projected to be inundated by sea level rise, 50 percent of the roadstock in the cell is estimated to be destroyed. The specific kilometres of road affected will correspond to the initial roadstock allocation from the national -> provincial -> CRU grid cell levels.

Once the kilometres of roads inundated are determined for each grid cell, the determination of costs for replacing these roads is performed. The costs for replacement are based on individual determinations in each grid cell for each road type. In the case of sea level rise, current costing analysis is done using the cost to build a new kilometer of road of each type as shown in Table 5-1. Other adaptation options are not explored with this analysis. The totals for each cell are then combined at a provincial level to provide a total road impact cost.

Table 5-1: Costs of rebuilding inundated roadstock from SLR of one meter

Costs of New Road			
	Paved	**Gravel**	**Unpaved**
Primary	$ 500,000	$ 226,000	$ 128,000
Secondary	$ 150,000	$ 135,000	$ 75,000
Tertiary	$ 70,000	$ 75,150	$ 41,750

5.5. Metrics of Measuring Impacts

The impact of climate change on road infrastructure can be measured in several ways. While total cost is an important metric for policy makers, an additional concern is the relative effect that expenditures being reallocated towards climate change might have on development funding in other critical areas, including road inventory expansion. To provide a set of metrics for understanding the broader impact of climate change, we use three metrics as follows:

- ***Total Cost:*** The estimated costs of climate change impacts with a 5 percent discount rate applied.
- ***Opportunity Cost:*** The amount of paved road inventory that could have been built with the funding that is diverted to climate change costs. The opportunity cost is calculated by first taking the amount of money required for climate change response divided by the cost of a kilometre of paved secondary road, and then using that amount divided by the existing paved road inventory. This gives a percentage of paved road inventory that could have been increased if funds were not allocated to climate change response.
- ***Adaptive Advantage:*** The benefit in percentage savings between the Adapt and No Adapt policies.

Using these three metrics, the study results are presented for both a proactive Adapt approach and a reactive No Adapt approach. For the adaptation approach, a third consideration is presented, the concept of maintenance savings which indicates the amount of standard maintenance that will be saved if an adaptation approach is adopted. These categories are detailed as follows:

Adapt and No Adapt: Two different policy approaches are examined for all road types and climate projections. The "Adapt" analysis assumes perfect foresight with respect to climate change impacts and a policy that applies these forward-looking climate projections to upgrade new roads as they are re-built and maintained. The Adapt Policy scenario incurs up-front costs to adapt a road to mitigate future damages that are projected from increases in precipitation or temperature. For unpaved road infrastructure, roads are upgraded to an adapted gravel road and therefore are less susceptible to increased precipitation impacts. The "No Adapt" analysis assumes no adaptation changes are put in place. Roads are rebuilt according to previous baseline standards. The costs incurred are from increased maintenance necessary to retain the design life of the original road as degradation of the road infrastructure occurs from climate change stressors.

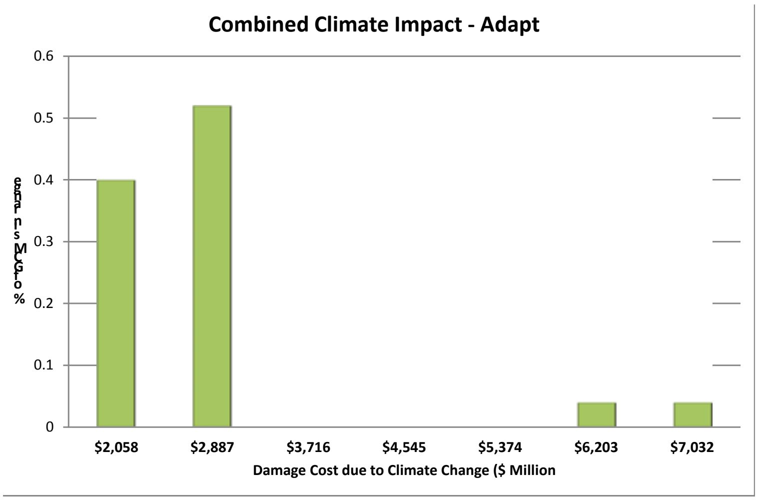
Maintenance Savings*:* The Maintenance Savings category is included to emphasize the costs and benefits associated with adaptation in Vietnam. This metric is applied to unpaved (dirt) roads. Many of the costs related to an unpaved road network are related to precipitation damage or traffic levels. Upgrading these roads to gravel surfaces can reduce the annual maintenance requirements since gravel has greater resistant to both precipitation and traffic. Therefore, the Maintenance Savings category represents both the savings in traditional maintenance that would have been required for the dirt surfaces, together with the additional maintenance that would be required due to increased precipitation from climate change

5.6. Study Results

A combined analysis of the flooding and climate (precipitation, temperature) impact on the road infrastructure of Vietnam provides a picture of potential climate impact through 2050. The numbers presented in this section are for total cost of impact on new construction, maintenance and repairs, for the existing road inventory from 2010-2050. An analysis of the Adapt and No Adapt policy are provided. The median GCM is a reflection of the GCM that is an 'average' of the 25 GCMs run. However, as discussed below, the results displayed in the histogram indicate that the GCMs are not evenly distributed throughout the range. Therefore, depending on the concern of policy maker, the extremes or quartile numbers may be more appropriate than the median.

As Figure 5-1 indicates, the majority of climate projections (92%) project an impact after adaptation of no more than USD$2.9 billion dollars when discounted. Only two GCMs project extreme climate impacts with a total cost greater than USD$7 billion. Even at the lowest projections, the USD$1.2 billion cost impact has an opportunity cost of 32%, indicating that more than 24,000 KM of secondary, paved road could be built with the money diverted to climate change under the lowest, adaptation scenario. The minimum combined Adapt projection is an impact limited to climate stressors (precipitation and temperature); the minimum flooding-specific GCM analysis has no increased impact on the roadstock.

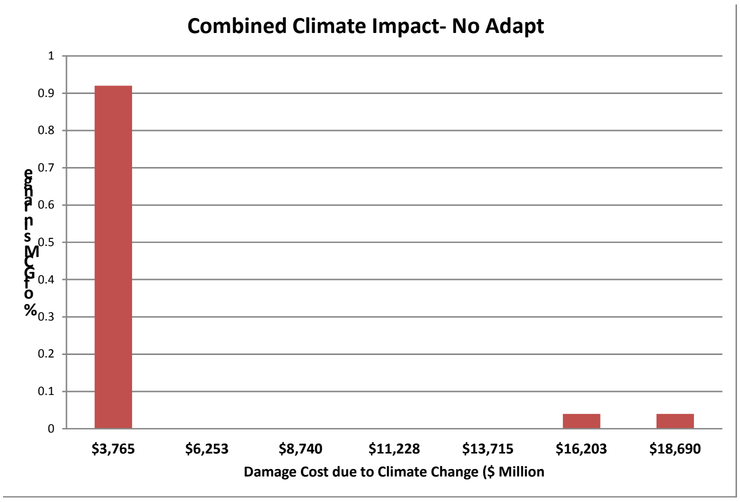
Figure 5-1: Histogram of combined climate impact on road infrastructure through 2050



The uneven distribution of the combined costs (majority of the GCM cost predictions lie in the lowest two categories) is due to the uneven distribution of Flooding Impact data as discussed below. Because the combined climate change impact numbers are the combined flooding and climate stressor costs, this uneven distribution is carried through to the combined analysis.

Similar to the Adapt analysis, 92% of the GCMs (22 out of 25) in the No Adapt scenario are in the lower two distributions of the histogram (Figure 5-2). This indicates that only a few of the GCMs project more extreme climate impacts. The minimum cost impact for the No Adapt scenario is a USD$49 million increase in cost over the Adapt scenario. Similarly, the median and maximum GCM results reflect an increase over the adapt scenarios of USD$660 million and USD$11.6 billion, respectively. In this case, the adaptive advantage indicates that policymakers should consider a proactive approach to adapting to climate change. In the maximum scenario, the No Adapt approach has an opportunity cost of 482%, the equivalent of 367,000 KM of new, secondary paved road that could be built if costs were not diverted to climate change. The median GCM has an opportunity cost of 92%, the equivalent of over 70,000 kilometers of new, secondary, paved roadstock.

Figure 5-2: Histogram of combined climate impact on road infrastructure through 2050



Maintenance savings provides an important analysis tool for further understanding the benefits of the adaptation policy approach. Particularly, because there is a cost incurred in the upgrading of dirt and gravel roads, it can be largely offset economically by the savings from yearly maintenance required on lower-quality road infrastructure. When Maintenance Savings is incorporated into the Adaptive Advantage, the savings is nearly tripled, to a total of USD$2.0 billion. The social and economic benefits derived from an upgraded road infrastructure should also be accounted for in a local analysis and decision-making process.

In Table 5-2, the 'Median' GCM analysis has an Adaptive Advantage of USD$4.8 billion. This savings is the difference between the No Adapt and Adapt policy costs. When maintenance savings are incorporated into this advantage, the savings are nearly doubled to a total of USD$9.3 billion. This highlights the potential benefits derived from a proactive adaptive policy approach. For the ‘Minimum’ GCM analysis, the relative Adapt cost is lowered from USD$3.6 billion to USD$1.9 billion including maintenance savings. Maintenance savings lower the relative Adapt cost and raise the Adaptive Advantage in all scenarios that present a savings incurred between the Adapt and No Adapt policies. Certain GCMs (not shown) do not present a difference in Adapt and No Adapt costs. This result is primarily based on climate stressor impacts in these scenarios being derived from single events where post-event repair costs are equal to or less than the costs of proactive adaptation. An example is the MIROC3_2(medres)_A2 GCM where the cost of adaptation equals the cost of reactive maintenance. However, even with this GCM a benefit is derived from Adapting to the Flooding projections (USD$78 million). These varying levels of benefit display the need for a comprehensive analysis of potential impacts that include the potential multiple impacts of climate change on the road infrastructure.

Table 5-2: Adapt and No Adapt Costs and Adaptive Advantage for Combined Climate Change Impact (Precipitation, Temperature, Flooding)

ADAPT					**Adaptive Advantage**	
Rank	**GCM**	**Cost (USD$ Million)**	**Opportunity Cost**	**Maintenance Savings**	**(USD$ Million)**	**Opp. Cost**
Maximum	a1b_ipsl_cm4	$ 7,032	141%	$ -	$ 11,658	341%
Median	a1b_inmcm3_0	$ 2,225	51%	$ 1,586	$ 660	42%
Minimum	a2_bccr_bcm2_0	$ 1,229	32%	$ 453	$ 49	5%

NO-ADAPT			
Rank	**GCM**	**Cost (USD$Million)**	**Opportunity Cost**
Maximum	a1b_ipsl_cm4	$ 18,690	482%
Median	a2_gfdl_cm2_1	$ 2,885	92%
Minimum	a2_bccr_bcm2_0	$ 1,278	37%

5.6.1. Temperature, Precipitation and Flooding Results

5.6.1.1. Climate Impact on Road Infrastructure: Precipitation and Temperature

The disaggregation of the overall climate impact numbers highlights the potential effect of precipitation and temperature on the climate costs. As illustrated in Figure 5-3 and Figure 5-4, the impacts are distributed throughout the Adapt and No Adapt scenarios. Both Adapt and No Adapt have similar costing impacts, which are reflected in the Adaptive Advantage of 5-10% from the minimum and maximum GCM impact scenarios (Table 5-3). The Adapt scenario has an almost even distribution, with 12% of the GCMs in the lowest two categories (less than USD$1.57 billion) and 16% of the GCMs in the highest category (greater than USD$2.44 billion). The remaining GCMs are fairly evenly distributed throughout the total cost (Figure 5-3). The No Adapt impact analysis has a slightly more end-weighted distribution, with 36% and 28% distributed in the first two and last two categories, respectively (Figure 5-4).

Figure 5-3: Histogram of climate (precipitation and temperature) impact on road infrastructure through 2050 - Percent of GCMs with respective impact results

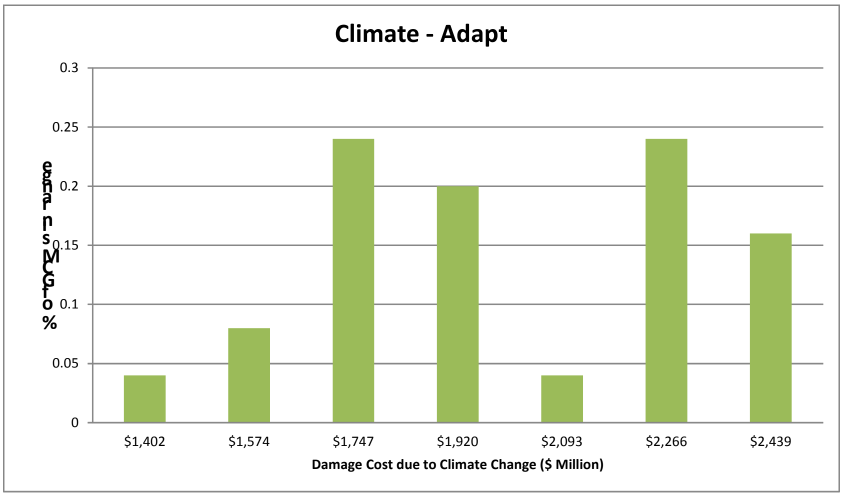


Figure 5-4: Histogram of climate (precipitation and temperature) impact on road infrastructure through 2050 - Percent of GCMs with respective impact results

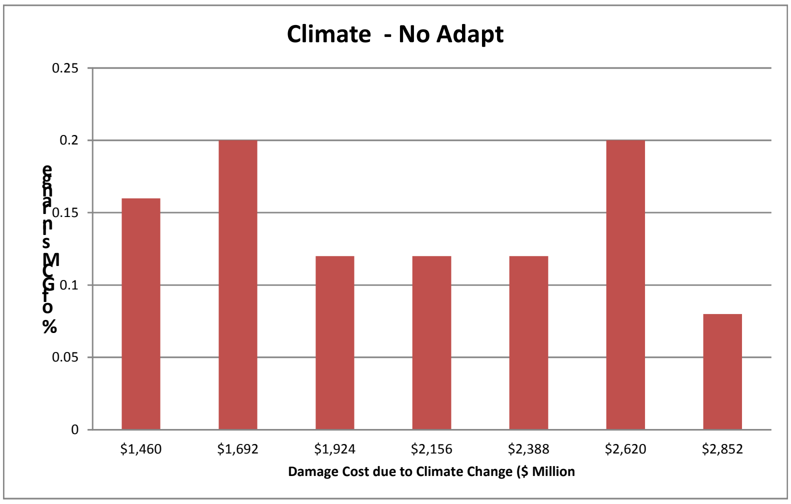


Table 5-3: Adapt and No Adapt Costs and Adaptive Advantage for Climate Stressor Impact on Roadstock (Precipitation, Temperature)

ADAPT					**Adaptive Advantage**	
Rank	**GCM**	**Cost (USD Million)**	**Opportunity Cost**	**Maintenance Savings**	**(USD Million)**	**Opp. Cost**
Maximum	a1b_ccma_cgcm3_1	$ 2,439	66%	$ 1,362	$ 413	10%
Median	b1_inmcm3_0	$ 1,892	51%	$ 946	$ 61	5%
Minimum	b1_miroc3_2_medres	$ 1,549	32%	$ 843	$	
NO-ADAPT						
Rank	**GCM**	**Cost (USD$ Million)**	**Opportunity Cost**			
Maximum	a1b_ccma_cgcm3_1	$ 2,852	76%			
Median	a2_gfdl_cm2_1	$ 1,953	56%			
Minimum	b1_miroc3_2_medres	$ 1,228	37%			

The flooding impact on the road infrastructure of Vietnam is weighted towards the lower predictions, with 88% and 92% of the predictions in the lowest two categories for the Adapt and No Adapt analyses, respectively. In both analyses, the IPSL_CM4_A1B GCM is the maximum cost impact because of its higher projections of flooding increases relative to the other GCM comparisons.

Under both analyses, seven of the GCMs predict no flooding cost impacts. This indicates that these GCMs predict no flood events larger than the equivalent of a 15-year flood which is considered the design baseline for the road infrastructure. The Adapt maximum impact scenario has a cost of USD$4.6 billion, an opportunity cost of 75% or 57,000 KM of new, secondary, paved roads. The No Adapt maximum impact scenario is considerably higher at USD$16.2 billion. The distribution of the GCM results for the No Adapt scenario is heavily weighted into the first category (92%), but the range of the highest two GCMs may raise a concern for policymakers looking at the potential worst-case climate change impact scenario.

When looking at the maximum impact scenario, there is an adaptive advantage of 341% - the equivalent of nearly 260,000 KM of new, secondary, paved road network. There are 2 GCMs that predict high impact costs for flooding in both scenarios. However, this scenario must be considered in relation to the minimum scenarios which indicate no impact from flooding. This can be seen in Table 5-4.

Table 5-4: Adapt and No Adapt Costs and Adaptive Advantage for Impact of Flooding on Roadstock

<table>
<tr><th colspan="4">ADAPT</th><th colspan="2">Adaptive Advantage</th></tr>
<tr><th>Rank</th><th>GCM</th><th>Cost
(USD Million)</th><th>Opportunity Cost</th><th>(USD Million)</th><th>Opp. Cost</th></tr>
<tr><td>Maximum</td><td>a1b_ipsl_cm4</td><td>$4,625</td><td>75%</td><td>$11,658</td><td>341%</td></tr>
<tr><td>Median</td><td>a2_ccma_cgcm3_1</td><td>$14</td><td>10%</td><td>$21</td><td>29%</td></tr>
<tr><td>Minimum</td><td>Multiple</td><td>$-</td><td>0%</td><td>$-</td><td>0%</td></tr>
<tr><th colspan="4">NO-ADAPT</th><td colspan="2" rowspan="5"></td></tr>
<tr><th>Rank</th><th>GCM</th><th>Cost
(USD Million)</th><th>Opportunity Cost</th></tr>
<tr><td>Maximum</td><td>a1b_ipsl_cm4</td><td>$16,283</td><td>416%</td></tr>
<tr><td>Median</td><td>a2_giss_model_e_r</td><td>$35</td><td>38%</td></tr>
<tr><td>Minimum</td><td>Multiple</td><td>$-</td><td>0%</td></tr>
</table>

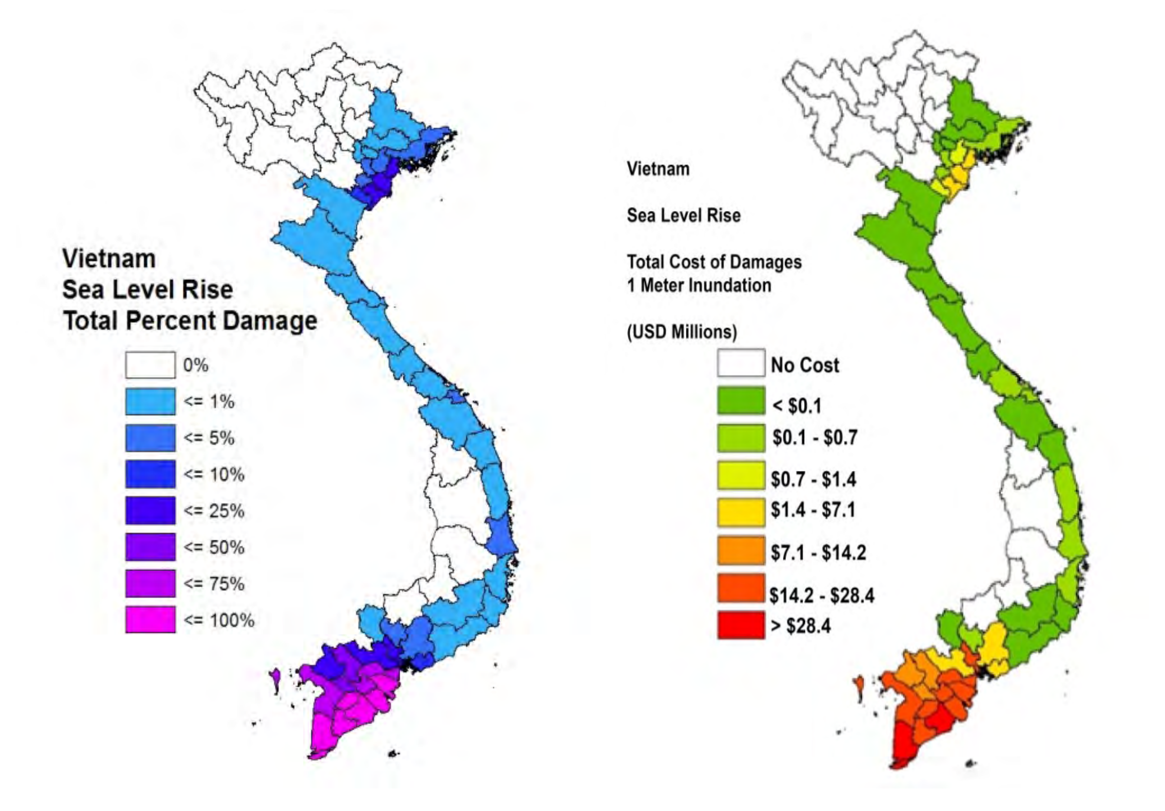
5.6.2. Sea Level Rise Results

The study results presented here are based on a one meter sea level rise which is the basis of the inundation data adopted for the study. A sea level rise of one meter will affect the existing estimated road infrastructure in Vietnam at an extent of 19,000 KM of road infrastructure inundated and destroyed; just under 12% of existing road infrastructure. This is a cost of approximately USD$297 million in discounted 2010 dollars to replace the inundated infrastructure (Table 5-5). The projected sea level rise is distributed unevenly, with the majority of damages affecting coastal regions in the Southern part of the country. There are several provinces where a complete inundation is projected, resulting in a loss of at or near 100%. These include Bac Lieu, Hau Giang, Soc Trang, Tra Vinh and Ca Mau. The ten most affected provinces are located in the Mekong River Delta region and have an average of 77% of road infrastructure destroyed, a total of nearly 15,200 KM. Figure 5-5 illustrates the percentage damage and total cost estimates at both regional and provincial levels.

Table 5-5: Total SLR Damages from 1 meter SLR. Discounted to 2010 costs at 5% discount rate

	Total % Damage	Total Road Damage	Paved Primary	Paved Secondary	Paved Tertiary	Gravel Tertiary	Unpaved Tertiary
Total Damage (KM)	12%	19,142	1,621	3,775	3,719	9,024	1,003
Total Damage ($USD Million)	-	$ 297	$ 115	$ 80	$ 37	$ 54	$ 11

Figure 5-5: Depicts the Total Percent Damage and Total Cost of Damage estimated for one meter SLR by provincial administrative region



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

5.6.3. Regional Level Results

Vietnam is a diverse country with geography ranging from coastal lowlands to higher plains and mountainous terrain in the North. Because climate change affects these areas differently, especially SLR impact, a regional level analysis provides a greater understanding of the areas potentially affected by climate change. In the case of Vietnam, the difference between Adapt and No Adapt policies provides an example of the effect planning and forward preparation to climate change can have on mitigating the impacts.

For regional analysis, two GCMs were selected to represent the higher and median impact. Respectively, these are CNRM_CM3_A1B and MPI_ECHAM5_B1. These were selected because they represent the maximum and median temperature impact increases. Their respective results are displayed at the Regional level below (Table 5-6; Figure 5-6; Table 5-7; Figure 5-7). In all regions, the Adapt policy approach has a lower total and opportunity cost than the No Adapt approach. The following sections highlight these effects in each of the geographic regions within Vietnam.

Table 5-6: Regional analysis (maximum hot climate scenario)

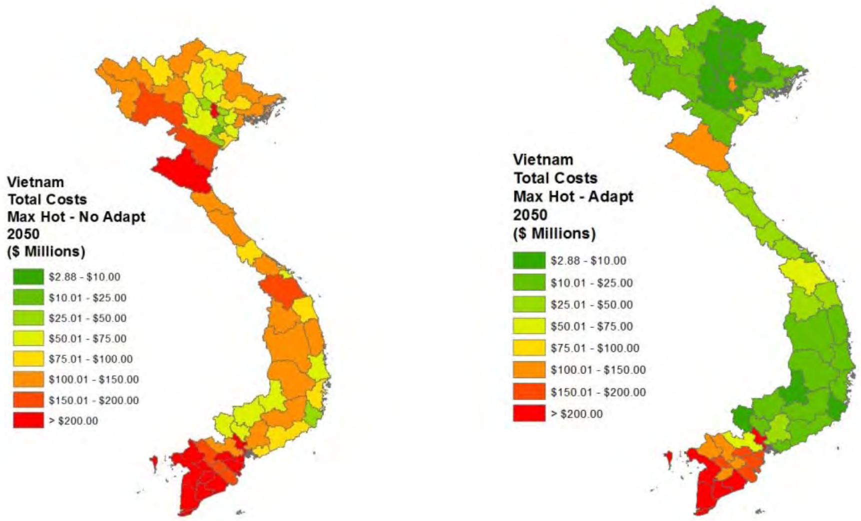
CNRM_CM3_A1B (Maximum Hot)				
Region	**Adapt (USDMil)**	**No Adapt (USDMil)**	**OC Adapt**	**OC No Adapt**
Central Highlands	3.5	16.9	10%	48%
Mekong River Delta	24.2	36.9	129%	197%
Northern Central Area and Central Coastal Area	4.6	16.5	16%	57%
Northern Midlands and Mountain Areas	1.7	14.2	7%	58%
Red River Delta	3.9	25.2	15%	69%
Southeast	7.9	25.2	33%	54%

5.6.3.1. Central Highlands

The Central Highlands region is least affected by SLR with no provincial damages being reported. The lack of damages in this region is because there is inland protection and none of the provinces in the region have coastal boundaries. Therefore, all the costs below are from climate and flooding impact stressors.

The Adapt policy approximates a savings of nearly USD$13.4 million in the Maximum Hot Scenario. This cost is the difference between expanding the existing infrastructure by nearly 50% as opposed to an incurred cost of 10% opportunity cost with the Adapt Policy.

Figure 5-6: Combined Total Cost Damages by Province Level in USD Millions for the Maximum Hot scenario

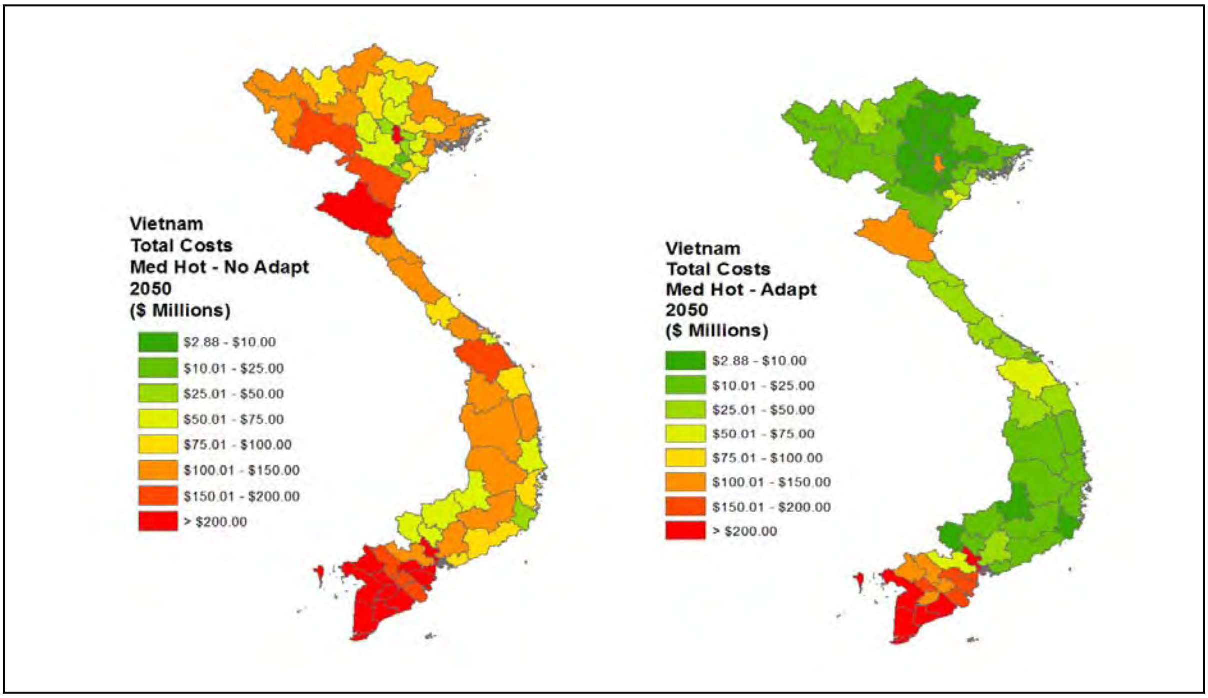


Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Table 5-7: Regional analysis (median hot climate scenario)

MPI_ECHAM5_B1 (Median Hot)				
Region	**Adapt (USDMil)**	**No Adapt (USDMil)**	**OC Adapt**	**OC No Adapt**
Central Highlands	7.7	12.9	22%	36%
Mekong River Delta	27.4	30.3	147%	164%
Northern Central Area and Central Coastal Area	6.9	9.5	25%	34%
Northern Midlands and Mountain Areas	2.9	7.5	12%	31%
Red River Delta	5.3	13.1	18%	38%
Southeast	13.9	21.7	17%	63%

Figure 5-7: Combined Total Cost Damages by Province Level in USD Millions for the Maximum Hot scenario



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese *state.*

5.6.3.2. Mekong River Delta

As seen in the tables and figures, in both GCMs, the Mekong River Delta region incurs the greatest damages in both cost and opportunity cost from combined climate change impacts. This impact can be largely attributed to the SLR analysis. This is the southernmost region in Vietnam and the majority of the land area is at an elevation of three meters or lower. The thirteen provinces have SLR inundation estimates ranging from 14%-99.5% of all road infrastructure. This inundation also has an impact on agriculture and other existing industries in these areas. Seasonal flooding and inundation from typhoons and natural weather events are an existing concern that may be exacerbated by SLR and increased precipitation and flooding under climate change. The No Adapt costs in this region account for 77% (USD$24.2 million) of the total SLR costs for the country. The provinces of Bac Lieu, Hau Giang, Soc Trang, Tra Vinh, and Ca Mau have SLR inundation projections of 96-100%. The combination of the SLR damages with the flooding projections and increased precipitation accounts for the proportionally higher costs relative to all the other regions.

5.6.3.3. Northern Central Area and Central Coast Area

The climate change impact on the Northern Central Area and Central Cost Area is potentially as high as USD$16.5 million using the No Adapt Maximum Hot scenario. This is an opportunity cost of 57%, compared to an Adapt policy opportunity cost of 16%. This is a savings of USD$11.9 million. The Median Hot scenario has a lower projected impact (34% and 25%, No Adapt and Adapt, respectively) but still evidences a benefit from an Adapt policy.

In this region, approximately 1% of the roadstock is affected by SLR. The provincial inundation ranges from .03% -1.3%. Phu Yen has an estimated inundation of 44 KM of road, compared to Da Nang’s estimate of 29 KM damaged.

5.6.3.4. Northern Midlands and Mountain Areas

With Adaptation, the Northern Midlands and Mountain Area region has the lowest opportunity cost and total cost from climate change. This is partially due to the lack of SLR impact: the greatest impact is less than 1% in Bac Giang, with an impact of 0.06% or 3 KM of road. The climate impacts from temperature, precipitation and flooding have a cost potential of USD$14.2 million, but with Adaptation that can be reduced to just over USD$1.7 million. In this region, an Adapt policy would greatly benefit the existing road infrastructure and save a significant amount of money.

5.6.3.5. Red River Delta

The impact of SLR on the Red River Delta area has an average of 6%, but ranges within provinces from 0-21%. The climate impact stressors have an impact on road infrastructure and a resulting benefit from an Adaptation policy of nearly USD$21.3 million under the Maximum Hot scenario. The Opportunity Cost savings from an Adapt policy are similar between the median and maximum scenarios in this region. However, the Opportunity Cost savings from the No Adapt scenarios have a significant difference with 38% and 69% between the median and maximum scenarios respectively. Because of the densely populated areas in the Red River Delta and urban areas including Hanoi, the potential impact of the worst case scenario on the economy of the region should be considered.

5.6.3.6. Southeast

The Southeast Region is a smaller region but contains important urban centres including Ho Chi Minh City and Province. The SLR impact ranges from 0-21%, with Ho Chi Minh at the upper end of 20% inundation. With a roadstock of approximately 6800 KM, this represents a potential loss of 1360 KM. Given the population density and important political and economic sectors in this area, a policy analyzing risk for inundation and climatic stressors on the roadstock should be accounted for. The Adapt policy savings of USD$17.3 million in the Southeast Region makes a case for a proactive adaptation policy to ensure connectivity in the province.

5.7. Limitations

The current study is based on several key components which introduce uncertainty into the quantitative analysis within the study. The climate data presented here is based on the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al 2007). The dataset represents current approaches to modelling potential climate change, but is based on probabilistic modelling. Thus, a degree of uncertainty is introduced in terms of climate impacts. This is one reason why the current study utilizes multiple climate models to arrive at conclusions. Additionally, as stated previously, the study relies on existing material studies to derive the impact stressors. Although the study bases its findings on recognized authorities and studies, the quantitative cost estimates are dependent on the findings from these and similar studies. Issues such as specific pavement types, local conditions, construction and maintenance techniques can all combine to impact specific cost impacts. Therefore, the quantitative cost results may differ based on alternative studies.

The limitations of the SLR analysis have been discussed in the above sections, but are restated here. Because of lack of data regarding the distribution, timing, and height of SLR in future projections, a uniform, one meter analysis was completed for this study. This may be improved upon if more robust climatic data becomes available. However, this does provide a guideline for analysis by highlighting regions and areas that are highly susceptible to changes in SLR due to low-lying coastal elevations.

These limitations should be considered when analyzing the quantitative results of this study. However, the qualitative relationships presented here will remain consistent even if the referenced studies are altered. Specifically, the relative impact on the country will remain consistent and the overall findings remain as stated.

5.8. Discussion and Conclusion

The importance of roads to development and long-term growth in Vietnam requires public officials to balance short-term needs versus long-term planning. The addition of potential climate change effects increases the requirement for balance as the potential benefit from a decision may not appear for several decades. The current study introduces one method for examining these effects from a quantitative perspective. The developed stressor-response functions illustrate the potential to integrate the predicted temperature, flooding, and precipitation changes resulting from climate change with traditional costing methods to anticipate cost impacts in specific locations. Additionally, using existing expenditures, road inventories, and the calculated cost impacts, the study provides an initial indication of the opportunity costs for each country.

The study illustrates that based on the impact of predicted temperature and precipitation changes; the opportunity cost to Vietnam requires further study by public officials. Specifically, the inclusion of maintenance savings when adaptation occurs is essential to gain a comprehensive perspective on the effects of climate change on the road infrastructure. Of particular importance to Vietnam due to the variance in geography is the need for a holistic picture of the potential impacts of climate change. By incorporating a SLR analysis, this paper provides a baseline analysis emphasizing the important challenge that climate change presents to Vietnam. With over 3,400 KM of coastline, Vietnam is susceptible to impacts along the entire Eastern side of the nation from sea level rise. The Terrain is: low, flat delta in south and north; central highlands; hilly, mountainous in far north and northwest. As documented in the study, this geography creates a scenario where extensive damage to road infrastructure may occur if a one meter sea level rise is realized.

The result of this study indicates that further study should be considered at a local level in districts where severe damage from inundation is predicted. Adaptation options such as coastal defences, road hardening, and road relocation should be examined. However, consideration should be given to the projected time frame when sea level rise may occur and whether some infrastructure may be needed if neighbouring land area is inundated. Each of these issues may be considered at a more detailed level in subsequent studies undertaken at regional levels

Overall, these numbers establish a basis from which Vietnam needs to approach the climate change challenge. The opportunity costs associated with potential climate change impacts have the potential to further delay infrastructure development plans. These delays are associated with the potential for social development to be impaired as access to critical services and expansion of economic ties is delayed. The challenge to governmental organizations is how to incorporate the multitude of conflicting requirements associated with the potential impacts into a cohesive policy that achieves balance between short-term needs and the potential long-term effects of climate change on infrastructure.

In conclusion, the developed methodology represents a first step toward developing an integrated and comprehensive economic evaluation of the effects of climate change on road infrastructure. The results from the analysis will inform the economic models that comprehensively analyze the effects of climate change on the economy of a country. The resulting challenge to governments from the final results of this analysis will be how to incorporate a multitude of conflicting requirements into a cohesive policy that achieves balance between short-term needs and the potential long-term effects of climate change on infrastructure.

6. Coastal Zones, Sea Level Rise, and Cyclones

This chapter considers the impact of sea level rise and storm surge on the Red River Delta region of Vietnam. The Red River Delta region consists of nine provinces: Bac Ninh, Ha Namh, Hai Duong, Hung Yen, Nam Dimh, Ninh Binh, Thai Binh, Ha Tay, and Vinh Phuc; and two municipalities: Hanoi and Hai Phong. Much of the delta area is characterized by low elevations. The capital city of Ha Noi is located eight meters above sea level, on average. Other major cities in the region include Hai Phong and Nam Dinh, which are both located three meters above sea level, on average. Figure 6-1 depicts the study area for this analysis.

By combining a range of sea-level-rise (SLR) scenarios for 2050 with the potential maximum storm surge level for the current 100-year storm, this report analyzes permanently inundated lands and temporary flood zones. U.S. Geological Survey's HydroSHEDS 90-meter elevation data is used to identify the inundated and flooded areas. Three SLR scenarios are considered, each with a different level of rise: low (0.156 meters), medium (0.285 meters), and high (0.378 meter). The Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model is used to define the potential maximum surge for simulated storm activity in the study area (Jelesnianski et al., 1992).

This chapter includes three sections. First, background information on coastal flooding in the Red River Delta is presented. Second, a thorough description of the applied methodology is provided. Third, the results of the analysis are presented and discussed. Our analysis finds that sea-level rise through 2050 could increase the frequency of the current 100-year storm, which is associated with a storm surge of roughly 5 meters, to once every 60 years. Approximately 10 percent of the Hanoi region's GDP is vulnerable to permanent inundation due to sea-level rise, and more than 40 percent is vulnerable to period storm surge damage. We conclude that coastal adaptation measures, such as a planned retreat from the sea, and construction of a more substantial seawall and dike system, are needed to respond to these threats.

6.1. Background: Coastal Flooding in Vietnam

Of all developing countries, recent studies have shown Vietnam to be one of the most vulnerable to sea level rise. Using six indicators, Dasgupta *et al.* (2009) assess the impact of SLR on 84 coastal developing countries. Considering the use of land, population, gross domestic product, urban extent, agricultural extent, and impacted wetlands, Dasgupta *et al.* (2009) demonstrate that Vietnam, with one meter of SLR, ranks among the top five most-impacted countries. Additionally, the World Bank (2009) ranks Vietnam among the twelve Bank client countries most at risk from sea level rise due to climate change.

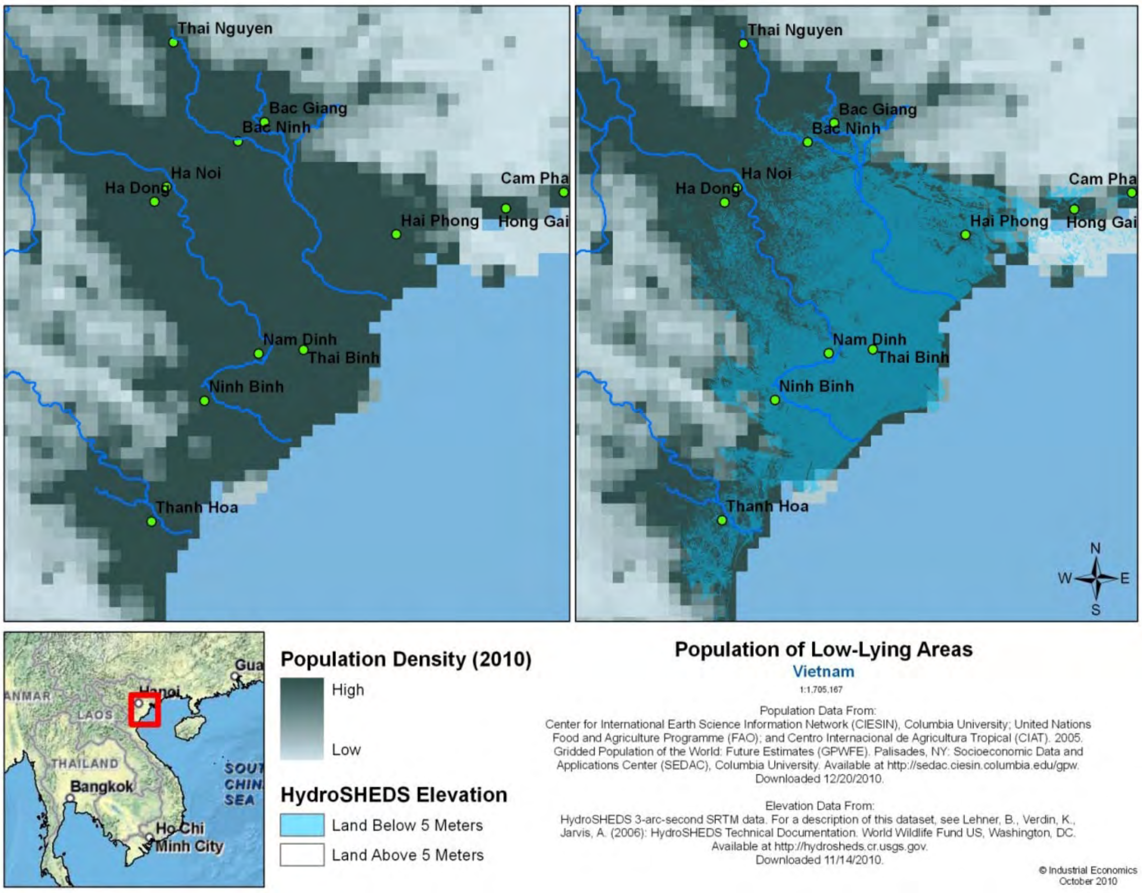
Figure 6-1: Red River delta region study area

Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Vietnam is likely to be one of the most vulnerable nations in the word due in part to the location of major urban centres and intensely cultivated lands in low-lying areas. In 2010, the Red River Delta region, which surrounds Vietnam's capital city of Ha Noi, was home to approximately 23 percent of Vietnam's total population (General Statistics Office of Vietnam, 2010). The provinces in this region represent the most densely populated in Vietnam outside of Ho Chi Minh City (General Statistics Office of Vietnam, 2010). Figure 6-2 illustrates the confluence of population density and low-coastal land in the Red River Delta region. The Red River Delta region is also one of the country's major agricultural regions. Nearly 60 percent of households in the region depend on income provided by agriculture (World Bank, 2010b).

Between 1954 and 2000, an average of 6.9 typhoons per annum made landfall along Vietnam's coast (MoNRE, 2003). The high winds and storm surges associated with these typhoons inflict a vast amount of damage on the coastal region. Precipitation that accompanies these typhoons also induces widespread flooding in regions at an elevation of less than one meter above sea level. These floods result in significant damage to those low-lying regions, like those within the Red River Delta and floodplain. Table 6-1 outlines the historic cyclone events that have caused damage to the Red River Delta region between 1990 and 2008.

Figure 6-2: Population of low-lying areas in red river delta region



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Table 6-1: Historic tropical cyclone incidents which have caused damage to the red river delta region between 1990 and 2008

Date	Storm Name	Provinces Impacted	Housing Lost (# houses)		Agriculture Lost (Ha)			
			Collapsed, Washed-Away	Sub-merged	Rice Fields, Damaged	Rice Fields, Lost	Farm Produce, Damaged	Farm Produce, Lost
Sep-05	Storm no. 7 (Damrey)	Hai Phong, Thai Binh, Nam Dinh, Ninh Binh	626	35,886	139,649	1,300	12,128	1,000
Sep-05	Storm no. 6	Hai Phong, Thai Binh, Nam Dinh, Ninh Binh	1	138	42,129			
Jul-05	Storm no.2 (Saola)	Hai Phong, Thai Binh, Nam Dinh, Ninh Binh, Ha Nam	2	206	48,534		4,027	
Aug-03	Storm no. 3	Hoa Binh, Ha Tay, Bac Giang, Bac Ninh, Hai Duong, Ha Nam, Hung Yen, Hai Phong, Thai Binh, Ninh Binh, Nam Dinh		201	3,400	130		
Sep-96	Storm no.4	Nam Ha, Thai Binh, Hai Phong, Ninh Binh	3,190	74,050	21,411	2,615	8,420	3,190
1996	Storm no.2	Nam Ha, Thai Binh, Hai Phong, Ninh Binh, Hoa Binh, Ha Noi, Ha Tay	29,842	444,017	117,002	39,504	11,773	7,645
Aug-95	Storm no.5	Ninh Binh, Nam Ha, Thai Binh			1,500			
Jul-91	Storm no.3	Hai Phong	5		1,500			

Source: CCFSC, 2010.

Two of the strongest typhoons to hit Vietnam in the last 30 years made landfall in 2005 (Mai *et al.*, 2009). Typhoon Saola, the smaller of the two, made landfall on July 31, predominantly affecting the coastal areas of Quang Ninh and Hai Phong provinces. Wind force near the eye of the storm reached nine on the Beaufort scale (75-88 kilometres per hour). Saola caused several kilometres of sea dike damage, especially on the island of Cat Hai where dikes needed to be completely replaced (Mai *et al.*, 2009).

Typhoon Damrey, which made landfall in Vietnam on September 27, is considered the most severe storm to hit Vietnam in the last 50 years. Damrey affected all coastal provinces of the Red River Delta region with Beaufort scale 12 (118-133 kilometres per hour) wind forces in the eye of the storm. High storm surges coincident with high tides led to extensive overtopping of sea dikes in the area. Storm surges from Damrey reached a height of three to four meters and the seawater penetrated inland three to four kilometres. Flash floods following Damrey destroyed at least 1,194 houses and damaged another 11,576 in upland areas. More than 130,000 hectares of rice fields were submerged and damaged, most of which had not been harvested prior to Damrey (Mai *et al.*, 2009). Although it is difficult to associate singular events like the damaging typhoons of 2005 with climate change, deadly events like these clearly demonstrate the extreme vulnerability of the region to exaggerated climate variability.

The threat from cyclones in Vietnam is compounded by the potential impacts of climate change, including sea level rise and increased rainfall. Sea levels in Vietnam are estimated to increase two and a half to three centimetres per decade due to climate change (MoNRE, 2003). In addition, delta areas are expected to subside over time, which may exacerbate damage caused by sea level rise in the Red River Delta. Unless a sufficiently high and strong dike system is built, sea level rise will further decrease land area in the Red River Delta. Climate change is expected to increase climate variability in Vietnam, decreasing rainfall during the dry season and increasing rainfall in the wet season. Overall, annual rainfall is expected to increase (MoNRE, 2009). Inundation, the loss of land, and saltwater intrusion caused by sea level rise, increased rainfall and cyclone events will pose serious threats to farmers. Between 1976 and 2005, flooding and saltwater intrusion contaminated 40,000 hectares of cultivated land and destroyed over 100,000 tons of food (Mai *et al.*, 2009). The rate of destruction may increase due to climate change. These impacts may be felt through agricultural exports and could possibly affect national food security (Chaudhry and Ruysschaert, 2007).

Cyclones also contribute to serious coastal erosion in Vietnam, which is expected to worsen due to climate change (Mai *et al.*, 2009). Vietnam has experienced both structural longshore erosion, which takes place along unprotected coastlines, and foreshore erosion, which leads to a deepening of the foreshore in front of sea dikes (Mai *et al.*, 2009). In Vietnam, structural erosion occurs at about 10 to 20 meters per year, while foreshore erosion occurs at a rate of 0.3 to 0.6 meters per year. Over the past 100 years the shoreline in Vietnam has retreated some 3,000 meters and approximately 18,000 hectares of land have been lost (Mai *et al.*, 2009).

6.2. Methods

The effects of climate change on cyclones can include changes in the intensity, frequency, and the track of individual storms. Changes in temperature are a potentially important factor in altering storm patterns, but, because cyclones are relatively rare events, differences in storm generation activity that might be experienced by 2050 are difficult to discern with current methods. Because historical data on storm surges in Vietnam is sparse, extrapolating trends of past storm activity is generally not useful.

The effect of sea-level-rise is an equally important effect of climate change on the potential damage that may result from cyclones. Higher sea level provides storm surges with a higher “launch point” for the surge, which may increase both the real extent and the depth of the surge in areas already vulnerable to coastal storms. In addition, future sea-level rise, while uncertain, is more reliably forecast to 2050 than future storm activity. In general, the increase in sea level would make existing storms significantly more damaging, even for minimal changes in storm activity. This analysis focuses on the more reliably forecast marginal effect of SLR on the extent and effective return period of these already damaging storms. Using a simulated dataset for storms and surges along with three alternative forecasts for future SLR in Vietnam, we estimate the effect of climate change induced SLR on surge risk due to cyclones. The overall method involves four steps:

1. *Simulate storm generation activity over the 21st century.* Our method generates 3000 seeded events, and estimates which of these events become cyclones and where they might track.
2. *Use wind fields as inputs to a storm surge model.* We use the U.S. National Weather Service's SLOSH model to estimate how wind-driven water during a cyclone event generates a storm surge over coastal land.
3. *Generate a cumulative distribution function of storm surge height for selected key locations in the SLOSH domain.* SLOSH results generated for each of the simulate events provide a base case of surge heights for future storms, absent sea-level rise
4. *Estimate effect of SLR on return time of storms.* Using the distribution of storm surge in the base case, we then estimate how SLR effectively increases the frequency of damaging storm surges, for three scenarios of future SLR in 2050.

We describe each of these steps briefly in the remainder of this section.

6.2.1. Storm Generation

Existing event set generation techniques begin with historical compilations of hurricane tracks and intensities, such as the so-called "best track" data compilations maintained by forecasting operations such as the National Oceanic and Atmospheric Administration's Tropical Prediction Center (TPC) and the U.S. Navy's Joint Typhoon Warning Center (JTWC). These records typically contain the storm's centre-position every six hours together with an estimated intensity, either maximum wind speed or central pressure, every time period. Early risk assessments (e.g. Georgiou et al., 1983; Neumann, 1987) fit standard distribution functions, such as lognormal or Weibull distributions, to the distribution of maximum intensities of all historical storms coming within a specified radius of the point of interest. Then, by drawing randomly from such distributions, these early risk assessments used standard models of the radial structure of storms, together with translation speeds and landfall information, to estimate the maximum wind achieved at the point of interest. A clear drawback of this historical extrapolation approach is that frequency estimates for high-intensity events are quite sensitive to the shape of the tail of the assumed distribution. Mainly because there is little supporting data, these tails are, by nature, notoriously difficult to quantify.

Many wind risk assessment methods rely directly on historical hurricane tracking data to estimate the frequency of storms passing close to points of interest, and must therefore assume that the intensity evolution is independent of the particular track taken by the storm. Moreover, the relative intensity method must fail when storms move into regions of small or vanishing potential intensity. This is often the case in higher latitudes, where enormously destructive storms have occurred, though infrequently. In such regions the historical record is extremely sparse, resulting in vanishing potentials.

As a step toward circumventing some of these difficulties, we have developed a technique for generating large numbers of synthetic hurricane tracks, along each of which we run a deterministic, coupled numerical model to simulate storm intensity. The method is based on randomly seeding a given ocean basin with weak tropical cyclone-like disturbances, and using an intensity model to determine which of these develop to tropical storm strengths. A filter is applied to the track generator to select tracks coming within a specified distance of a point or region of interest, such as a city or county. In filtering the tracks, a record is kept of the number of discarded tracks; this is used to calculate the overall frequency of storms that pass the filter. In this work, we selected the city centre of Ha Noi, Vietnam as the focal point; as a result, we also capture storms that have major impacts seaward of Ha Noi, in the Red River Delta.

Once the tracks have been generated, a coupled hurricane intensity model is then run along each of the selected tracks to produce a history of maximum wind speeds. This model is driven by monthly climatological, atmospheric and upper ocean thermodynamic information, but also considers ambient environmental wind shear that varies randomly in time according to the procedure described previously. This coupled deterministic model produces a maximum wind speed and a radius of maximum winds, but, owing to the coarse spatial resolution of the model, the detailed aspects of the radial storm structure are not used here. Instead, we use an idealized radial wind profile, fitted to the numerical output, to estimate maximum winds at fixed points in space away from the storm centre. The overall method has been described in several published sources (see, for example, Emanuel *et al.* 2008).

For each point of interest, the intensity model is run in a Monte Carlo simulation with several thousand iterations to produce desired statistics, such as wind speed exceedance probabilities. Both the synthetic track generation methods and the deterministic models are efficient enough to estimate exceedance probabilities to a comfortable level of statistical significance with appropriate computational software.

6.2.2. The "Sea, Lake, and Overland Surge from Hurricanes" Model

Sea, Lake, and Overland Surge from Hurricanes (SLOSH) is a computerized model developed by the Federal Emergency Management Agency (FEMA), United States Army Corps of Engineers (USACE), and the National Weather Service (NWS) to estimate storm surge depths resulting from historical, hypothetical or predicted hurricanes by taking into account a storm's pressure, size, forward speed, forecast track, wind speeds and topographical data (Jelesnianski et al., 1992).

Graphical output from the model displays colour-coded storm surge heights for a particular area. Heights are presented as feet above the model's reference level, the National Geodetic Vertical Datum (NGVD), which is the elevation reference for most maps. Among other things, the SLOSH model is driven by wind fields derived from the storm generation techniques presented above.

Storm surge generation calculations are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads and other physical features. We coded these aspects of the SLOSH grid, and they are among the most time-intensive components of the overall method.

The SLOSH model is generally accurate within plus or minus 20 percent. For example, if the model calculates a peak 10-foot storm surge for the event, users can expect the observed peak to range from 8 to 12 feet. The model accounts for astronomical tides, which can add significantly to the water height, by specifying an initial tide level, but does not include rainfall amounts, riverflow or wind-driven waves. Only wind-driven “stillwater” flood heights are accounted for in SLOSH.

The point of a hurricane's landfall is crucial to determining which areas will be inundated by the storm surge. This information is also available from the storm generation methods discussed above, but the synthetic nature of those results and the fact that it represents a forecast, adds uncertainty to the landfall location. We apply the SLOSH model as its developers suggest: to define the potential maximum surge for a location when the precise landfall location is uncertain.

6.2.3. SLR overlay and effect on storm return times

Storm surge results from the base case, which has no SLR, provide a probabilistic representation of the likelihood of storm surge heights at a particular point on the coast over a future period. We use this to define the probabilistic behaviour of storm surges in the 21st century. This storm surge exceedance curve can then be modified to reflect the effects of sea-level rise on surge height. The effect of SLR on the effective return time can then be quantified. The modification of the exceedance curve is done for three future SLR scenarios through 2050.

The impact of land subsidence was also used to assess impact sea levels in the region. Unfortunately, no tide gauge data were available for locations within the Red River Delta. However, using mean sea level trend data for nearby Hon Dau from the Permanent Service for Mean Sea Level (PSMSL, 2005), subsidence in the Red River Delta was approximated at 0.03 meters (30 millimetres) by 2050. A change this small will not have a measurable impact on our results and was thus ignored.

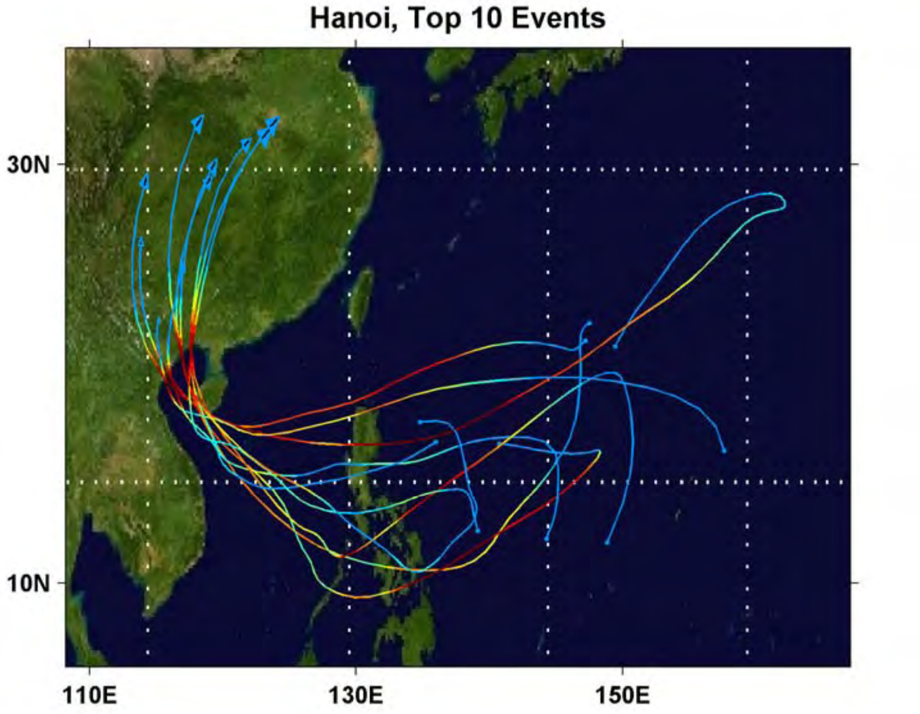
The three SLR scenarios used are low (0.156 meters), medium (0.285 meters) and high (0.378 meter). These same scenarios were used in analyses supporting the World Bank’s Economics of Adaptation of Climate Change (EACC) (World Bank, 2010a) project and are based on the work of the Intergovernmental Panel on Climate Change (IPCC) (Meehl *et al.*, 2007) and Rahmstorf (2007). The low scenario is based on the midpoint of the range of GCM model results reported in the IPCC AR4 (Meehl *et al.*, 2007); the medium scenario is based on Rahmstorf’s (2007) modelling of the SLR implications of the A2 temperature trajectory; and the high scenario is based on Rahmstorf’s “maximum” scenario (2007).

A function for the effect of SLR on effective return time is generated through the following procedure. First, the storm surge height for a particular “reference storm” in the base case data is identified. In the results presented below, we chose the 100-year storm surge height without any sea-level rise as our reference. We then examine the modified exceedance curves for the three SLR scenarios to determine the modified return period for that storm surge height under each of three scenarios. Finally, least-squares regression techniques are used to define the relationship between return period and SLR magnitude. Typically this relationship is not linear.

6.3. Results

The results of this four-step process are presented below. Figure 6-3 presents the tracking of ten storms generated from the process outlined above. These represent storms with the greatest wind speeds. The colours of the tracks indicate the intensity of each storm, according to the Saffir-Simposon scale: from the least intense, blue (Category 1), up through green (Category 2), yellow (Category 3), orange (Category 4), and red (Category 5), the most intense. The tracks indicate that storms that reach Category 5 level can reach the Hanoi area, which is show in the central left of the map. These storms typically arise from the south and diminish rapidly in intensity as they move north over land.

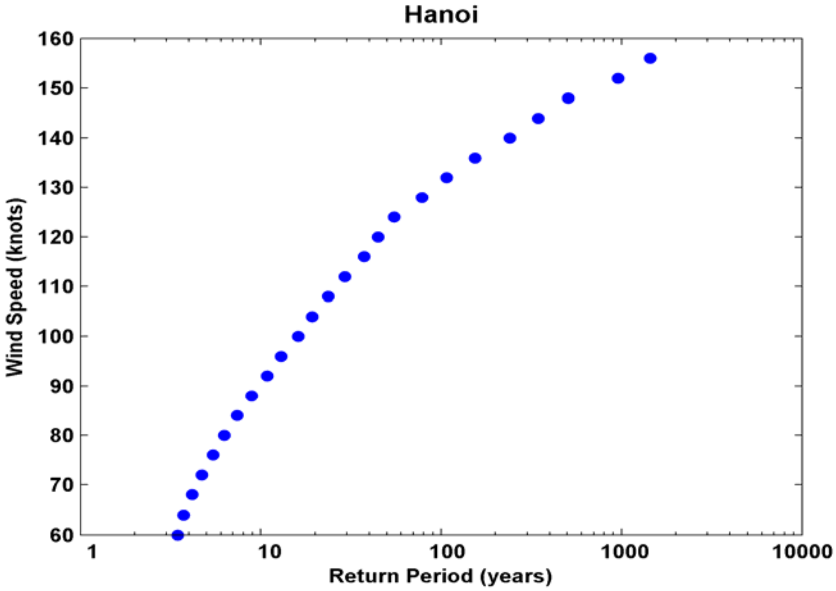
Figure 6-3: Storm tracks



Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

Figure 6-4 shows the exceedance curve for wind-speeds in Hanoi. The 100-year windstorm is associated with wind speeds of approximately 130 knots, which represents a Category 4 storm on the Saffir-Simpson scale. A storm with a 10 year return period is associated with wind speeds of approximately 90 knots, which represents a strong Category 2 storm. The distribution of wind speed return times correlates well with the risks from storm surges, as estimated by the SLOSH model. Figure 6-5 shows the exceedance curves for storm surges under a number of different scenarios. Although sea-level-rise continues unabated, storm surges are insignificant approximately 65 percent of the time. When storm surge events do occur there is potential for the surge level to be quite high, with some cases approaching 11 meters.

Figure 6-4: Wind speeds and estimated return times



Finally, Figure 6-6 provides our estimates of the changes in effective return time for the current 100-year storm surge event as a result of SLR. The return-time curve is estimated with an exponential and a polynomial function. Though there were only a few sampling points, the polynomial exhibited the greatest coefficient of determination (R^2). As shown in Exhibit 7, the historical 100-year event at Ha Noi can be expected to occur more frequently with SLR. Rather than occurring every 100 years, by 2050, it can be expected to occur approximately every 65 years in the Low SLR scenario, every 59 years in the Medium SLR scenario and every 54 years in the High SLR scenario. Similar reductions are seen in the return periods of other storms as well.

Figure 6-5: SLOSH-estimated storm surge exceedance curve, with and without SLR

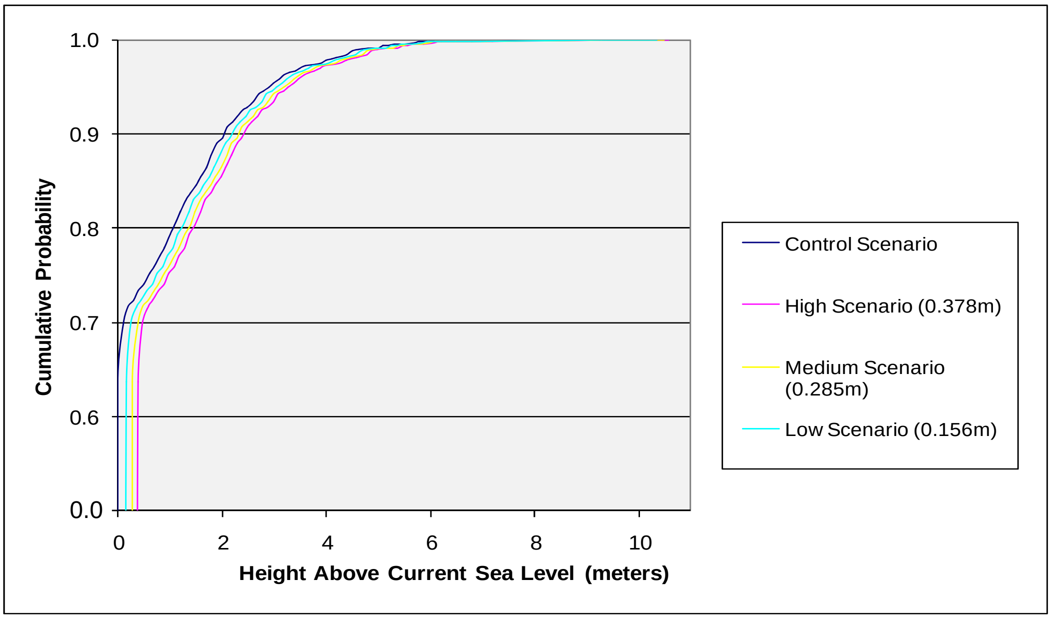
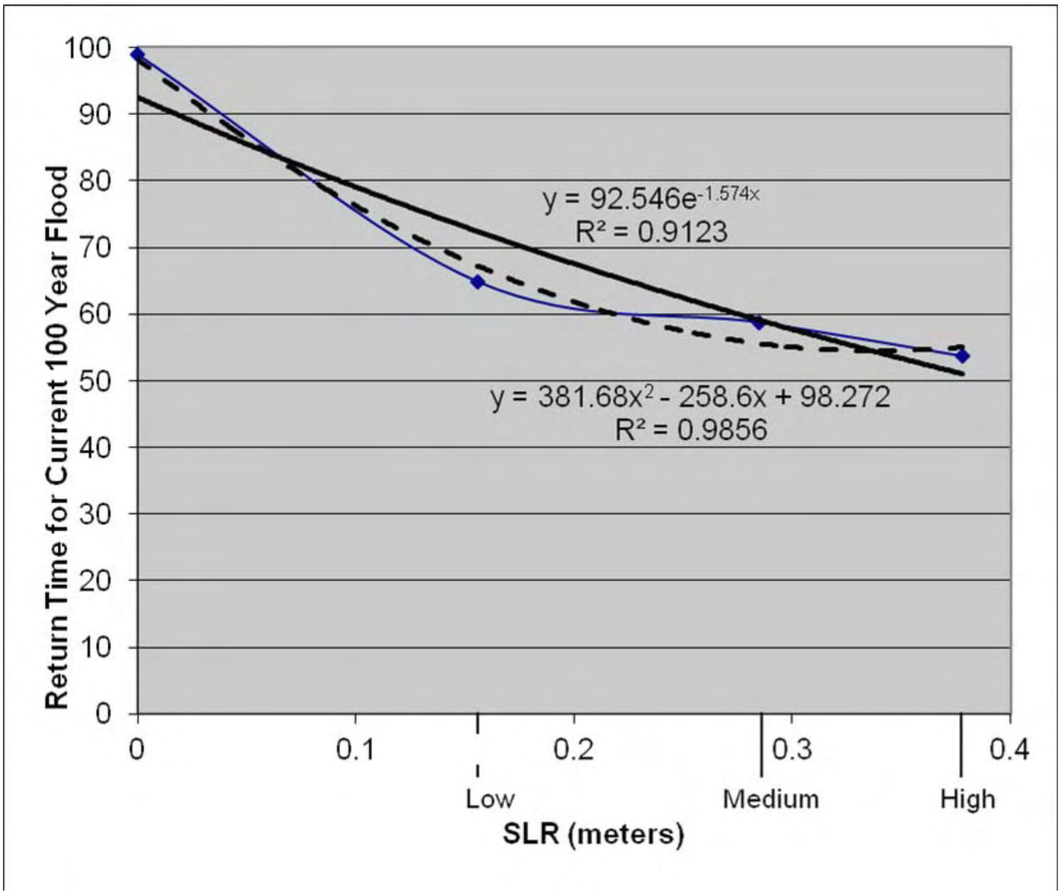


Figure 6-6: Estimated change in effective return time for the 100-year storm as a result of SLR



6.4. Economic Impacts

From this analysis, sea-level-rise will lead to permanent inundation of a significant portion of the low-lying Red River Delta area. In addition, storm surge will lead to increasingly severe and frequent episodic flooding. Figure 6-7 depicts areas that are at greatest risk from SLR and subsequent storm surge. The areas at risk will experience varying levels of damage due to SLR and storm surge. Areas at lower elevations will be flooded more completely and for longer periods, causing greater damage, while areas at higher elevations will experience less severe impacts. This research is constricted by the limited availability of high-resolution elevation data. With higher-resolution elevation data, future work will be able to conduct a more thorough spatial analysis of the relative risks faced by specific areas of the Delta.

Figure 6-7: Areas affected in 2050 by SLR and storm surge

Elevation Data From:
HydroSHEDS 3-arc-second SRTM data.
For a description of this dataset, see Lehner, B., Verdin, K., Jarvis, A. (2006): HydroSHEDS Technical Documentation. World Wildlife Fund US, Washington, DC.
Available at http://hydrosheds.cr.usgs.gov.
Downloaded 11/14/2010.

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Note: This study covers those parts of Vietnam that could be analyzed with available information therefore the map in the figure in no way intends to reflect the full territorial integrity of the Vietnamese state.

More information about the properties at risk from SLR and storm surge can be garnered from land-use data for the coastal counties in the Red River Delta region, including the counties of Nam Dinh, Thai Binh, Hai Phong, and Ninh Binh. Table 6-2 provides additional detail on the current levels of urban residential, rural residential, commercial, industrial, institutional, agricultural, aquacultural, rice paddies and forest within these provinces.[5] This exhibit also details the amount of land at risk of permanent inundation by SLR (areas below a one meter elevation) and episodic flooding by the current 100-year storm surge event (areas below a five meters elevation).

Table 6-2 shows that significant portions of the coastal provinces within the Red River Delta are at risk from sea level rise and storm surge. Over 70 percent of areas with high-valued land uses such as urban residential, rural residential, commercial and industrial uses are at risk from flooding up to five meters. Over 90 percent of land used for rice paddies is at risk. This is particularly troubling as the Red River Delta supports nearly half of the country’s rice production (Mai *et al*., 2009).

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[5] This land-use data included areas that were not given a specific designation. In these areas the land-use category is unknown and thus these areas are not included in these calculations.

Land value data would be the ideal tool for assessing the economic damages associated with storm surges and sea level rise. Because detailed land value data in Hanoi was not available for this study, gross domestic product (GDP) was used as a proxy for land values. Following the methodology employed in the Dynamic and Interactive Vulnerability Assessment (DIVA) model (Vafeidis *et al.*, 2008), this study used gridded population data at 2.5-minute resolution from the Centre for International Earth Science Information Network (CIESIN, FAO, and CIAT, 2005) combined with estimated 2010 country-level GDP data for Vietnam (CIA, 2009) to calculate a proxy for site-specific economic values.

For inundated lands, any land value would be permanently lost. Storm surge would result in a loss of the annual GDP value for the year in which the storm occurs. The implicit assumption of this methodology is that land with a greater population is of higher value. While there are good reasons to suggest this may understate values for some less-populous lands (e.g., agricultural lands) and perhaps for some more-populous regions as well, we believe that this is a reasonable assumption when considering damages over a relatively large area. A similar approach has been used in the DIVA model for many years (Vafeidis *et al.*, 2008).

Table 6-3 presents the GDP at risk of being permanently lost due to SLR inundation and the GDP at risk of being lost in a given year due to episodic flooding by the current 100-year storm event. Approximately $6.53 billion is at risk in the Red River Delta study area due to SLR and an additional $25.4 billion is at risk due to storm surge caused by a 100-year storm. These figures represent 10.9 and 42.5 percent of the total GDP within the Red River Delta study area, respectively. Considering Vietnam as a whole, GDP at risk within the Red River Delta study area due to SLR represents 2.36 percent of the total GDP for the country; GDP at risk due to storm surge represents 9.18 percent of total GDP.

Table 6-2: Land use areas - current totals and areas at risk from SLR and storm surge by 2050

Area considered		Land use							
	Urban Residential	Rural Residential	Commercial	Ind-ustrial	Institutional	Agri-cultural	Aqua-cultural	Rice Paddies	Forest
CURRENT AREA IN COASTAL RED RIVER DELTA PROVINCES (SQUARE KM)									
All Elevations	103	725	25.0	19.8	127	149	358	3,040	214
AREA AT RISK OF PERMANENT INUNDATION (SLR) AND EPISODIC FLOODING (CURRENT 100-YEAR STORM SURGE EVENT) (SQUARE KM)									
Below 1 meter	15.7	97.9	2.36	5.06	11.6	21.0	241	455	32.0
Below 5 meters	76.2	635	18.3	15.7	90.8	81.9	349	2,800	80.2
PERCENT OF LAND AREA AT RISK OF PERMANENT INUNDATION AND EPISODIC FLOODING									
Below 1 meter	0.15	0.14	0.09	0.26	0.09	0.14	0.67	0.15	0.15
Below 5 meters	0.74	0.88	0.73	0.79	0.72	0.55	0.97	0.92	0.38

Note: Data rounded to three significant figures.

Table 6-3: Attributed annual GDP at risk from SLR and storm surge by 2050

Area considered	Attributed Annual GDP (million 2010 Dollars)	Percent of total GDP within study area	Percent of total GDP For Vietnam
CURRENT AREA IN COASTAL RED RIVER DELTA PROVINCES			
All Elevations	$59,700	100%	21.6%
AREA AT RISK OF PERMANENT INUNDATION (SLR) AND EPISODIC FLOODING (CURRENT 100-YEAR STORM SURGE EVENT)			
Below 1 meter	$6,530	10.9%	2.36%
Below 5 meters	$25,400	42.5%	9.18%

Note: Data rounded to three significant figures.

Source: Gridded population data from the Center for International Earth Science Information Network (http://sedac.ciesin.columbia.edu/gpw/); GDP per capita and GDP for Vietnam from the Central Intelligence Agency World Factbook (https://www.cia.gov/library/publications/the-world-factbook/index.html).

6.5. Discussion

This analysis demonstrates a proof of concept for storm surge and SLR risk analysis for a region of Vietnam. Although several data limitations were identified, a method was developed for assessing spatial damages from SLR and storm surges with existing data in the Red River Delta region of Vietnam. In the current baseline scenario without SLR, our simulated storm generation activity and storm surge modelling showed that cyclones in the Red River Delta region are infrequent but severe. Modifying the storm surge exceedance curve from the current baseline scenario to account for SLR modestly increases risk. Cumulative areas affected across several land-uses and relative GDP values were used to estimate the economic impact and increased risk from sea-level rise and storm surges. Due to limitations of the elevation data used, affected areas could only be defined at the integer level. Therefore, only minimal distinction can be made between areas impacted by SLR versus those impacted by storm surge.

The implications of this analysis for adapting the Red River Delta to future climate change present an interesting direction for future research. Options for adapting the area to address these potentially severe risks of inundation and episodic flooding include constructing or reinforcing new and existing levees, constructing tidal dike systems to address episodic flooding of agricultural areas, elevating vulnerable structures in low-lying areas subject to episodic flooding and planning a managed retreat from the areas which face the most severe risks. Alternative adaptation approaches could utilize financial mechanisms, such as crop and property insurance programs. Such programs, like all others, should be carefully analyzed for their financial and economic implications. In the case of financial mechanisms, care should be taken to ensure that insurance premiums are both actuarially fair and, if they are to be effective, reasonably affordable.

Typically, such strategies would be analyzed and recommended only after a benefit-cost assessment that considered the value of the lands and structures at risk, the costs of adaptation and the timing of the risks. Such an approach is demonstrated in Neumann et al. (2010) for areas of the United States, for example. Unfortunately, elevation and economic data currently available for this study in Vietnam was not sufficiently well resolved to support such an analysis. With continued cooperation and dialogue among local stakeholders and analysts, creative approaches to filling these data gaps could be designed that would support better risk and adaptation analyses, which may, in turn, support more refined adaptation planning in this region.

7. Economywide Impacts

In order to assess the implications of climate change for growth and economic development, the impact channels discussed in the earlier sections are introduced one by one. In all, six impact channels or scenarios are considered. These are listed below with the name of the impact channel/scenario at the beginning.

1. *Agriculture*. Impacts of temperature and precipitation changes for crop production by region combined with unmet irrigation demand.

2. *Roads*. Implications of climate change from CliRoad.

3. *Hydropower*. Percentage changes in hydropower production are imposed in accordance with Figure 4-22.

4. *SLRlow*. Sea level rise is assumed to reach 16 centimetres by 2050. This rise occurs linearly over the simulation period.

5. *SLRhigh*. Sea level rise is assumed to reach 38 centimetres by 2050 and is imposed in the same manner as SLRlow.

6. *Cyclone*. Probabilistic cyclone strikes across each of the 56 scenarios with only the marginal impact due to sea level rise imposed as a shock.

These impact channels are imposed in a cumulative fashion. So, the scenario Roads contains the shocks for the Agriculture and Roads impact channels. The last scenario, Cyclones, contains the shocks from the first three scenarios as well as SLRhigh. With low sea level rise, the marginal impact of cyclones due to elevated storm surge is too small to merit presentation.

7.1. Multisector Economic Model

Sector model results are passed down to a dynamic computable general equilibrium (DCGE) model of Vietnam, which estimates the economic impact of the baseline and climate change scenarios, including spillovers from the four focal sectors to the rest of economy (i.e., indirect or economy-wide linkages). Our DCGE model belongs to the structural neoclassical class of CGE models (see Dervis et al. 1982).[6] Such DCGE models are well-suited to analysing climate change. First, they simulate the functioning of a market economy, including markets for labour, capital and commodities, and therefore can evaluate how changing economic conditions are mediated via

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[6] For a detailed specification of the generic DCGE model, see Diao and Thurlow (2012). For recent applications of a similar model to climate change, see Arndt et al. (2008, 2010).

prices and markets. Second, DCGE models ensure that all economy-wide constraints are respected, which is crucial for long run climate change projections. Finally, CGE models contain detailed sector breakdowns and provide a 'simulation laboratory' for quantitatively examining how the individual impact channels of climate change influence the performance and structure of the whole economy.

Economic decision-making in the DCGE model is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. A variety of substitution mechanisms occur in response to variations in relative prices, including substitution between factors, between imports and domestic goods, and between exports and domestic sales.[7] The Vietnam model contains eight regions and 30 sectors, including electricity generation, transport services, and ten agricultural subsectors. Thirty seven factors of production are identified: three types of labour (by education level- primary, secondary, and tertiary and then further divided between rural and urban zones), capital, agricultural land, agricultural capital, livestock, and fish stocks. The agricultural capital, land, livestock and fish stocks are distributed across the eight sub-national regions. This sectoral and regional detail captures Vietnam's economic structure and influences model results.

Climate change affects economic growth and welfare in the DCGE model via four principal mechanisms. First, productivity changes in rain-fed agriculture are taken from CliCrop/WEAP and the DCGE then determines the amount of resources that should be devoted to each crop given their profitability relative to other activities (i.e., 'endogenous adaptation'). Second, the DCGE model directly incorporates fluctuations in hydropower production from IMPEND. Third, CliRoad is incorporated directly into the DCGE model. The length of regional road networks from CliRoad is used in the DCGE model to help determine the rate of productivity growth. A shorter road network lowers transport productivity and increases the cost of moving goods between producers and consumers. Finally, the DCGE model incorporates the effects of SLR by reducing the total amount of cultivable land in each region by the land inundation estimates presented above. Other potential impact channels, such as health and tourism, are recognized but not explicitly considered.

The long timeframe over which climate change will unfold implies that dynamic processes are important. The recursive dynamic specification of our CGE model allows it to capture annual changes in the rate of physical and human capital accumulation and technical change. For example, if climate change reduces agricultural or hydropower production in a given year, it also reduces income, which in turn reduces savings. This reduction in savings displaces investment and lowers production potential.[8] Similarly, higher road maintenance costs imply less infrastructure investment and shorter road networks both now and in the future. Extreme events, such as flooding, also cause infrastructure destruction with lasting effects. Generally, even small differences in accumulation can cause large differences in economic outcomes over long time periods. Our DCGE model is well-suited to capture these path dependent effects.

7.2. Results: Climate Change Impacts

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[7] Production and trade function elasticities were drawn from Dimaranan (2006).

[8] Given our long run focus, our macroeconomic 'closure' assumes that changes in aggregate absorption are proportionally distributed across nominal private and public consumption and investment via distribution neutral changes in savings rates (see Lofgren et al. 2002). Government savings are flexible, tax rates are fixed and the real exchange rate adjusts to maintain an exogenously determined current account balance.

7.2.1. Baseline Scenario

In order to estimate the economic cost of climate change for Vietnam, it is necessary to first specify a baseline scenario that reflects development trends, policies and priorities in the absence of climate change. The baseline provides a reasonable trajectory for growth and structural change of the economy from 2007 to 2050 that can be used as a basis for comparison.

Economic growth in the DCGE model is determined by rates of factor accumulation and technical change. For labour supply, we assume that the stock of labour will grow at 2.5, 2.0 and 1.5 percent for tertiary, secondary, and primary labour categories respectively. We assume that the expansion of cultivated crop land will grow at one percent per year making growth in agricultural production increasingly dependent on the adoption of improved technologies rather than land expansion. Improvements in the education levels of the workforce are assumed to enhance productivity growth, with productivity rising for tertiary and secondary workers (i.e., at 2.0 and 1.0 per cent per year, respectively) compared to no factor specific technical advance for primary educated workers. Baseline annual growth in hydropower generation and regional road networks are determined by the sector models using historical climate data. Under the above assumptions, Vietnam’s economy continues to grow at about 5.4 percent per annum, with agriculture’s contribution to gross domestic product (GDP) falling from 16 percent to 7.6 percent during 2007–50. This strongly positive growth in per capita GDP leads to continued significant improvements in average household welfare.

7.2.2. Economy-wide Impacts

Figure 7-1 shows the average level of real GDP for the period 2046-2050. The average is presented in order to limit the implications of shocks in a particular year. Beginning with Agriculture, we find the implication of climate change to be relatively mild *when the land losses caused by sea level rise are excluded.* In other words, only the implications of the yield shocks summarized in Figure 4-8 and unmet irrigation demands summarized in Figure 4-9 are imposed. The implications of these shocks for the national economy and for growth are relatively small for two reasons. First, the shocks themselves are not particularly large in most instances. Second and importantly, the agriculture share of GDP by 2046 to 2050 is not very large. This is illustrated in

Figure 7-2, which shows that the agriculture share of GDP by 2046-50 varies strictly between seven and eight percent of GDP across all scenarios. Because the agriculture share of GDP tends to decline (a strong empirical regularity), variations or reductions in agricultural GDP have an increasingly muted effect on the national economy and overall economic growth rates.

Moving on to the Roads scenario depicted in Figure 7-1, the implications of climate change become more pronounced, and may be positive, but are more likely to be negative at a national scale. These implications are driven by CliRoad (again, excluding infrastructure lost due to sea level rise). Figure 7-3 provides a summary of the distribution of road network length relative to the baseline no climate change scenario. As indicated earlier, CliRoad is incorporated directly into the CGE model. Road network length influences the rate of total factor productivity growth in the model. In addition, investment in roads is assumed to move proportionately with growth in government spending. As a result of these interactions, road network length differs in every scenario.

Figure 7-1: Level of Real GDP at Factor Cost (average from 2046-2050)

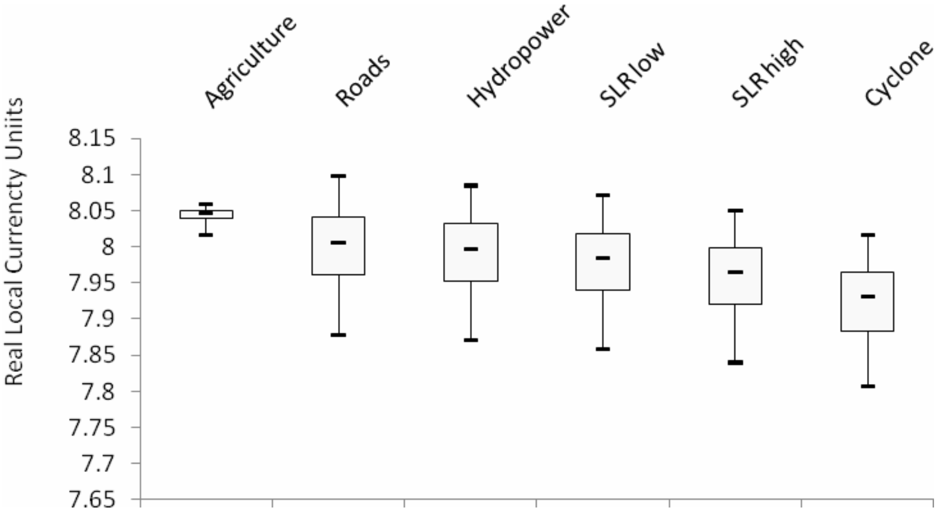
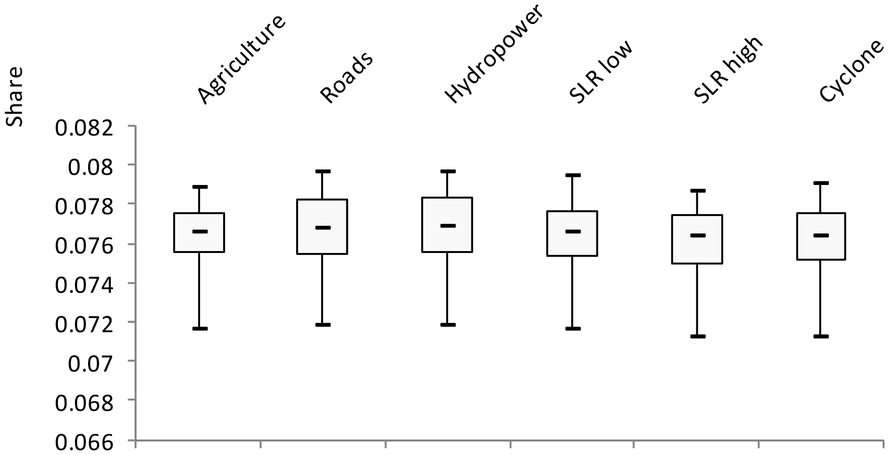
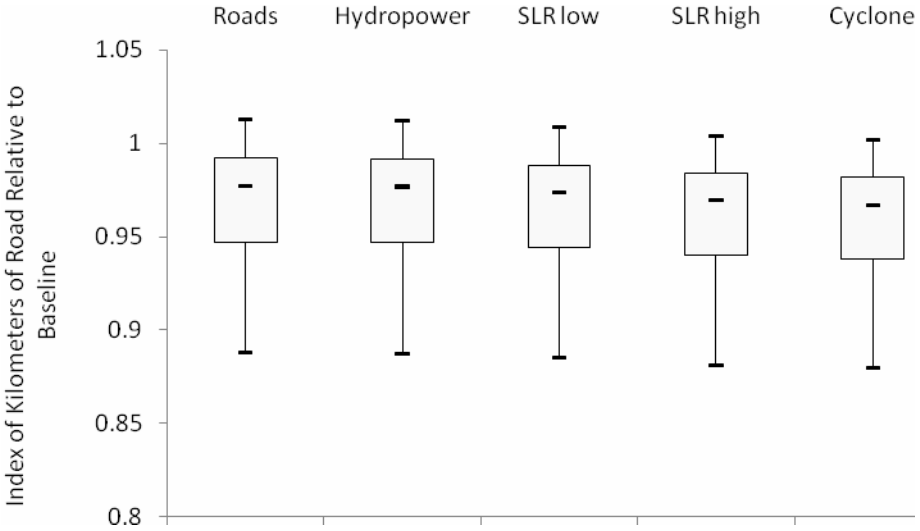


Figure 7-2: Share of agriculture in GDP (average from 2046-2050)



In some scenarios, road network length is greater under climate change than without climate change. Dryer scenarios tend to be more favourable to road network length due to reduced washouts from precipitation and flooding. Nevertheless, most scenarios generate reductions in road network length. This is due to three factors. First, all GCM scenarios produce increases in temperature. Higher maximum temperatures increase the rate of degradation of paved roads unless steps are taken to render roads robust to higher temperatures. In the model, these adjustments are not undertaken, hence temperature rises lead to increases in maintenance costs, which in turn displaces new road investment. Second, even though nationally precipitation declines slightly, the intensity of precipitation tends to increase, leading to a higher rate of washouts, particularly for unpaved roads. Third, the increase in precipitation intensity leads to, in most scenarios, a small rise in the frequency and intensity of flooding events. In a few GCM runs, large scale flooding events become much more frequent, leading to important declines in the total road stock.

Figure 7-3: Index of road network length relative to the baseline (average of 2046-2050)



Degradation or destruction of infrastructure is different from agricultural impacts because the effects on infrastructure endure. Once a road is washed away, the negative effect remains until the road is rebuilt. However, with constant resources allocated to roads, reconstruction of a section of road that is washed away due to heavy rainfall or flooding implies fewer resources available for construction of new roads or regular rehabilitation of existing roads. Hence, climate change influences the rate of accumulation of the road stock, which in turn influences the rate of productivity growth in productive sectors. Because rates of accumulation are influenced, the effects can accumulate and become relatively large over time. In contrast, for agriculture, climate change (as modelled) influences production in a given year, but not necessarily rates of growth in productive capacity through time. If growing conditions are poor, production declines; however, if growing conditions are favourable, production increases.

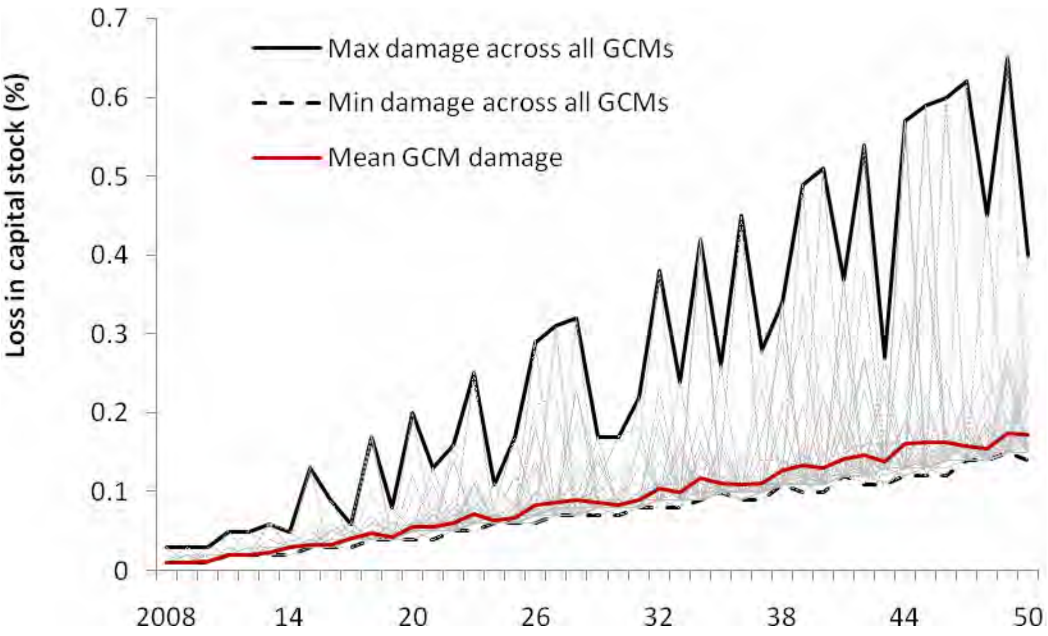
The third scenario adds the shocks listed in Figure 4-22 with respect to hydropower. As shown in Figure 4-22, impacts on hydropower production are essentially centred about zero in the 2040s. However, in the 2020s and 2030s, when hydropower represents a larger share of total electricity supply, the impacts tend to be negative. The effect is to slightly reduce growth over the period, resulting in a slight reduction in median GDP (across GCM runs) during the period 2046-2050. It is interesting to note that maximum GDP across all climate scenarios is reduced in hydropower relative to roads. Recall that dry scenarios are typically favourable to roads, but would not be favourable to hydropower production.

The implications of sea level rise are negative across all scenarios and basically shift the distribution of GDP outcomes downward. As discussed, sea level rise is uncorrelated with the particular GCM selected. Hence, the same sea level rise shocks are applied across all scenarios. The two principal drivers of losses from sea level rise are loss of agricultural land and loss of road infrastructure. As emphasized earlier, elevation data was obtained at one meter steps while climate change is expected to deliver at most 38 centimetres of sea level rise by 2050 (but potentially much more by 2100). It is, as a result, impossible to analyze the exact impacts of sea level rise to 2050 without additional assumptions. We assume that, with 38 centimetres of sea level rise, 38 percent of the area that would be submerged by one meter of sea level is assumed to be submerged. We also assume that this area constitutes principally agricultural land and road infrastructure. Other forms of capital, such as machines and significant permanent structures, are unaffected because they can either be moved or will tend to be placed on higher ground. Based on these assumptions, the scenario SLRhigh is essentially proportionally worse than SLRlow.

The scenario Cyclone considers the marginal impact of cyclones relative to the baseline. As discussed, we assume that there is no change in the frequency or intensity of cyclone strikes. Much of the damage from cyclone strikes is a function of wind velocity; however, this is held constant between the baseline and the climate change scenarios. As a result, the marginal impact of cyclones due to climate change is restricted to the interactions between storm surge and sea level rise. Thirty eight centimetres of sea level rise causes the storm surge to extend further inland and increases the depth of submersion in affected areas.

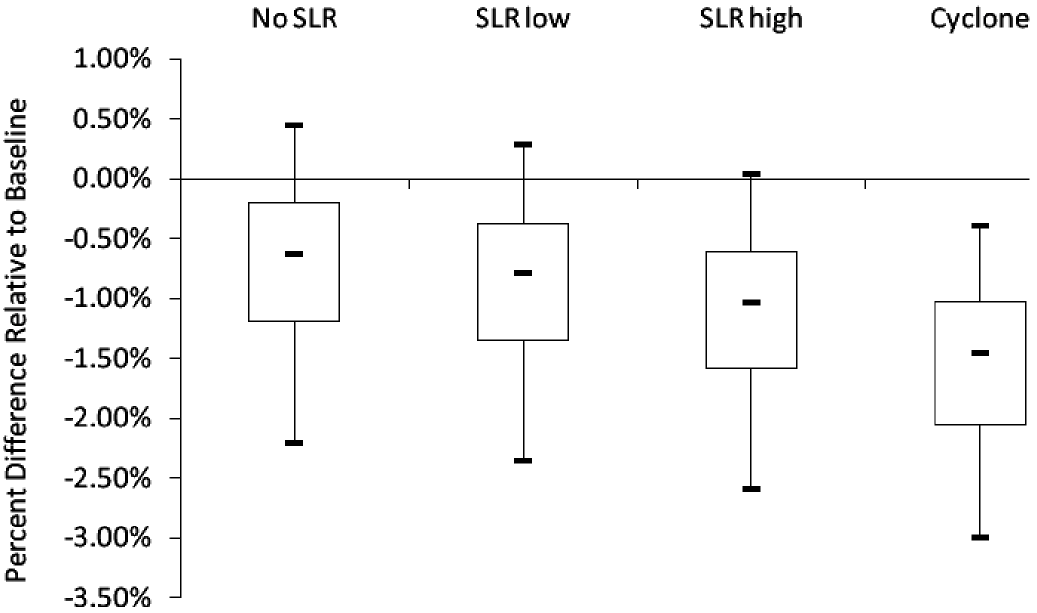
Because larger storms result in more powerful surges and a greater area inundated, we assume that marginal damages increase non-linearly with the power of the storm. This is illustrated in Figure 7-4, which shows the minimum, maximum, and mean marginal loss of capital stock associated with cyclone strike and 38 centimetres of sea level rise. Each year across the 56 GCM runs, cyclones are drawn randomly. As a result, we strongly expect to see some strong cyclone activity in at least one GCM in each year. While mean effects are small even out to 2050 (about 0.1 percent or 1/1000 of the stock of capital lost), losses from relatively larger cyclone events are much more significant, topping out at 0.6 percent of the capital stock for a single event. These damages shift downward the distribution of GDP outcomes.

Figure 7-4: Marginal damages to capital stock due to cyclones and high sea level rise



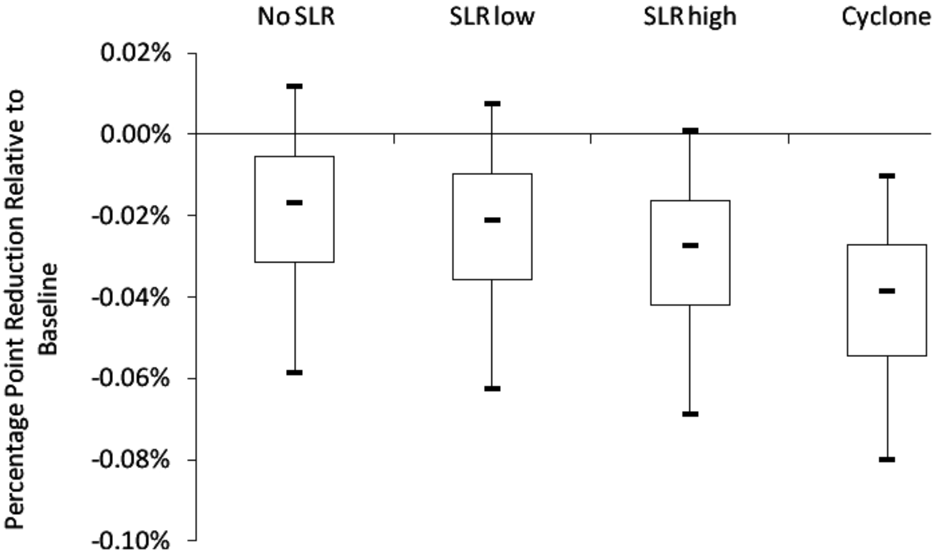
Nevertheless, cyclones' total effects on economic growth are not large relative to the full projected GDP of Vietnam. Figure 7-5 illustrates the distribution of the percent reduction in the level of GDP during the period 2046-2050. The scenario labelled "No SLR" is the Hydropower scenario (e.g., the combination of the Agriculture, Roads, and Hydropower impact channels). The SLRlow scenario represents the least strong distribution of impacts, considering all impact channels as well as low SLR. The level of GDP in that period ranges between a positive 0.25 and -2.5 percent, with the majority of outcomes between -0.5 and -1.5 percent. With high sea level rise and cyclones (scenario Cyclone), the level of GDP in the period 2046-2050 is between 0 and 2.5 percent lower. In other words, if baseline GDP were indexed at 100 in the period 2046-2050, GDP levels would be reduced to between 100 and 97.5. These results are broadly consistent with World Bank (2010c).

Figure 7-5: Reduction in real GDP relative to the baseline (average 2046-2050)



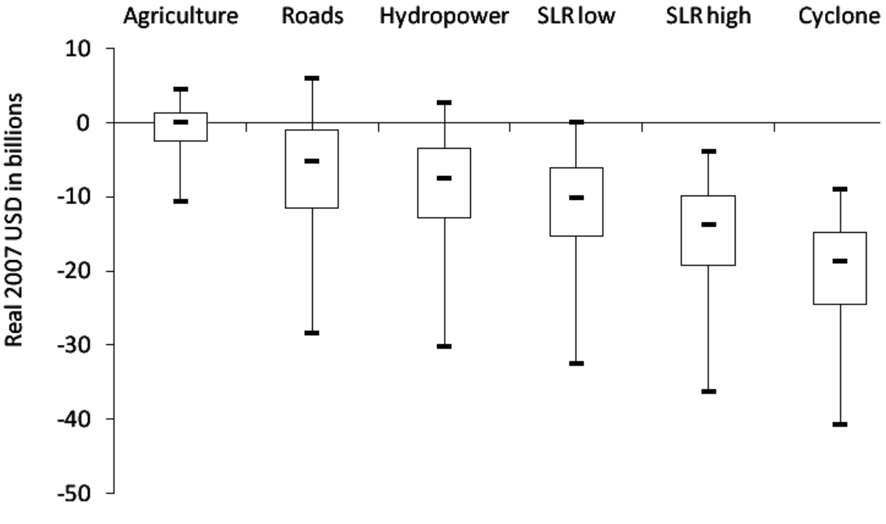
Because growth is a cumulative process, these reductions in GDP levels translate into a small reduction in average annual GDP growth over the simulation period as illustrated in Figure 7-6. In the Cyclone scenario, the GDP growth rate is reduced by between 0.01 percentage points and 0.08 percentage points. In other words, if the expected average baseline growth rate without climate change is 5.4 percent per annum, then the growth rate would be expected to be between 5.32 and 5.39 percentage points. In sum, other factors beyond climate change are likely to be more important in determining overall economic growth rates in Vietnam out to about 2050.

Figure 7-6: Implications of climate change for average annual GDP growth rates



At the same time, because Vietnam's GDP is expected to exceed USD500 billion by 2050, the losses caused by climate change in these scenarios are large in absolute terms. Figure 7-7 illustrates the net present value of losses over the period 2007-2050, measured in terms of the difference in GDP at factor cost between the climate change scenarios and the no climate change baseline scenario. The net present value is obtained using a discount rate of five percent. Taking the range between the most favourable outcome of scenario SLR low and the least favourable outcome of the scenario Cyclone, the net present value of losses ranges from about zero to about USD40 billion (measured in real 2007 USD). The majority of outcomes group in the range between losses of USD6-15 billion. These are substantial losses that intelligent adaptation policy could reduce considerably.

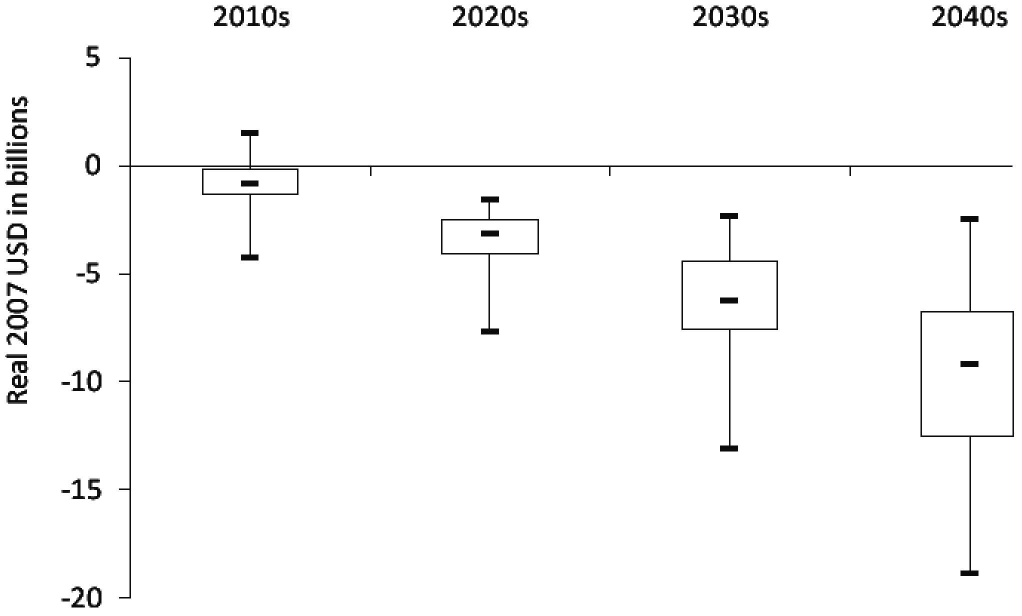
Figure 7-7: Net present value of losses due to climate change



Note: A discount rate of 5% is applied.

Finally, Figure 7-8 presents the net present value calculation of Figure 7-7 by decade for the Cyclone scenario only. Even though these values are all discounted back to 2007 (the base year for the analysis) at a five percent rate, later decades contribute much more strongly to the net present value of total losses than earlier decades. By the 2040s, losses are substantial. As climate change impacts are expected to be much more severe after 2050, the figure powerfully highlights the wisdom of using the next few decades to prepare for gradually more severe climate impacts.

Figure 7-8: Net present value of losses due to climate change by decade for the scenario Cyclone (billions of real 2007 USD)



Note: A discount rate of 5% is applied.

8. Conclusion

Going out to 2050, the following effects on Vietnam's climate are observed: temperature rises by about one to two degrees centigrade; there are relatively mild effects on precipitation, with a slight tendency towards a decrease and relatively mild effects on evapotranspiration. The combination of a light decrease in rainfall and increase in evapotranspiration leads to a small decline in the median of the climate moisture index, meaning a mild 'drying out' of a wet climate. Changes in runoff are also mild, and about as likely positive as negative (median slightly negative). These changes are typically not sufficient to generate large declines in agricultural production, nor are they projected to generate (in most instances) very large increases in events, such as flooding, that would threaten infrastructure. In addition, hydropower production tends to be negatively affected, but the effects are not large enough to serve as a major brake on economic growth.

Sea level rise delivers some of the largest economic effects, especially when the level's rise is high and when sea level rise is combined with cyclone strike. The Mekong River Delta is particularly vulnerable, with significant shares submerged in 2050 under the high sea level rise scenario. Overall, climate change worsens the economic growth prospects of Vietnam out to 2050. Despite this, climate changes macroeconomic impact, *out to about 2050,* is not particularly large. Non-climate factors are likely to be more important determinants of growth rates over at least the next few decades.

Nevertheless, as the net present value of losses indicates, climate change's macroeconomic effects are appreciable and adaptation policies are merited. The adaptation agenda includes:

- investment in information systems to monitor climate change impacts, including improved geographic information systems with emphasis on elevation data for low lying provinces, river flow, and close following of global sea level rise projections;
- development of heat resistant crop varieties;
- improved efficiency of use of water; and
- changes in design standards for infrastructure, such as roads, to endure a warmer and more variable climate.

Serious choices revolve around the implications of sea level rise combined with cyclone strike. There are essentially two proactive options: First, the government of Vietnam could channel economic activity towards higher ground in an evolutionary fashion. Second, the government could invest in protective infrastructure. These are not mutually exclusive options, and decisions in response to climate change do not need to be made immediately. Nevertheless, while more study is required, the available evidence indicates that a gradual channelling of activity to higher ground is more likely to be economically efficient and is certainly less risky than inaction. A major detractor to protective infrastructure investments is that they raise the stakes. Both the costs of protective coastal infrastructure and the capital that will inevitably be placed in the shadow of that protection are vulnerable to cyclone strike of sufficient magnitude. Hence, with a protective strategy, there is always the possibility that one will lose a great deal more than just the certain costs of building the protective infrastructure.

The gradual channelling of economic activity to safer, higher elevation zones, on the other hand, recognizes that the vast majority of the capital stock of 2050 has not yet been built. The location and vulnerability of that stock is, as a consequence, essentially a matter of choice. As discussed, sea level rise risks are largely (but certainly not exclusively) concentrated in the Mekong River Delta. Usefully, even ignoring climate change, there is considerable logic to fomenting urban development poles outside of Ho Chi Minh City (and Hanoi). Hence, policies to foment other urban development poles are likely to be "no regret" options in the event that sea level rise concerns are reduced through global mitigation policies or revised scientific findings. Nevertheless, for the gradual evolution strategy to in fact be gradual and hence efficient, the channelling of economic activity to higher ground should begin reasonably soon, especially if the upper ends of sea level rise projections appear to coincide with observed sea level rise.

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