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Impact of Climate Change on Irrigation, Crops and Hydropower in Vietnam

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Abstract

Vietnam is among the countries that are assumed to be highly affected by the impacts of climate change through sea level rise; increased temperature and changes in precipitation resulting in changes in crop water requirements and yields; and changes in river flow with impacts on hydropower and the ability to meeting water requirements for municipal, industrial and agricultural uses. Fifty-six climate change scenarios for Vietnam were selected that span a range of wet to dry future climates for Vietnam. A set of biophysical models were employed to project the impacts on water supply, water demand and hydropower generation out to the year 2050. These climate scenarios show a drying trend in the north with an increase of precipitation in the central and southern regions. Model results suggest that dry season runoff will generally be reduced and that wet season peak runoff will be increased compared to current conditions with mean …/

Keywords: climate change, water systems, agriculture, hydropower, Vietnam

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annual runoff, with extreme climate scenarios indicating increases up to 20 percent and decreases to 16 percent. Crop modeling results suggest that irrigation demand will mostly increase over Vietnam. The integrated river basin analysis over the 22 basins of Vietnam shows that overall hydropower generating capacity is typically only mildly affected by 2041 to 2050.

Tables and figures appear at the end of the paper.

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1 Introduction

Future climate change will cause changes in temperature, precipitation patterns and snowmelt, thus altering the hydrologic cycle, global circulation patterns and local weather patterns. It will have a direct impact on water resources and freshwater ecosystems, consequently affecting the function and operation of existing water infrastructure as well as water management practices. Previous analysis has indicated that Vietnam is among the countries that are assumed to be highly affected by the impacts of climate change (Dasgupta et al. 2007).

In 2005, agriculture and forestry accounted for about 23 percent of GDP in Vietnam; while 60 percent of the Vietnamese workforce was engaged in agriculture, forestry and fishing related activities. Due to the complex interactions of climatic variables with the hydrologic cycle together with the uncertainty involved in regional projection of how precipitation may change; impact assessment of climate change and variability on agricultural production, stream flow, irrigation water availability and hydropower remains a challenging issue.

This paper is one of four papers that document the findings from a UNU-WIDER research project: 'Development under Climate Change'. As one of the project's country level case studies, these four papers estimate climate change's biophysical and economic impacts on Vietnam using an integrated or multi-sector modeling framework. Additional impact channels include road infrastructure (Chinowsky et al. 2012) and cyclones and storm surge (Neumann et al. 2012). These sectoral impact channels are combined to provide an economywide assessment of climate change for Vietnam (Arndt et al. 2012). Our paper focuses on efforts to model climate change impacts on agricultural and hydropower production. While the research as presented here is a comprehensive, stand-alone analysis of the agriculture and water resource sectors, the temporal and spatial scale are driven by the needs of the integrated economywide modeling

2 Spatial scale of analysis

Integrated economic-biophysical analyses of any nature are faced with the difference in spatial and temporal scale of data that impacts modeling approach and scale. Vietnam can be divided into three homogenous climate regions that fall into a north-south gradient. These regions show differences in historical climate patterns as well as differences in the impacts projected by global circulation models (GCMs, climate models). These regions are shown in Figure 1.

A total of 22 river basins, areas ranging from 1,500 to 45,000 km^2, were identified based on the USGS Hydro 1K database. Figure 1 shows the river basin catchments used in this analysis. Some of the catchments are trans-boundary, for example the lower part of Mekong river basin, Red and Lo basins. For northern sub-basins, the upstream portions that extend to China are also included in the analysis.

The river basins are grouped to define the spatial extent of the climate zones. The northern climate zone is made up of the Red River system basin containing Da, Thai Binh, Lo and Cu sub-basins with a total area of 210,380 km^2. This basin contains some of the largest reservoirs existing as well as those under construction like Hoa Binh and Son la. The central climate zone is the coastal sub-region, a very narrow land strip between mountains and sea, is composed of a lot of small separate basins which are aggregated into bigger size catchments for this analysis. The southern part includes Dong Nai and Sesan sub-basins, including the downstream part of Mekong river basin delta and Cuu Long basin. The aggregation and areas of catchments are summarized in Table 1.

The economic model of Vietnam distinguishes between eight regions: central highlands, Mekong River delta, north central coast, north east, north west, Red River delta, south central coast, and south east. These are an aggregation of the 58 provinces and 5 centrally governed cities. This is an appropriate scale for economic analysis, but for water resources, river basins are the unit of analysis so a mapping of the 22 river basins to the 8 economic regions was done. There is an imperfect one to one mapping but adequate for the scale of the economic assessment from the authors' experience in similar studies.

3 Climatology overview

3.1 Historical climatology

Precipitation data was obtained from the Climatic Research Unit[1] (CRU) as part of the CRU global climate dataset available through the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre. Historical monthly precipitation data for global land areas from 1901 to 2000, gridded at two different resolutions (2.5° latitude by 3.75° longitude and 0.5° latitude/longitude) were constructed and are available for use in scientific research (Hulme 1992, 1994; Hulme et al. 1998) The 0.5º dataset was downloaded from the website and aggregated over the 22 sub-basins to provide a historical, base-case precipitation time series for each sub-basin in this analysis.

The average annual precipitation for the northern sub-basins is about 1588 mm, of which the highest is a value of 1785 mm in the Ma-Chu sub-basin. The central and the southern sub-basins have relatively higher rainfall with average annual values of 2431 mm and 2019 mm, respectively. Historical temperature data for the period of 1901 through 2000 was also obtained from the CRU. The gridded dataset was aggregated for the sub-basins of this study. The annual temperature distribution is fairly uniform across the sub-basins, with average temperature value of 23.3°C. Although there is a slight upward trend in temperature, the record can be assumed to have remained nearly uniform. According to this data, temperature has only risen about 0.3°C in the past 100 years.

Table 2 shows the average weather indicators (using the CRU dataset) over Vietnam. The indicators used here are precipitation (in mm/year), temperature (˚C), potential

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1 gu23wld0098.dat (Version 1.0) was constructed and supplied by Mike Hulme at the Climatic Research Unit, University of East Anglia. This work was supported by the United Kingdom's Department of the Environment, Transport and the Regions (Contract EPG 1/1/48).

evapotranspiration (PET: mm/year), and the Climate Moisture Index (CMI: dimensionless). PET was calculated using the modified Hargreaves technique described in Droogers and Allen (2002) and Hargreaves et al. (2003). The CMI is an indicator of aridity, which depends on average annual precipitation and average annual PET. If PET is greater than precipitation then the climate is considered to be dry, whereas if precipitation is greater than PET then the climate is wet. When PET is greater than precipitation then CMI = (precipitation/PET) - 1. When precipitation is greater than PET then CMI = 1 - (PET/precipitation). A CMI of –1 is very arid and a CMI of +1 is very humid. As a ratio of two depth measurements, CMI is dimensionless.

3.2 Climate scenarios

A total of 22 Global Circulation Model (GCMs) underlie the CMIP3 multi-model dataset archive (Meehl et al. 2007). The Special Report on Emissions Scenarios (SRES) prepared by the IPCC suggests socioeconomic scenarios to cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. In this analysis, the A2, B1 and A1B scenarios were selected to represent the worst, the most optimistic and average cases respectively. These three scenarios developed by SRES, combined with the 22 GCMs, make up the 56 climate change scenarios that were considered in this analysis (not every GCM ran every SRES scenario).

The median temperature rises by about 1.4°C by the end of 2050. The maximum predicted change of temperature by the end of 2050 is about 2.3°C degrees rise from the base case. The decadal average change of temperature, with respect to the base-case, for the 56 GCM-SRES scenarios is illustrated in Figure 2. All scenarios predict an increase in temperature for Vietnam.

For precipitation, the models are not in agreement on whether Vietnam will experience an increase or decrease in precipitation. The median precipitation for the 56 scenarios decreases for all sub-basins. The percentage change in precipitation is shown to range between -25 percent and +20 percent. Average precipitation changes across the northern, central and southern parts of Vietnam for each climate scenario are plotted in Figure 3.

Figure 4 illustrates the range of changes in CMI for Vietnam as a nation. It suggests that the models predict Vietnam will be drier (showing decreases in CMI), although some models are predicting a wetter climate. This is to be expected, since temperatures are predicted to increase while precipitation is not predicted to increase significantly. Figure 4 also shows that most of the models are predicting an increase in PET. Overall, the majority of GCM-SRES projections predict a hotter and drier climate for Vietnam though a hotter and wetter climate is also quite possible.

4 Climate change impact on runoff

As discussed in the previous sections, possible future cases of temperature and precipitation were generated by imposing GCM climate scenarios of anomalies in temperature and precipitation, over the base case historical weather variables. These cases of future climate variables are run through a hydrologic model to generate future runoff corresponding to the different scenarios under consideration.

4.1 Methodology and data

Surface water runoff is modeled using CLIRUN-II, the latest available 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 with a lumped watershed defined by climate inputs and soil characteristics averaged over the entire watershed, simulating runoff at a gauged location at the mouth of the catchment. For this analysis a monthly time step is used to simulate the runoff from provided weather variables. CLIRUN-II has both simulation and calibration modules. A calibration procedure was used to determine the coefficient values that are specific to the catchment under consideration. Based on 100 years of observed historical data from 1900 through 2000, the model was first calibrated for each of the selected 22 basins resulting in best-estimated values of model parameters for each sub-basin under a preset calibration goal.

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 monthly streamflow 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. Accordingly, 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 by the Global Runoff Data Center (GRDC). After the calibration procedure finished, the resulting modeled runoff was also checked for any unrealistic runoff values by looking at minimum and maximum values. The coefficients obtained as a result of this calibration procedure were then input to the simulation module to generate runoff corresponding to the climate change scenarios.

Runoff data was obtained from the Vietnam Institute of Hydrology meteorology and Environment for Red River, Thai Binh and Dong Nai sub-basins. This monthly runoff dataset for the northern sub-basin 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° by 0.5° resolution was obtained from global runoff database generated by the GRDC. This gridded dataset was aggregated to the 22 sub-basins identified.

Out of the 22 level-4 sub-basins, it was possible to obtain reliable runoff data for eight of the sub-basin from The Vietnam Institute of Meteorology, Hydrology and Environment (IMHEN); spanning 1971–2005 on northern Vietnam for the basins NamNa, Da, Thaom, Gam and Pho Day Within the Red River and Thai-Binh river basins at sub-basin outlets. Data from two more runoff stations were available in the southern sub-basins in Dang-Nai catchment. This made a total of ten observed runoff data sets obtained out of the 22 sub-basins. These ten sub-basins were calibrated both on observed streamflow data and GRDC global runoff data and the best parameters were selected based on R^2 and model error (difference of observed and simulated) results of the calibration are indicated in Table 3. The majority of the catchments exhibited a good fit between the observed and simulated runoffs for calibration based on the GRDC datasets.

4.2 Insights

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 monthly runoffs from all the climate change scenarios are shown in Figure 5. Results indicate that the national dry season mean runoff will generally be reduced and the wet season peak will be increased from the base case scenario. The highest and lowest annual runoff, which were 20 percent higher and 16 percent lower, respectively, were observed from the GISS GCM eh A1 and UKOM HADGEM B1 scenarios, respectively. A comparison of the results, averaged over 2011-2050, is provided in Figure 6.

Even though some of the models have shown higher average runoff, not all sub-basins are affected equally. The results from most of the GCMs show a decrease in runoff for the sub-basins in the northern part of Vietnam, especially in the Red River basin. For the central and some of the southern sub-basins, however, the runoff has shown to be higher in most of the scenarios. Figure 7 shows the spatial distribution of change of runoff for GCMs resulting in extreme scenarios, national highest and lowest runoffs. Interestingly, in both cases, a decreasing pattern in the northern sub-basins is evident.

For comparison purposes, the GCM-SRES scenarios resulting in the three highest and three lowest runoff results are shown in Table 4 for each region. Ukmo_hadgem1 A1B shows a decrease in runoff in all the sub-basins, while Cccma cgcm31 A1B shows an increase in central and southern sub-basins but a decrease in the Red River sub-basin.

5 Agriculture and irrigation analysis

5.1 CliCrop model

For this study, the CliCrop model was used (Fant et al. 2012). 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 behavior.

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

Yield calculations are based on the ratio of actual and potential evapotranspiration (ET). 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, which is 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, potential ET, 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 potential ET (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 Fant et al. 2012). 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 et al. (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 particularly important 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 the precipitation itself was not enough to satisfy this condition, the model assumes the farmer will irrigate. This version of CliCrop, called 'CliCrop-PaddyRice', assumes there is sufficient water available via irrigation. This assumption results in very high yields, but puts a strain on the predicted water deficit.

If the irrigation supply depletes, the farmer will need to leave some of the field fallow, partially irrigate, or leave some of the rice paddies rain-fed. Whatever the famer decides in this case, paddy rice production will decrease. This type of production decrease is not shown in the yield factor produced by CliCrop. Unmet irrigation demand, which reduces yields, is discussed in a later section.

5.2 Baseline scenario

Table 5 shows the average yield factor for the baseline (no climate change) scenario for the regions and crops used in this study. These yield factors represent a fraction, where 1 is perfect yield and 0 is no yield. The reductions in yield (any value less than 1) are caused by water stresses predicted by the CliCrop model. Please note that for paddy rice an irrigated version of the CliCrop model was used, meaning that water stresses on the crop are minimal (resulting in relatively high yield factors). As mentioned above, the true climate impacts for paddy rice can be seen in the changes in water deficit. 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 for the base scenario is shown in Table 5. 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 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), a full year; and for paddy rice (multiple cropping over the year).

5.3 Yield factors

Figure 8 shows the changes in the yield factor for the seven crops using the box and whisker plot technique. Similar to the figures showing the predicted climate changes, each box and whisker plot represents the distribution of the projections of the 56 GCM scenario pairs. As this plot shows, the yield results tend to vary for the different crops and by climate scenario, 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 likely 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. These seasonal shifts are not shown in the previous climate change plots, which are based on annual means. 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 an accurate indicator of the effects of the changing climate predictions.

5.4 Water deficit

Figure 9 shows the changes in water deficit (an indicator for changes in irrigation demand) for the seven crops using the box and whisker plot technique. Again, the box and whisker plot represent the distribution of the projections of the 56 GCM scenario pairs.

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 in Section 3.1), 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. The impact on yields depends upon whether the water resources are available to meet the increases in irrigation demands. This issue will be considered in the next section.

5.5 Sea level rise and other impacts on crop production

Since CliCrop is a one-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 study. Other studies have predicted that sea level rise and more frequent storm surge caused by climate change will 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. According to a study by the International Food Policy Research Institute (IFPRI), paddy rice production in the Mekong Delta is predicted to decrease 13 percent by 2050 due to a 30 centimeter sea level rise by 2050 (Yu et al. 2010).

5.6 Synthesis

With the GCMs predicting temperatures rising, relatively no change in precipitation for Vietnam, and decreases in soil moisture, the people of Vietnam should be prepared for more unfavorable climate conditions for crop production. Further, 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 dramatic 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 very complicated issue, 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, specifically floods and droughts. Options for developing more water storage capacity and efficiency should be considered in order to prepare for both extremes. 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. In a general sense, smart early planning and adaptation will likely be more beneficial in the long-term future.

6 Water resources analysis

6.1 Methodology and system modeling

Water evaluation and planning (WEAP) system is a decision support system for integrated water resources management and policy analysis developed and managed by the Stockholm Environment Institute. In this analysis, the 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. Hydropower energy generation and percentage of unmet consumptive demand are two of the main indicators used for impact assessment on resource utilization.

Typically, 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 series of 40 years (1951–91) of runoff data 'no climate change' are used for the base case scenario and the alternative scenarios are based on the runoff generated corresponding to the 56 GCMS modeled using CLIRUN-II, and irrigation water requirement outputs computed by CLICROP for the corresponding GCM models.

Schematics of existing and planning water resource development options for northern catchments Red-Thai Binh River basin and southern sub-basin, mainly Dong Nai, are provided by the Vietnam Institute of Hydrology, Meteorology and Environment. The schematic includes existing development as well as planned water resource development options, location of major dams and irrigation water diversion points.

The simplifications applied in representing water supply points for irrigation demand is that water transmission links only connect demand sites and rivers within the same sub-basin. Even though this configuration does not consider transfers between the sub-basins, it does not introduce much error on the final result of the analysis since most of the inter-basin transfers are negligible. However, special considerations were made for some sub-basins with significant amount of water transfer among them, such as the transmission link between Hong and Thai Binh sub-basins conveying approximately one third of the flow from Red River before Hanoi and at Duong River, where water is transferred from the Dong Nai sub-basin to Dong Thap Muoi catchment.

Since the irrigated area could be distributed anywhere over the sub-basin, multiple locations of demand nodes of water abstraction for irrigation demand are considered within the same sub-basin. This would simulate the effect of water abstraction at different locations in a single sub-basin. This allows the model to allocate the available water in best possible combination of water abstraction.

6.2 Irrigation water demands

In Vietnam, irrigation places the largest burden on water resources. The amount of water allocated for irrigation development has risen from 47 billion cubic meters (BCM) to 74 BCM in the last 20 years. Although the percentage of water allocated for irrigation is reduced owing to the increased water demand as a result of growing demand for industrial development and domestic consumption, the total proportion for irrigation is still estimated to be over 82 percent of its total water utilization.

The extent of cultivated area was obtained from the spatial production allocation model (SPAM) dataset developed by IFPRI. SPAM provides global estimates of spatial data of crop production, area and yield for 20 major crops by five arc-minute resolutions. SPAM made four spatial products available for public use namely harvested area, physical area, production and yield. The physical area dataset from the SPAM 2000 version 3.0.2 was used in this analysis. It was used to obtain the 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 account of. However, the CliCrop water deficit accounts for multiple growing seasons.

Data was aggregated by sub-basin to produce annual irrigated area by crop for each sub-basin. The annual irrigated area is about 7.9 million hectares in which rice accounts for about 46 percent of the total area. The total irrigated area expanded at a rate of 2.9 percent annually in the period 1980-87 and 4.6 percent between 1988 and 1994. The latest reports indicate that it has increased roughly by 3.4 percent on average between 1998 and 2011. However, it was not possible to obtain reliable data regarding future plans in expansion of irrigated area; thus, in this analysis, it was assumed that maximum irrigation potential of 9.4 million hectares (based on AQUASTAT from FAO 1997) will be achieved by the year 2050. Therefore, the current irrigation area is projected linearly. This gave rise to 0.6 percent expansion of irrigated area per year.

The CliCrop model output was used to estimate future irrigation crop water requirements under climate changes for all the 56 climate change scenarios. It provided 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 for Vietnam was provided by AQUASTAT (FAO 1997), which indicated that irrigation withdraws 77.8 billion meters cubed of water. Total water deficit values obtained from the CliCrop model indicated 54 billion m^3, indicating that irrigation supply efficiency of 70 percent. Although there is a possibility of enhancing efficiency of irrigation systems in the future, in this analysis, the value of 70 percent efficiency was adopted uniformly to all the scenarios.

6.3 Hydropower water demands

Hydropower is one of the major sources of electric energy 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 and increase the total installed capacity to 14,670 MW.

There are over 14 hydropower power plants operating currently with 4,577 MW of installed capacity providing long term 20,112 GWH of energy per year. This number is about 30 percent of the total energy potential of Vietnam. The highest generating capacity is in the Da River basin, Hoa Binh dam, accounting for 40 percent of the total energy generated in Vietnam. Two more plants are being constructed upstream in the Da River, which are expected to be completed by 2012 increasing the total in the Da River basin to nearly double the existing capacity.

At present, 14 medium to large hydropower projects invested by EVN are under construction and are considered in this analysis. The total long-term energy generation from this hydropower plans is estimated to be about 22,656 GWH. The biggest plant is Son La hydropower plant with 2400 MW, which is expected to be completed by late 2012. Operating and under construction hydropower plants considered in this analysis are provided summarized by sub-basins in Table 6.

EVN has identified 408 potential sites in the national master plan for small hydropower development ranging from 1 to 30 MW and capable of generating 13500 GWH for a total capacity of 2,887 MW (PECC1 2004). This combined with the existing hydropower and hydropower under construction will bring Vietnam to 86 percent of generating potential.

6.4 Municipal and industrial water demands

Domestic and industrial water demand data are obtained from AQUASTAT, which is a global information system on water and agriculture (FAO 1997; 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.

Estimated values for domestic and industrial water demand are estimated at 3.074 BCM/year and 1.206 BCM/year, respectively. These are converted to per capita per year terms resulting in values of 13.84 and 35.3 m^3. These water demands are assumed to be directly proportional to population; therefore, the water demand calculations were carried out for each sub-basin according to the total population. These demands are also projected to 2050 following population growth rate estimates. Population estimates for each sub-basin were extracted from gridded population densities data (2010) distributed by the Center for International Earth Science Information Network (CIESIN) at Columbia University.

6.5 Results of water resource analysis

To assess the impact on irrigation water supply, the relative unmet demand result from the WEAP analysis was the main indicator used. Under the base case scenario, results indicated that there is already a stress in the system in Da and Pho Day sub-basins. A long-term average of 200 million m^3 of annual unmet demand is observed. For the remaining scenarios with climate change, the analysis indicates that the unsatisfied irrigation demand will generally increase with time. Box plots of unmet water supply for irrigation relative to the reference case for the 56 GCMs are shown in Figure 10. The median value reaches about 2.1 BCM for the year 2050. The worst case scenario indicates a maximum deficit reaching 7 BCM.

As described in the previous sections, climate change will negatively affect runoff principally in the northern sub-basins, especially in the Red River basin. This is also reflected in the spatial distribution of unmet irrigation demand in which the majority of deficit is occurring in the Red River basin mainly as a result of the lower runoff in this region. Figure 11 shows relative unmet demand in the three regions for the year 2050. Note that the range of results is also larger for the northern sub-basins ranging from 6 BCM deficits to 2 BCM excess demand with respect to the base case scenario.

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 7. It can be inferred that even in the case of increased runoff, Cccma cgcm31 A1B model, the extra amount of water shown during 2020s will be used by the year 2050 due to the gradual increase of irrigation water demand.

The median level of hydropower generation shows a slight overall decrease over the climate change scenarios. The percentage reduction in the 10-year average generating capacity of reservoirs for the selected climate scenarios is shown in Figure 12. 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 also shows range of variability. Figure 13 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 percent over the 40 years.

7 Summary and conclusions

One of the striking findings of this research is the wide range of impacts. Impacts often vary dramatically by region, crop and by climate change scenario. In many cases, the sign of change may be different across the geographic regions of Vietnam. Even when restricting to 56 future possible climates, some extreme scenarios emerge. Overall, the agricultural impacts show higher frequency of negative impacts while the hydropower impacts show a slight tendency for negative impacts. Fairly consistent drying is observed in the northern region with implications for runoff, hydropower, irrigation demand and irrigation supply.

The modeling conducted here is meant to provide valuable information in its own right and to provide inputs into an economywide model of Vietnam in order to add up the impacts across the national economy. The objective of providing economywide coverage drove the choice of methods employed.

While the application of 56 climate scenarios gives a much better sense of the range of possible outcomes than recourse to only a handful of climates would provide, we are still not able to assign a probability distribution to the 56 climate change scenarios and thus to the resulting impacts. We must treat each scenario as 'equally unlikely'. This is a limitation. For investment planning under risk, it is valuable to provide ranges and concentrations of results as presented here. However, we should ideally also provide probabilities in the form of explicit histograms.

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Table 1: Climate regions and river basin and areas

Location	Catchments	Area (km^2)
Northern	Da	104,568
	Lo – Gam - Chay	34,423
	Thai Binh	27,323
	Ma - Chu	24,184
	Gang Giang -Ky Cung	11,849
	Others	8,034
	Subtotal	*210,380*
Central	Ca	37,718
	Gianh- Thach Han - Huong	20,101
	Thu Bon - Tra Khuc - Kone	26,233
	Subtotal	*84,053*
Southern	Ba	13,469
	Sesan & Srepok	30,143
	Dong Nai	42,215
	Others	19,474
	Subtotal	*105,302*
Total		399,735

Source: Authors' creation.

Table 2: Vietnam average weather values for the historical (baseline) scenario

Region	Precipitation (mm/year)	Temperature (˚C)	PET (mm/year)	CMI
North East	1525	22.5	979	0.33
North West	1551	21.7	1126	0.25
Red River delta	1755	23.4	837	0.50
North central coast	2109	22.9	1006	0.51
South central coast	2073	22.5	1048	0.48
Central highlands	1914	24.5	1166	0.38
South East	1862	26.8	1220	0.33
Mekong River delta	1954	25.3	1028	0.43
North East	1525	22.5	979	0.33
North West	1551	21.7	1126	0.25

Notes: PET is potential evapotranspiration and CMI is climate moisture index.

Source: Authors' creation.

Table 3: Calibration result of catchments with observed streamflow stations

Catchment	OBS Model Error (% MAR)	OBS R^2 (%)	GRDC Model Error (% MAR)	GRDC R2 (%)
NamNa-6	-0.012	65.21	-0.108	82.07
Da-7	-0.027	83.01	-0.009	94.79
Da-8	-0.027	57.01	0.094	88.36
Thao-9	-0.024	76.07	-0.047	92.94
Thao-10	0.001	79.55	0.003	95.03
Gam-11	-0.012	80.01	-0.012	94.63
Lo-22	-0.034	79.36	-0.039	95.18

Source: Authors' creation.

Table 4: Top three GCM models with 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%

Notes: GCM is general circulation model and emissions scenario.

Source: Authors' creation.

Table 5: Average yield factor and water deficit for the baseline scenario.

Region	SC	AC	RB	CF	TE	PC	PM	PS	PW
Average yield factor									
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
Average water deficit									
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

Notes: SC is sugarcane; AC is other annual crops; RB is rubber; CF is coffee, TE is tea, PC is perennial crops; PM is paddy rice (main); PS is paddy rice (summer-autumn); and PW is paddy rice (winter-spring).

Source: Authors' creation.

Table 6: Existing and under construction hydropower generating capacity in operation

River basin	In operation in 2011		Under construction in 2011	
	Power (MW)	Long-term energy (GWH)	Power (MW)	Long-term energy (GWH)
Lo Gam	108	430	562	2488
DA	1,920	8,160	2920	12150
BA	70	360	220	825
Se San	1,188	5,791	381	1596
Dong Nai	1,263	5,177	820	2894
Srepok	28	194	840	2703
Total	4,577	20,112	5,743	22,656

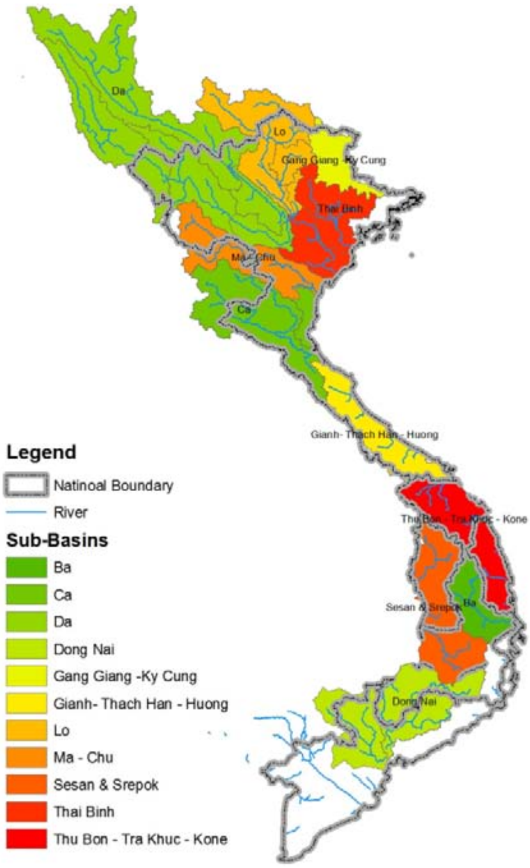
Source: Authors' creation.

Table 7: 10-year average unmet irrigation demand by climate change scenario (millions of cubic meters)

GCM scenario	Location of catchments	2011-20	2021-30	2031-40	2041-50
Minimum runoff (Ukmo_hadgem1 A1B)	Northern	1906	3750	4461	5285
	Central	1049	1213	1754	1903
	Southern	1242	794	1424	1516
Median runoff (Inmcm3_0 B1)	Northern	594	715	1498	2341
	Central	427	397	868	932
	Southern	684	363	1400	1503
Maximum runoff (Cccma cgcm31 A1B)	Northern	-1900	-1435	-2211	-918
	Central	-255	78	-457	223
	Southern	325	574	456	741

Source: Authors' creation.

Figure 1: Climate zones and river basins in Vietnam



Source: Authors' creation.

Figure 2: Temperature changes from the reference, 2012-50

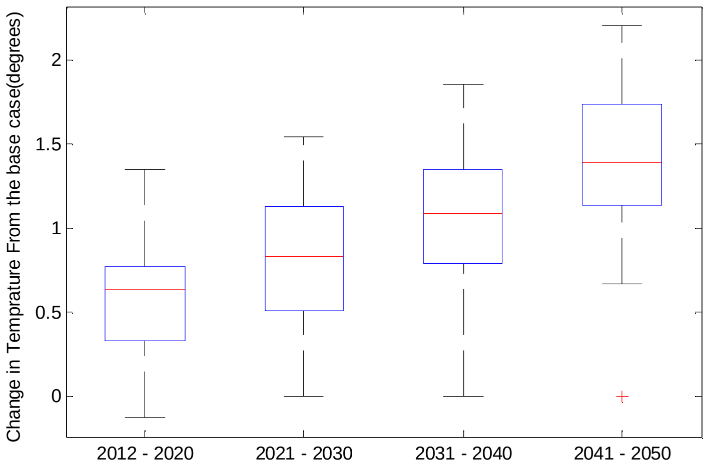


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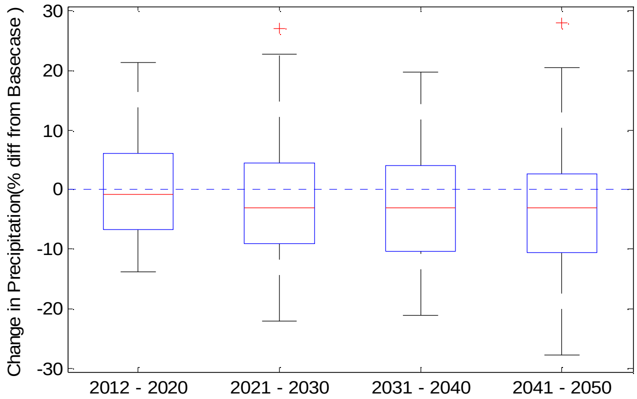
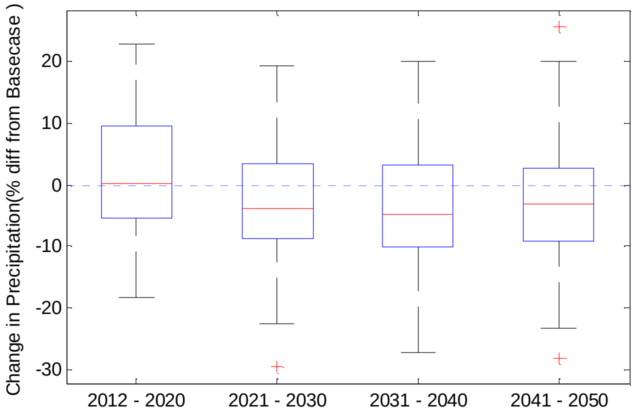
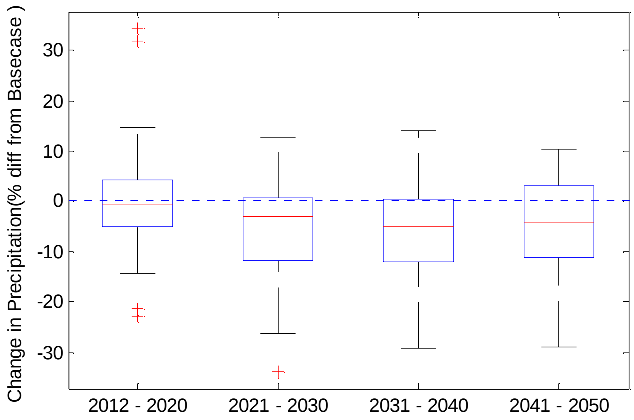
Figure 3: Precipitation anomalies by region and time period, 2012-50



Average precipitation change for Northern Catchments



Average precipitation change for Central catchments



Average Precipitation change for Southern Catchments

Source: Authors' creation.

Figure 4: Changes in climate moisture index (CMI) and potential evapotranspiration (PET) from baseline to the 2041-50 mean for Vietnam

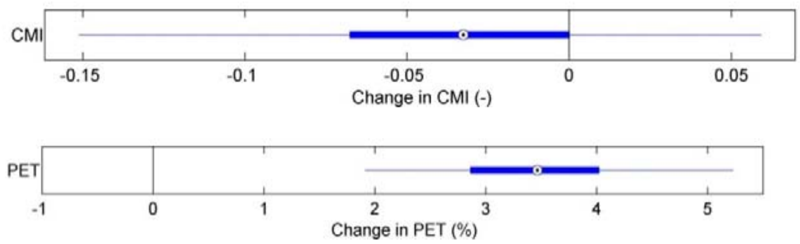


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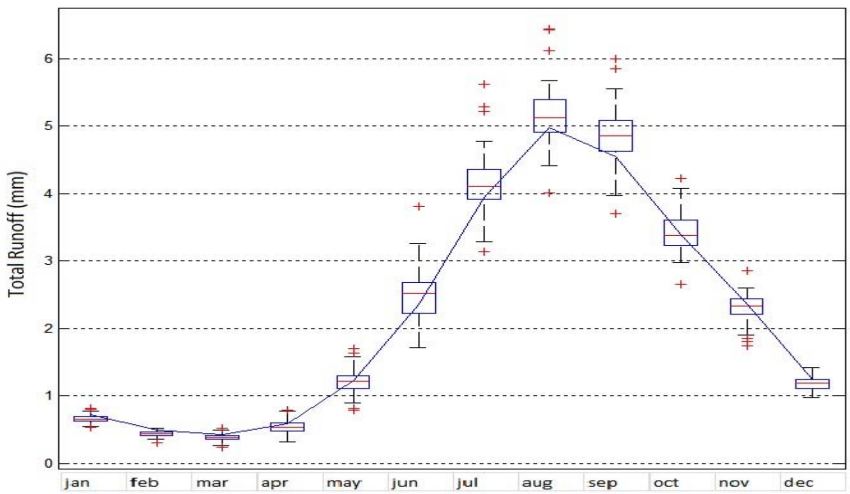
Figure 5: Monthly average runoff comparison of base case and all the 56 GCM runoff output



Source: Authors' creation.

Figure 6: Monthly runoff comparison of base case against highest and lowest national annual runoff results of CLIRUN.

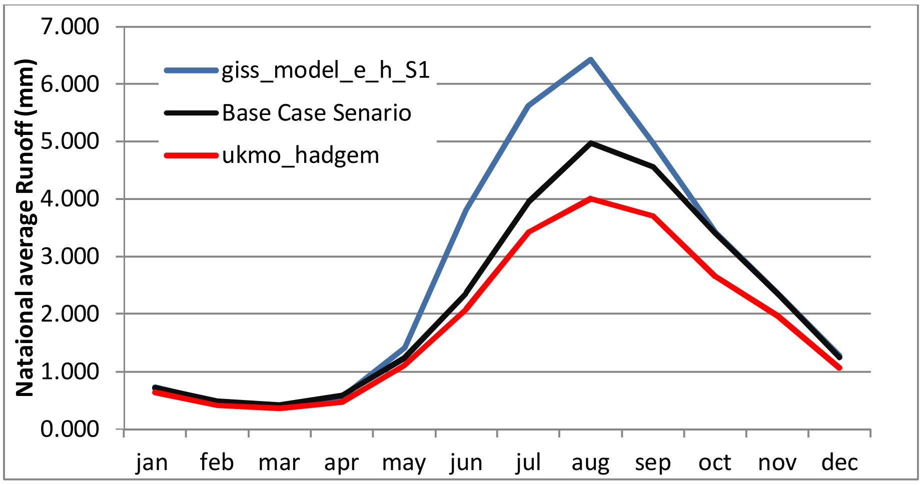


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Figure 7: Spatial comparison of runoff result for dry and wet scenarios

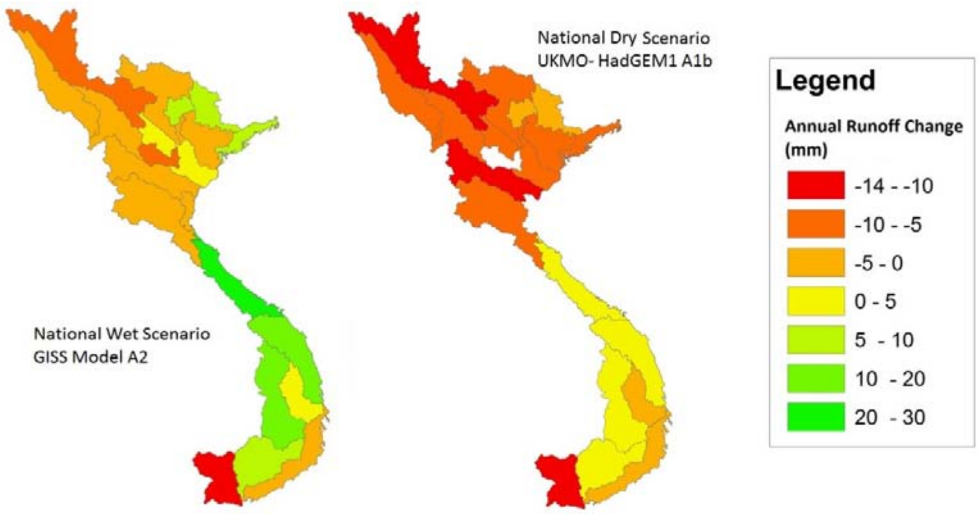

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Figure 8: Changes in yield factor from baseline to the 2041-50 mean

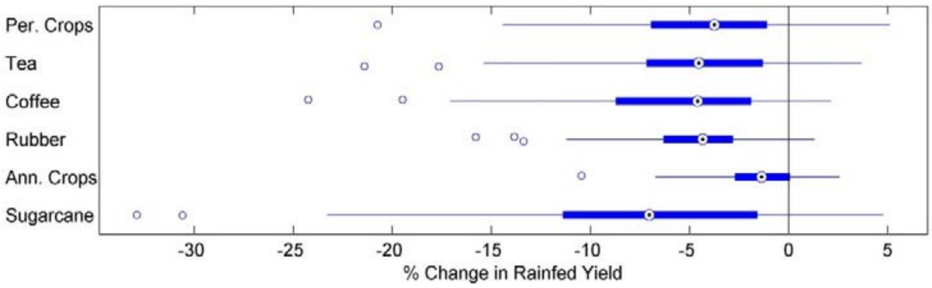

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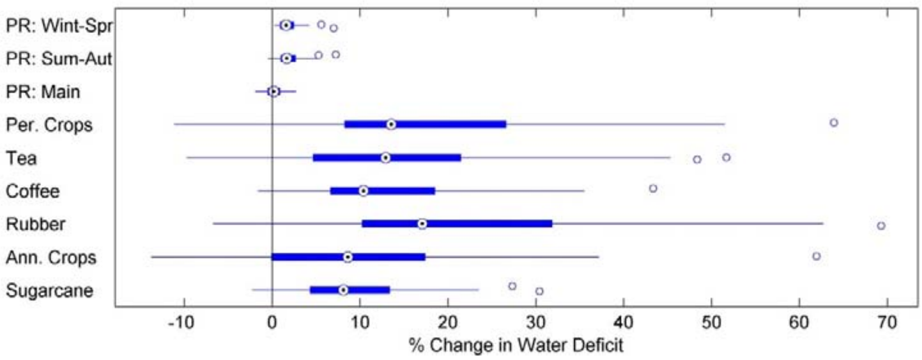
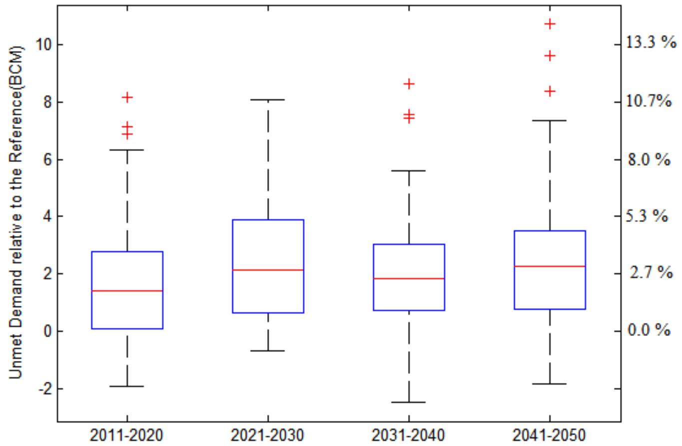
Figure 9: Changes in irrigation demand from baseline to the 2041-50 mean



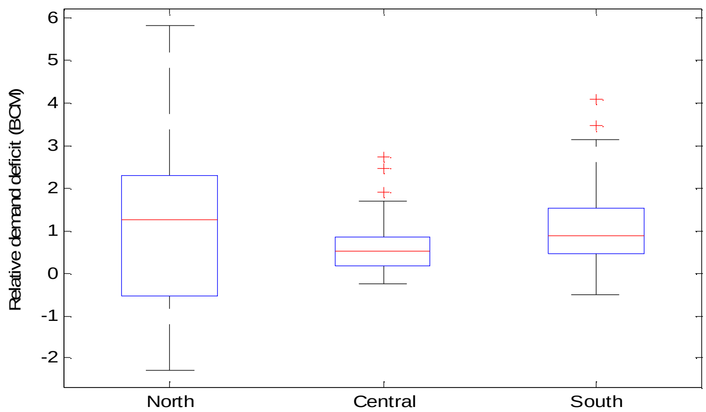
Source: Authors' creation.

Figure 10: Unmet irrigation demand relative to baseline



Source: Authors' creation.

Figure 11: Relative unmet demand in the three regions for the year 2050



Source: Authors' creation.

Figure 12: Hydropower production relative to the baseline

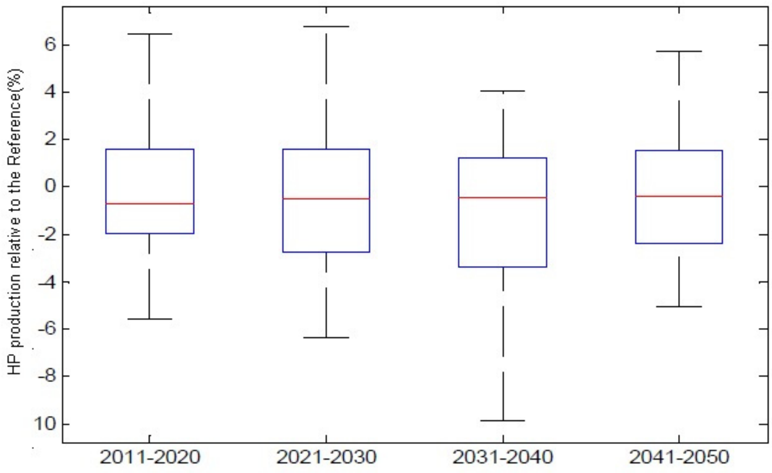


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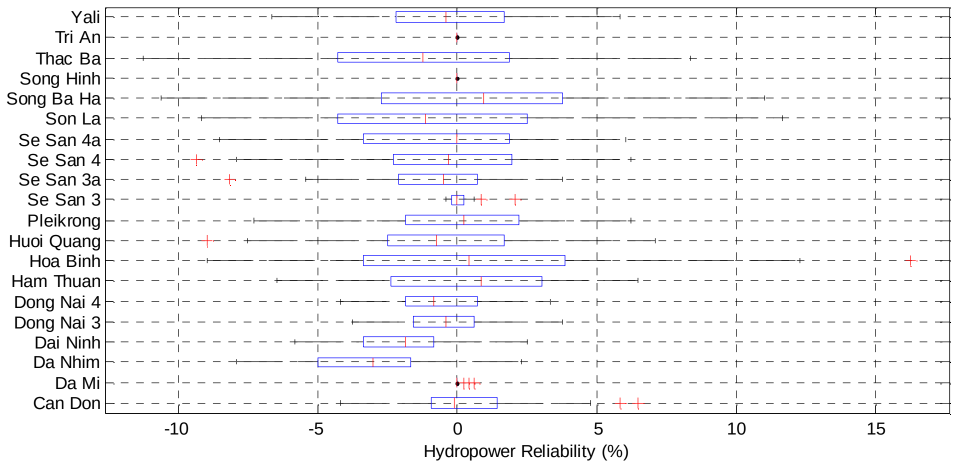
Figure 13: Hydropower reliability for selected dams



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