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Adaptation Options to Reduce the Vulnerability of Mekong Water Resources, Food Security and the Environment to Impacts of Development and Climate Change

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From: Personal collection of Mac Kirby
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Photographer: Mac Kirby

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EXECUTIVE SUMMARY

The waters of the Mekong River and its tributaries, flowing through one of the world's largest river basins, are used mainly for hydropower and irrigation but they also the life-giving waters of the amazing basin ecosystem that provides livelihoods of millions. Thus the river flow regime will be affected by climate change and by hydropower or irrigation developments in the Basin. The Basin Development Plan (BDP) Scenarios take account of development and management of water and related resources such as hydropower generation and irrigation expansion. This report presents: (i) the framework of the climate change analysis and its application to the BDP Scenarios; (ii) the results of the Decision Support Framework (DSF) models for the analysis of the climate change impacts and the selected BDP Scenarios on flow regimes; (iii) the results of the impact of climate change on floods and fisheries, (iv) the results of climate change impact on agricultural productivity and its consequences on food security; (v) adaptation strategies related to agricultural productivity; and recommendations for further studies to identify suitable adaptation strategies for dealing with such impacts.

The analysis comprises six scenarios defined by a BDP Scenario combined with a climate dataset. Scenario 1 uses observed climate data, whereas the other scenarios use Regional Climate Model (RCM) data:

S1: BDP baseline scenario + observed climate data for 1985 - 2000.

S2: BDP baseline scenario + adjusted RCM data for 1985 - 2000.

S3: BDP future development scenario + adjusted RCM data for 1985 -2000.

S4: BDP baseline + adjusted RCM data of A2 and B2 scenarios for 2010 - 2050.

S5: BDP future development scenario + adjusted RCM data of A2 and B2 scenarios[1] for 2010 - 2050.

S6: BDP future development scenario + adjusted RCM data of A2 and B2 scenarios for 2010 - 2050 + adaptation strategies.

The scenarios allow a test that the models with the RCM data reproduce their behaviour using observed data (comparing S2 with S1). Other comparisons give the impacts of development in the absence of climate change (S3 – S2), and with climate change (S5 – S4); of climate change without development (S4 – S2) and with development (S5 – S3); of development and climate change combined (S5 – S2); and finally they give the impacts of adaptation strategies (S6 – S5).

In this first assessment, two BDP Scenarios, the Baseline Scenario and the Lower Mekong Basin (LMB) 20-Year Development Plan Scenario, were selected in order to compare the impacts of climate change on the flow regime. Data on climate change were the future climate projection daily data for the two Scenarios A2 and B2 from the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC SRES) as provided by the SEA START Regional Centre and based on the ECHAM4 GCM from the Max Planck Institute for Meteorology, Germany. These were downscaled to the Mekong region using the PRECIS system.

In order to project the flow changes under different climate and development options, DSF simulation models, the SWAT hydrological model, the IQQM basin simulation model and the hydrodynamic ISIS model were used. The PRECIS climate data produced for 2,225 grid cells covering the entire Mekong River Basin at a resolution of 0.2 degree x 0.2 degree (equivalent to about 22 km x 22 km) were processed in three steps: (i) aggregation of data from grid cells

[1] A2 and B2 are two climate change SRES (Special Report on Emission Scenarios) scenarios studied by IPCC (2000). In brief, A2 corresponds to a storyline of high population growth with slower per capita economic growth and technological change, while B2 corresponds to a storyline of moderate population growth and economic development with less rapid and more diverse technological change.

to sub-basins; (ii) adjustment to fit simulated data with observed data for 1985 - 2000; and (iii) adjustments to the projected data for 2010 - 2050.

After simulated data from 1985 – 2000 were adjusted by a comparison with the observed data and applied to the future, the results showed changes in both precipitation and temperature. The PRECIS climate data revealed a trend of a slight increase in precipitation throughout the Mekong Basin, except in Cambodia and in the Vietnam Delta with a 1.2 – 1.5 mm/year a projected increase in precipitation from now until 2050. This means that the rainy seasons will be wetter; however the precipitation increase in Scenario B2 is less than that in Scenario A2. Wetter dry seasons in the Upper Mekong Basin (UMB) with an increase of 0.9 mm/year are also projected, but precipitation changes in the Lower Mekong Basin (LMB) are insignificant. Temperature is projected to increase by about 0.023°C/year. These projections are similar to those found by other studies.

The projections of the impacts of both climate change and development are somewhat different; mostly in terms of the level of the water flows. At times of high-water flow the impacts of climate change have an opposite effect to those of development. In Scenario S3 with the climatic conditions of 1985 - 2000, the impact of development is to decrease the river flow by 8 - 17% (the results of Scenario S3 minus those of S2), but from 2010 - 2050, the decrease is somewhat less, at about 7 - 14% (the results of Scenario S5 minus those of S4). These percentages are percentages of the changes in the scenario in which it is assumed that the Baseline will continue in the future. If climate change is taken into account, then the river flow in Scenario S4 is projected to increase by 2 - 11% in comparison to that in the past (Scenario S4 – S2). The combined effect of development and climate change may cause a decrease of up to 13% in discharge at one station, but an increase of 3% at another station, depending on the climate change scenarios and the location of the stations (Scenario S5 - S2). Such variations clearly show that the current development plan has not been prepared to encompass adaptations to climate change.

In the low-flow season, both the impacts of climate change alone and the effects of development alone bring about increases in the river flow. Climate change causes wetter dry season and snowmelt in the upper Mekong, and the development provides more water from reservoirs in this season, but their combined effect is more complex. Under the climatic conditions of 1985 - 2000, the impact of development, with a total live storage of over 75 billion m^3, is to bring about an increase of 30 - 60% in the river discharge (Scenarios S3 - S2), but under the future climate change conditions, the effects are less at about 18 - 40% (Scenarios S5 - S4) in comparison with the assumption of the Baseline continuing in the future. In this instance river flow would increase by about 18 - 30% (Scenarios S4 - S2). The effect of both climate change and development may cause an increase of discharge of up to 40 - 76% (Scenarios S5 - S2), depending on the climate change scenarios and the location of the stations.

When a combination of the effects of climate change and development are considered in both seasons, the annual discharge will decrease by about 3 - 8% as a result of the effects of development under both the past climate conditions and the future climate change (Scenarios S3 - S2, and Scenarios S5 - S4). On the other hand, climate change would increase the river discharge by 6 - 16% under both the Baseline and the Development Scenarios (Scenarios S4 - S2, and Scenarios S5 - S3). The effect of both climate change and development may cause an increase in discharge of about 2 - 12% (Scenarios S5 - S2), depending on the climate change scenarios and the location of the stations considered. These changes show that a seasonal analysis is needed to deal with development and climate change issues.

The contribution of snowmelt to the annual water yield (or runoff) at the Chinese-Lao border will be slightly increased, from 5.5% to 8% under climate change. Although the contribution of snowmelt in the dry season (for example, in March) is more significant, the percentage increase in river discharge does not change a great deal. Its effect becomes of minor importance at stations further downstream.

If the Baseline were to continue into the future with climate change, the number of days with a discharge higher than that of the high-flow seasonal mean is expected to increase. The effect of development is to significantly reduce this number at the upstream stations, but rather less at the downstream stations. While development can help in reducing the areas of flooding, climate change will increase these areas in worse years. Climate change could increase the areas with saline intrusion, but to a smaller extent than the increase in flooded areas, and development can help to reduce the affected areas. However, the uncertainty in the projection of future precipitation should be remembered when reaching these conclusions.

An empirical fisheries model developed for the Tonle-Sap Great Lake System was applied to predict how exploitable fish biomass in the LMB might respond to flows under future climatic conditions and planned basin development activities. An index of fish biomass was predicted for water levels and indices of flood extent and duration corresponding to six climate change and basin development scenarios under future emissions scenarios A2 and B2. The results indicate that given the extent of natural variability in the system combined with the predicted marginal changes in the flood indices, particularly under the 20 year future development scenarios, the effects of climate change on fish biomass in the TS-GL system during the next 40 years are unlikely to be detectable. Changes to the flood indices would need to be in the order of 30 % to have statistically detectable impacts on predicted fish biomass compared to the 10 % - 26 % increase in the indices predicted with the present dataset. Basin development activities are however predicted to have a significant effect on minimum (dry-season) water levels, raising them by approximately 30 cm depending upon the climate change scenario.

The effects of raised dry season water levels on system productivity and growth-related effects on fish biomass were accounted for in the analysis. Furthermore, earlier modelling studies suggest that the associated increase in dry season water availability is unlikely to benefit fish biomass significantly. Basin development activities not only have the potential to modify the hydrology and associated productivity of the river system, but in the case of dam construction, may obstruct fish migrations between critical habitats and raise natural mortality rates in fish populations. It is possible that blockages to fish migration particularly in the main stream of the Mekong are more severe in their impact on fish stocks than changes in flow regime. Consequently, there is an urgent need to consider these additional physical impacts alongside the impacts of future flow regimes. Indeed, the barrier effects of dams on fish migrations may become more important in a warming basin because they will diminish opportunities for fish to colonise areas with appropriate thermal conditions.

We examined the impact of climate change (changes in maximum and minimum temperature, rainfall, radiation, wind speed, CO_2 concentration and potential evapotranspiration) on the productivity of rainfed rice, dry season irrigated rice and maize of the basin using the model AquaCrop developed by FAO (Food and Agricultural Organization of the United Nations). These crops cover about 90% of the annual total harvested area of the basin. We divided the basin into 14 agro-climatic zone (3 in Laos, 4 in Thailand, 4 in Cambodia, 3 in Vietnam) based on rainfall and evapotranspiration, and selected a sub-catchment within each zone for setting-up the model. We modelled climate change as a change in climatic data and CO_2 emission only. The model was run for climate scenarios A2 and B2 for the period of 2010 to 2050. The CO_2 emission was considered both varying from year to year according to SRES scenario and keeping at year 2000 level for the future. We ran the model in 14 locations for rainfed rice, 3 locations for irrigated rice (1 each in Laos, Thailand and Vietnam) and 6 locations for maize (2 in each country). For the base case, the model has been set-up and validated for the data of 1996-2000. For rainfed rice, we ran the model considering different adaptation scenarios such as shifting transplanting date of rice, varying levels of fertilizer application and use of supplementary irrigation, etc.

Results suggest that yield or productivity of rice will increase for much of the basin except for a small part of Cambodia and Vietnam mainly in the A2 scenario, and about upper half of the basin in the B2 scenario. The increase is higher in Laos and Thailand and for A2 scenario than the B2 scenario. The change in productivity is mainly due to change in rainfall and increased CO_2 concentration in the atmosphere. The productivity of irrigated rice could be significantly higher all over the basin if increased irrigation requirements (11% for the basin) due to increase in temperature is provided. Increased temperature slightly affects the yield of irrigated rice but increased CO_2 concentration offsets this impact and helps significant net increase. The productivity of maize is not affected at all adversely by any change in climatic parameters. Yield may increase significantly all over the basin due to increased CO_2 concentration in the atmosphere.

Shifting the planting date of rainfed rice can increase the yield and minimize (no decrease) the impact in the areas where yield is adversely affected. Fertilizer use in the basin is currently at sub-optimal level (i.e. there is fertility stress) particularly in the areas in Laos, Thailand and Cambodia. Reducing the fertility stress and providing supplementary irrigation can further enhance yield. Food security of the basin in terms of total production is unlikely to be affected by the increased population, and the impact of climate change. There is even potential for the basin to maintain current levels of rice exports in the future if the current trend of productivity continues. This will be further augmented by the increase of CO_2 concentration in the atmosphere. However, food security of the individual depends on the distribution of food and the purchasing power of poor people who do not grow rice. The analysis does not take into account the indirect impact of rainfall such as floods, drought, dry spells, sea level rise, etc. and the impact of natural disaster such as cyclones, storm on the productivity. All these extreme weather events may have significant and widespread adverse impact on yield.

This study concludes by recommending that (i) analysis with more climate change models would be helpful to understand the uncertainty in climate change projections and their impacts; (ii) further study and testing of the adjustment methods are needed to ensure that the projection trend will be maintained properly while any bias from climate modelling is removed; (iii) more observed climate data (i.e. from more stations and of longer duration) and other data used in modelling such as land use, water use, reservoir regulation rules should be collected; (iv) in addition to the refined DSF models with more functions and improvement of simulation accuracy, supporting tools are needed to handle large datasets for climate change analysis, and simplification for a basin-wide assessment which is more focussed rather than one attempting to cover more sub-basin details is needed; and (v) the DSF, designed and set-up only for the analysis of changes in flow regime under different scenarios, should be supported by other models and analyses or improved with new components to become an integrated modelling package for analysing changes other than just those of the flow regime; and (vi) the AquaCrop model, currently calibrated for just a few years due to limitations of climate data, should be recalibrated and validated for recent years and used to simulate the yield for future conditions using the generated data of different GCM models as described in point (i).

Some considerations follow from this research for policy or action in the Mekong. However, the general studies in this report will require more detailed study (as above) in association with the suggested actions. The predicted more frequent and more extreme high flows may require consideration of flood mitigation. The finding that flow impacts on fish may not be as great as the impact of barriers suggests that dams on migration routes will require careful impact assessments. The adaptation strategies (changed planting dates, supplementary irrigation and increased use of fertilisers) will require development of education, extension and trials to the agricultural districts.

1. INTRODUCTION

1.1. Background

The Mekong River Basin is one of the world's largest river basins. Its length of 4,800 km makes it the twelfth longest in the world, while its area of 795,000 km^2 makes it the twenty-first in terms of size. Twenty two percent of the Basin lies in the People's Republic of China (China), 3% in the Union of Myanmar, 25% in the Lao People's Democratic Republic (Lao PDR), 23% in the Kingdom of Thailand (Thailand), 19% in the Kingdom of Cambodia and 8% in the Socialist Republic of Vietnam (Vietnam). The contribution of these countries to its mean annual discharge of 475,000 million m^3 (ranked the eighth largest in the world) are 16%, 2%, 35%, 18%, 18% and 11% respectively. The Lower Mekong Basin (LMB) covers a total downstream area of about 620,000 km^2 in the countries of Lao PDR, Thailand, Cambodia and Vietnam. Figure 1.1 illustrates the Mekong River Basin together with a longitudinal profile of the Mekong River from its headwaters to its mouth (MRC, 2005). In 2006, a population of over 60 million depended on the Basin resources for their livelihoods.

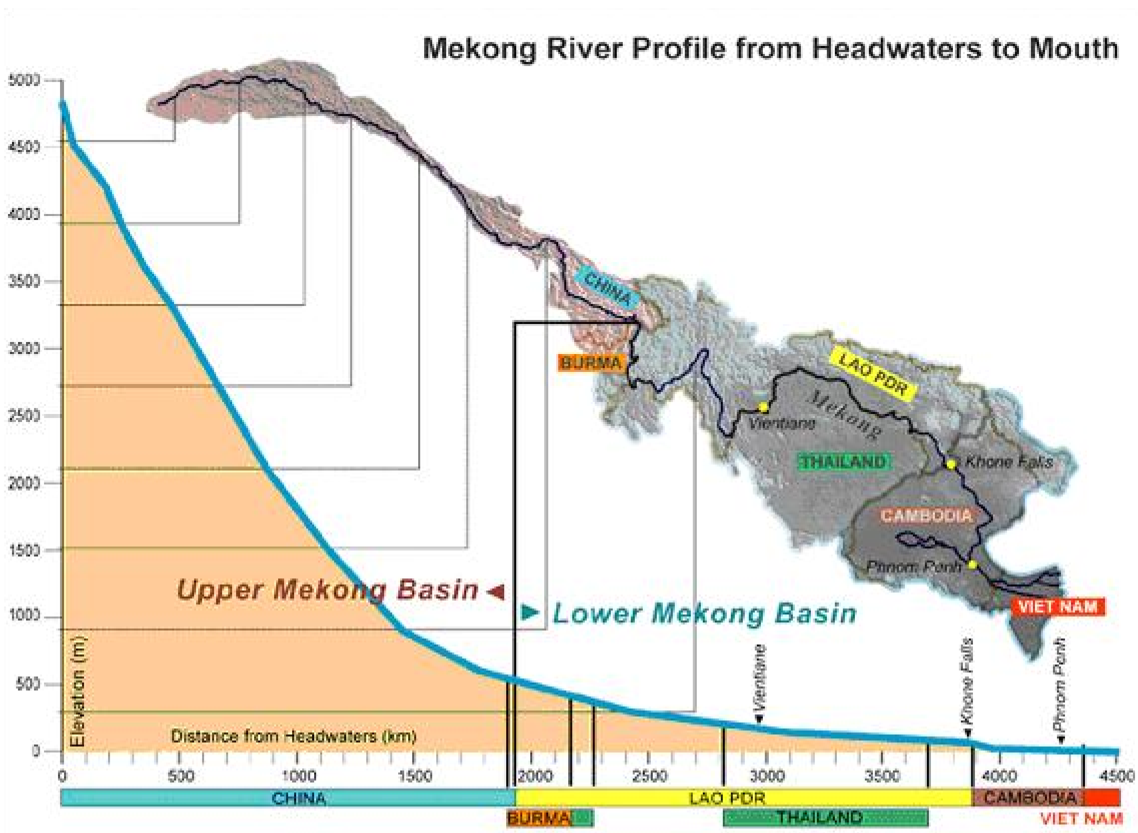


Figure 1.1 Mekong River Basin and longitudinal profile of the Mekong River (MRC, 2005)

The hydropower and irrigation sectors are the two major users of water in the Mekong Basin. Many mainstream hydropower dams have either been constructed or are being planned. These include the two existing hydropower dams, the Manwan and the Dachaosan, in the Lancang[2] mainstream, the Xiaowan and the Jinghong Dams under construction, and the Nuozhadu Dam for which preparations are being made for its construction. In Thailand, six major tributary reservoirs are in operation, namely the Ubol Ratana, Chulabhorn, Sirindhorn,

[2] In the UMB in Yunnan in China, the Mekong River is known as the Lancang River

Pak Mun, Lam Pao and Nam Oun Dams. These dams are for hydropower and irrigation in the north east of Thailand where a significant number of irrigation systems exist and more are planned. In Lao PDR, three major tributary reservoirs, namely the Nam Ngum, Nam Theun Hinboun and Huai Ho, are hydropower dams, and others, such as Nam Ngum 2 and Nam Theun 2, are under construction. In Cambodia, the Great Lake, linked to the Mekong River by the Tonle Sap River, covers an area varying from 3,000 km^2 in the dry season to 15,000 km^2 in the wet season, and is considered the heart of the LMB. It is also the largest source of freshwater fish in Southeast Asia. The reverse flow from the Mekong River to the lake along the 120 km of the Tonle Sap River creates complicated hydraulic and ecological processes in the area. In Vietnam, the largest reservoir for hydropower is the Yali Falls on the Se San River, a major tributary in the east of the Mekong Basin; an area identified as having a high hydropower potential. The Mekong Delta in Vietnam is the most important rice producing region in the country. In the low-flow season, the tidal effect in the Delta is observed up to Phnom Penh in Cambodia. About 2.5 million hectares in the Delta are irrigated and drained for rice cultivation. However, in the low-flow season agriculture is practised only in a small fraction of this area because of insufficient freshwater and the intrusion of seawater.

Current climate change estimates indicate that major environmental changes are likely to occur due to climate change in practically every part of the world (IPCC, 2007), with majority of these changes being felt through modification of hydrological cycle as e.g. floods, droughts and storm (TKK and SEA START RC, 2009). Yusuf and Francisco (2009) provide information on the sub-national areas (regions/districts/provinces) most vulnerable to climate change impacts in Southeast Asia. The assessment was carried out by overlaying climate hazard maps, sensitivity maps, and adaptive capacity maps following the vulnerability assessment framework of the United Nations' Inter-governmental Panel on Climate Change (IPCC). However, the study does not provide impact on single factors on the Mekong but combined them into an index of the overall climate change vulnerability of the region. The impact of climate change is neither clear nor uniform across the Mekong basin, but the studies suggest that in several regions the dry season may lengthen and intensify, and that the rainy season may shorten and intensify. Thus both seasonal water shortages and floods may be exacerbated, as may saltwater intrusion into the delta (Hoanh et al., 2003; Snidvongs et al. 2003; Chinavanno, 2004).

A recent global study by Allison et al. (2009) identified the countries of the LMB as some of the most vulnerable in tropical Asia to the effects of climate change on their fisheries. These impacts are likely to arise through complex behavioural, physiological and habitat change-related responses which must be considered in the context of other stressors including basin development activities. Higher temperatures and increasing, but more variable, precipitation-driven flows have the potential to directly and indirectly effect fish populations and dependent fisheries and livelihoods.

The population of the LMB is expected to increase to about 88 million by 2050 (based on medium variant projection, UN Population Division, 2006). The anticipated changes to climate and river flow are expected to affect agriculture and food production, the overall effect being to exacerbate the problems of supplying the increased food demand of growing populations (Hoanh et al., 2003; Snidvongs and Teng, 2006). Thus, agricultural enterprises face greatly increased demand for food on the one hand and several threats to production on the other.

Against this background, it is important to examine the potential impact of climate change and development on the flow regime, floods and fisheries, crop production, and food security of the basin, and feasible adaptation strategies.

1.2. Purpose of the study

The report aims to provide critical input to the Mekong River Commission's (MRC) regional Climate Change and Adaptation Initiative (CCAI) which was launched shortly after the formulation of this project. The CCAI is a collaborative regional initiative designed to address the shared climate change adaptation challenges of LMB countries in response to the potential effects of climate change on the socio-economic characteristics and natural resources of the LMB region. MRC has identified need for a more informed understanding of the potential impacts from climate change. To contribute to this aim, the purpose of this report is:

1. To present the framework of climate change analysis and its application to the Basin Development Plan (BDP) Scenarios;
2. To present the results from the application of the Decision Support Framework (DSF) models of the Mekong River Commission (MRC) in order to analyse the impacts of climate change and selected BDP Scenarios on flow regimes;
3. To present climate change impacts on floods and fisheries in the LMB;
4. To present the impact of climate change on the productivity of major crops grown in the basin and their consequences on the overall food security of the basin considering future population growth.
5. To present the results of applying simple adaptation strategies related to agriculture and food security; and
6. To determine further studies necessary to identify suitable adaptation strategies for dealing with such impacts.

1.3. Organization of the report

After the introduction described in this Chapter, a brief introduction to the DSF and the framework of the climate change scenario analysis is introduced in Chapter 2. Chapter 3 presents the processing of the PRECIS data for the provision of climate inputs for the analysis and the results of model runs for the Baseline Scenario with observed and PRECIS data. Changes in the flow regime due to both development and climate change are discussed in Chapter 4. Chapter 5 presents the climate change impacts on floods and fisheries of the basin. The impact of climate change on the agricultural productivity and adaptation to agriculture and implications for food security are presented respectively in Chapters 6 and 7. Finally, conclusions and recommendations for further studies are presented in Chapter 8. Methods for adjustment of GCM based on observed data and some tables and figures are presented in Appendices A, B and C.

1.4. Limitations of the study

In this first assessment of climate change impacts on flow regime, the analysis is based on existing climate change data downscaled to the Mekong Basin by the SEA START (South East Asia SysTem for Analysis, Research and Training) Regional Centre using the PRECIS (Providing Regional Climates for Impacts Studies) Regional Climate Model developed by the Hadley Centre, a leading climate research centre in the United Kingdom. In this study, PRECIS data were adjusted against the available observed data used for setting-up and calibrating the DSF models.

The DSF models used in this study were those versions available at the end of 2008. Some difficulties were encountered when these were run over the long period of 40 years. These difficulties are discussed in the recommendations in Chapter 8. The development scenarios used in this study were provided by BDP (Basin Development Plan) and IKMP (Integrated Knowledge Management Program) Modelling Teams at the end of 2008. This report deals only with the impacts of climate change and development on the flow regime at the Basin level. More detailed studies will be required in the coming years to account for newly collected observed data, updated development scenarios, including projections of land use changes, updated climate change data from RCM, and the refined DSF models currently being tested. Since the study covered the whole Mekong Basin it could not provide a detailed analysis of certain sub-basins or areas that require more data and modelling efforts.

The Mekong DSF uses daily climate input data at a fairly fine spatial resolution (small sub-catchments). For the climate change input data we therefore sought daily data at a reasonably fine scale. Such data were available from the RCM, but downscaled only for one global climate model. The data were available as a projected time series to 2100. We elected to use these data with the DSF to give a good picture of the long-term trend of future climate change impacts. An alternative approach, used by Eastham et al. (2008), used 50 year historic climate monthly sequences for each catchment, and scaled them to give a projection of the possible climate for a future year (2030 was chosen by Eastham et al.). This method gives both a mean and projected variability of the climate at a future year. Furthermore Eastham et al. repeated the method for 11 GCMs (the 11 models were those that performed best for the Mekong), thus giving the uncertainty amongst the IPCC models. The method thus gives a projection of the variability of the climate as well as the uncertainty amongst models. However, this method was not suitable for the present study as the monthly data were not suitable for the DSF model. The effort and time required to repeat the DSF modelling for an ensemble of GCMS downscaled with an RCM would also have been prohibitive and in any event was not available. Nevertheless, the work of Eastham et al. gives an idea of the likely uncertainty inherent in the choice of one GCM / RCM in the method used here.

RCM data for the Mekong basin are available until 2100, but the time horizon of our analysis is up to 2050 since this is more realistic for the current BDP Development Scenario. Because observed data in the DSF are available only for the 16 years from 1985 - 2000, and are used for the Baseline Scenario, future comparisons are also divided into 16 year periods, i.e. 2010 - 2025, 2026 - 2041, 2042 - 2050 thus covering the whole period of 2010 - 2050. The impacts of sea level rise, usually modelled with climate change, are not considered in this study. In addition, the adaptation of people and ecosystems, such as changes in river and canal configurations due to changing hydraulic conditions and human activities for strengthening the protection, and changes in the mangrove forest along the Delta coastline, will require more detailed studies which could not be covered by this project.

As the baseline climatic data are not available beyond 2000, the model for agricultural impact study was set up for the period of 1996-2000 though more recent crop data are available.

2. MRC DECISION SUPPORT FRAMEWORK AND CLIMATE CHANGE SCENARIO ANALYSIS

2.1. Background to the development of the Decision Support Framework (DSF)

On April 5 1995 in Chiang Rai, Thailand, the four Lower Mekong Basin countries of Cambodia, Lao PDR, Thailand and Vietnam signed the “Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin” (MRC, 1995), and so agreed “to cooperate in a constructive and mutually beneficial manner for sustainable development, utilisation, conservation and management of the Mekong River Basin water and related resources”. Three articles, namely Article 5: Reasonable and equitable utilisation; Article 6: Maintenance of flows on the mainstream; and Article 26: Rules for water utilisation and inter-basin diversions deal with the utilisation of the Mekong water.

In 1999, the Water Utilisation Programme (WUP) was established. One of its main tasks was the development of a planning tool, known as the Decision Support Framework (DSF), to assist in the implementation of Articles 5, 6 and 26 of the Agreement. In September 2001, development of the DSF began, and was completed in March 2004 (Halcrow, 2004).

2.2. Structure of Decision Support Framework (DSF)

The Decision Support Framework (DSF) comprises a knowledge base (KB) and a DSF User Interface and Tools giving access to a Basin Simulation Modelling Package. The Interface also gives access to Impact Analysis Tools (IAT) and Reporting Tools. Details of the structure are shown in Figure 2.1.

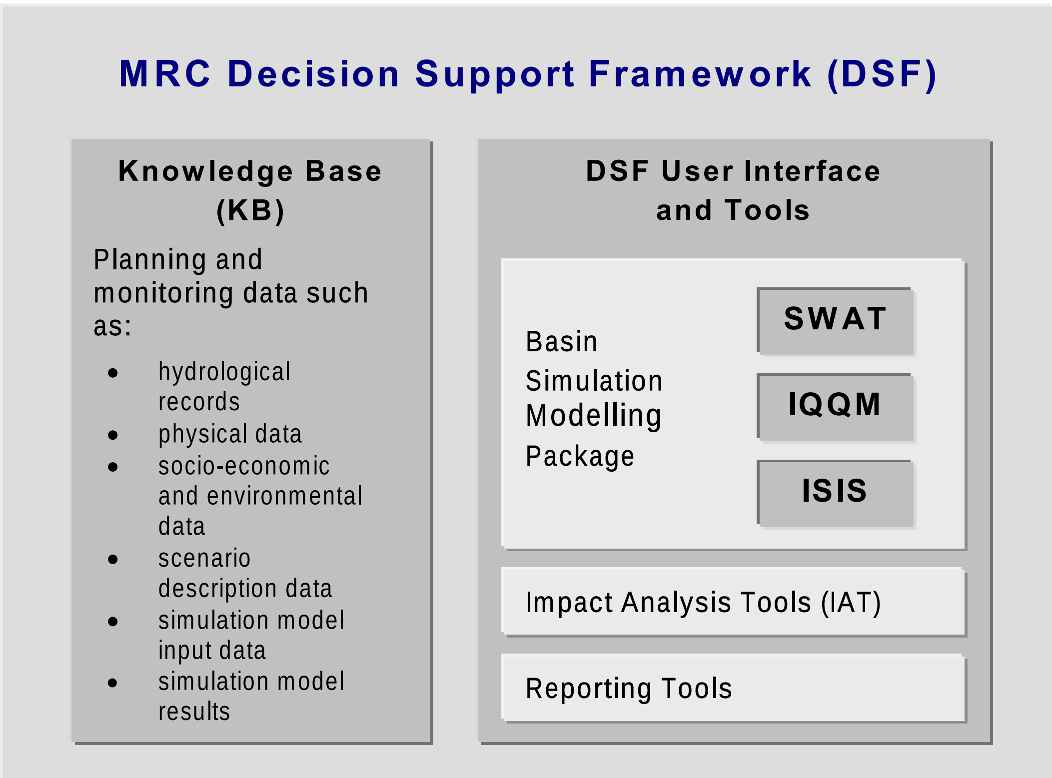


Figure 2.1 Structure of the Decision Support Framework (DSF)

1. The Knowledge Base contains information on the hydrologic and meteorological historic records, topographic data of the river network, land use, socio-economic and environmental conditions, scenario description and model input data as well as model outputs for the projection of changes in the flow regime under the different scenarios.
2. The Simulation Models enable the projection of flow changes under different climate and development options within the Basin. This element comprises three models, namely:

   A Hydrological Model

   The Soil and Water Assessment Tool (SWAT), a hydrological model developed by the US Department of Agriculture, has been set up under the DSF to simulate runoff based on certain parameters: observed daily climatic data, topography, soils and land cover of each sub-basin. Although the SWAT model is also able to investigate nutrient and sediment flows, at present, these cannot be analysed at a basin scale because of the limited availability of data.

   A Basin Simulation Model[3]

   The SWAT model also provides inputs to the Integrated Water Quantity and Quality Model (IQQM), originally developed for the Murray-Darling Basin in Australia but used for the LMB. This simulation model routes catchment flows through the river system, taking account of any control structures such as dams and irrigation abstractions in demand nodes. Daily discharges are generated throughout the River system and, in particular, at the primary outfalls of Kratie on the mainstream and the Great Lake in the Tonle Sap Basin.

   A Hydrodynamic Model

   The ISIS, a hydrodynamic model, developed by HR Wallingford and Halcrow, is used to simulate the water level, discharge and salinity in the River system from Kratie to the river mouth, and includes the Tonle Sap Lake and the East Vaico in Vietnam. The model represents the complex interactions caused by tidal influences, flow reversal in the Tonle Sap River and the over-bank flow during the flood season.
3. Impact Analysis Tools enable the projection of environmental and socio-economic impacts in response to changes in flow regimes by using Time Series Impact Analysis Tools. In addition, the DeltaMapper in the DSF is used to interpolate water level and salinity outputs at the ISIS nodes to grid-based flood depth, flood duration, salinity and salinity duration maps.

2.3. Application of the Decision Support Framework Models

Since 2004 the DSF Models have been used to analyse the Mekong flow regime under different scenarios. In the beginning, the full set of three DSF models was used for the entire LMB. The SWAT model was used for the area from the Chinese-–Lao border to Kratie in Cambodia (Figure 2.2) by dividing this area into 8 sub-models with 121 sub-basins, while the IQQM model was designed to receive inputs on water yield and runoff as calculated by SWAT. Inflow from China at the uppermost point of the IQQM model was estimated from the observed flow at Chiang Saen. Discharge at Kratie, as simulated by the IQQM, was used as the upstream boundary condition for the ISIS hydrodynamic model for the downstream area. SWAT was also applied to 16 sub-models (corresponding to the 16 sub-basins) around the Great Lake in Cambodia, and the East and West Vaico Rivers in Vietnam. The IQQM model was also set up for this area (Figure 2.2) to provide upstream boundary conditions around the Great Lake for the ISIS model, and to estimate water abstractions for irrigation in the

[3] The model is more of a Basin Flow Routing Model. However, Halcrow (who developed the DSF) and MRC including some other authors used this name.

eight provinces of Kratie, Kompong Cham, Kandal, Prey Veng, Kompong Speu, Takeo, Kampot and Svay Rieng in Cambodia. Another IQQM model was set-up to estimate the water abstractions from 120 irrigation sectors in the Vietnam Delta. These abstractions were used in the ISIS model. The ISIS model, thus, starts from Kratie and continues down to the South China Sea, and includes the floodplains along the Mekong mainstream, the Great Lake, the Tonle Sap River and the Vietnam Delta (Figure 2.2).

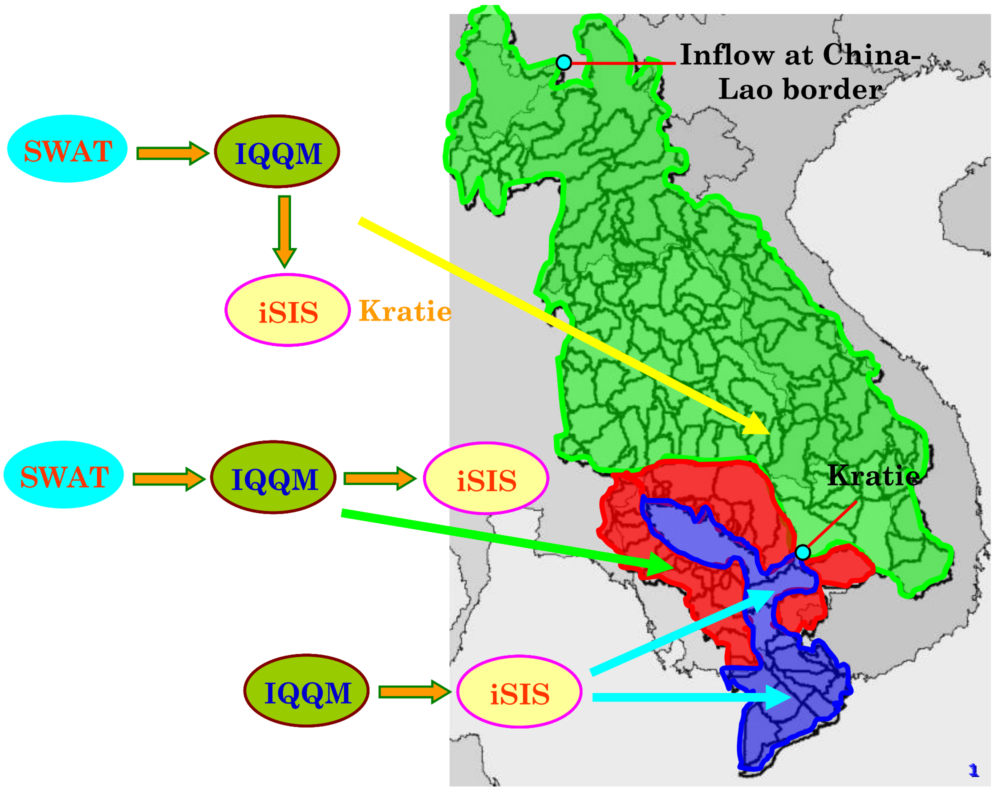


Figure 2.2 Application areas of DSF models

Between 2005 and 2006, the SWAT was re-calibrated by the MRC Modelling Team to represent more detailed topography, land use and soil conditions by dividing the upstream Kratie area into 510 sub-basins (Table 2.1) and the Great Lake area into 63 sub-basins (Table 2.2). In addition, multiple Hydrological Response Units (HRUs) were set up in each sub-basin instead of only one dominant HRU as in the previous version. In 2007, a preliminary SWAT model with 190 sub-basins for the Upper Mekong Basin (UMB) was set-up using secondary data and information from the web to compute the inflow to the LMB under snowmelt, land use change, operations of existing and planned dams, and possible climate change. Thus two options were available for scenario analysis, either by using the model for the UMB or by using the discharge data from Chiang Saen as in the previous BDP scenario analysis. These newer models are used for this climate change study.

Table 2.1 LMB SWAT models from the Chinese–Lao border to Kratie (Locations in Figure 2.3)

SWAT Model Code	Model Name	Number of Subbasins	Model Coverage Area (km^2)
LMB1	China-Lao border to Chiang Saen	30	31,479
LMB2	Chiang Saen to Luang Prabang	60	80,549
LMB3	Luang Prabang to Vientiane	36	30,035
LMB4	Vientiane to Mukdahan	94	90,138
LMB5	Mukdahan to Pakse	59	66,195
LMB6	Pakse to Kratie	118	101,133
LMB7	Chi up to Yasothon	62	46,608
LMB8	Mun up to Rasi Salai	51	44,665
	Total	**510**	**490,802**

Table 2.2 SWAT model around the Great Lake (locations are given in Figure 2.3)

SWAT Model Code	Model Name	Number of Sub-basins	Model Coverage Area (km^2)
GLK1	Stung Chinit	4	6,563
GLK2	Stung Sen	4	15,632
GLK3	Stung Staung	3	4,171
GLK4	Stung Chikreng	3	2,306
GLK5	Stung Siem Reap	5	3,089
GLK6	Stung Sreng	3	9,530
GLK8	Stung Mongkol Borey (included Stung Sisophon)*	6	14,718
GLK10	Stung Battambang (included Stung Sangker)*	5	5,131
GLK11	Stung Dauntri	5	3,494
GLK12	Stung Pursat	3	5,531
GLK13	Stung Boribo	11	7,445
GLK14	Prek Thnot	3	5,806
GLK15	Prek Te	2	4,302
GLK16	Prek Chhlong	3	5,363
GLK17	East Vaico	1	835
GLK18	West Vaico	2	4,135
	Total	63	98,051

Note: * GLK 7 and GLK 9 were combined into GLK 8 and GLK 10, respectively, therefore they are not in this list.

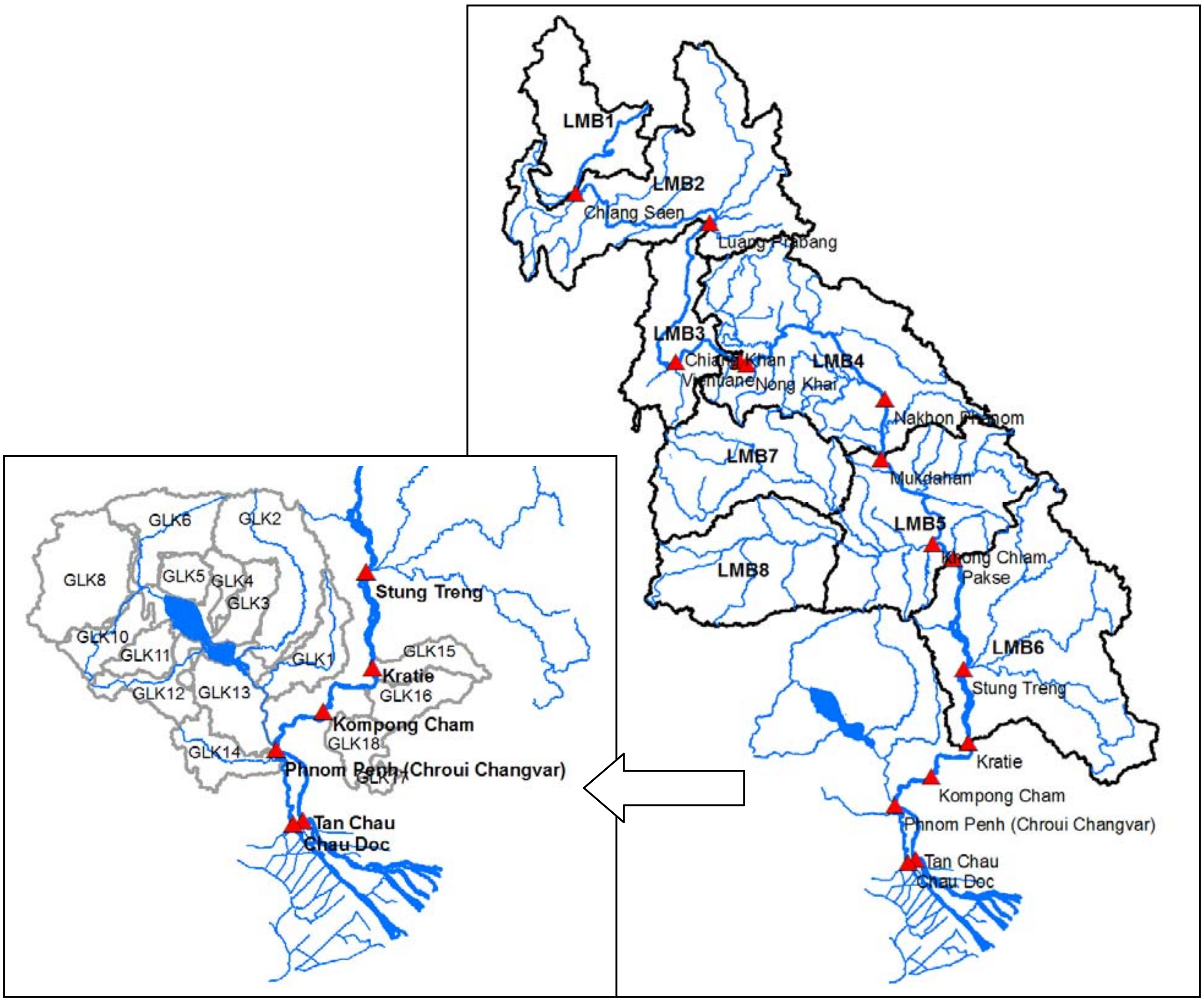


Figure 2.3 SWAT models in the Lower Mekong Basin and key stations in flow analysis

2.4. Design of the framework for climate change scenario analysis

Figure 2.4 presents the framework of the climate change (CC) scenario analysis in this first assessment. In this framework, a scenario model run is defined by a combination of a BDP Scenario and a climate dataset. The data included that observed from 1985 - 2000 and the Regional Climate Model (RCM).

Four groups of scenario model runs (coded S1 to S6) were implemented:

1. Scenario 1 (S1): without climate change, using observed data

   S1: BDP baseline scenario + observed climate data for 1985 - 2000. The model for this scenario had been calibrated by the MRC Modelling and the BDP Teams in previous studies (Halcrow, 2004; Beecham and Cross 2005; TSD Modelling Team 2007).

2. Scenarios 2 and 3 (S2 and S3): without climate change, using RCM data

S2: BDP baseline scenario + adjusted RCM data for 1985 - 2000.

S3: BDP future development scenario + adjusted RCM data for 1985 -2000.

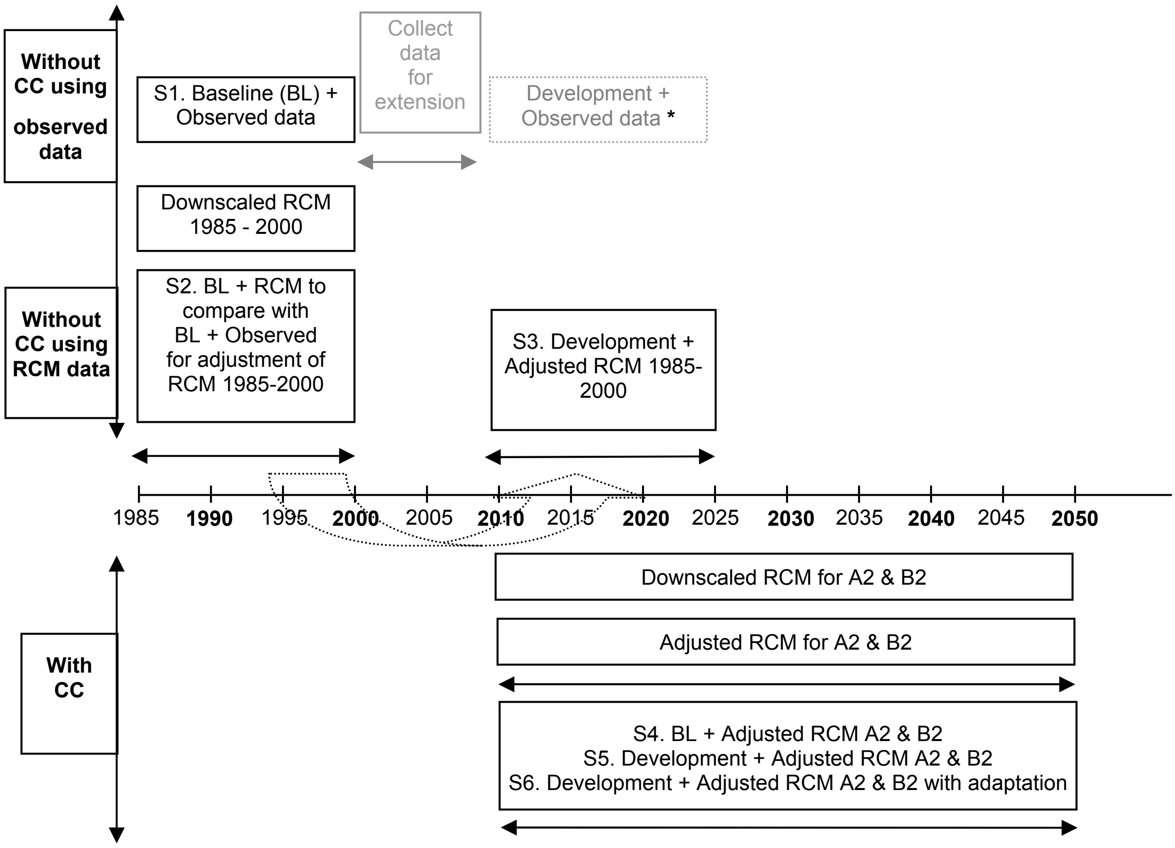
3. Scenarios 4 and 5 (S4 and S5): with climate change, using RCM data

S4: BDP baseline + adjusted RCM data of A2 and B2 scenarios for 2010 - 2050.

S5: BDP future development scenario + adjusted RCM data of A2 and B2 scenarios[4] for 2010 - 2050.

4. Scenario 6 (S6)

S6: BDP future development scenario + adjusted RCM data of A2 and B2 scenarios for 2010 - 2050 + adaptation strategies.



* This model run was under the BDP Scenario Analysis but it is replaced by Scenario S3 in this climate change study.

Figure 2.4 Framework of scenario analysis for impacts of climate change

Since the simulated data for Scenarios A2 and B2 for 1985 – 2000 are identical, only the RCM model dataset for A2 is used in S2 and S3, but for S4, S5 and S6, both the RCM datasets of Scenarios A2 and B2 are used.

[4] A2 and B2 are two climate change SRES (Special Report on Emission Scenarios) scenarios studied by IPCC (2000). In brief, A2 corresponds to a storyline of high population growth with slower per capita economic growth and technological change, while B2 corresponds to a storyline of moderate population growth and economic development with less rapid and more diverse technological change.

From model runs of these scenarios, the following analyses can be made:

- A comparison of S1 with S2 demonstrates that the adjustment to the RCM data of 1985 - 2000 is justifiable and appropriate for a simulation of the past hydrologic impacts and therefore the same adjustment could be applied for any future projections using RCM data.
- A comparison of S3 with S2 allows the identification of the impacts of development compared with the Baseline Scenario without climate change.
- A comparison of S4 with S2 allows a projection of the impacts of climate change if the Baseline Scenario continues in the future. Although Scenario S4 is not realistic because new development projects will be planned or implemented, it helps to show the impacts of climate change.
- A comparison of S5 with S4 allows the identification of the impacts when the Development Scenario is run under climate change conditions.
- A comparison of S6 with S5 allows the analysis of the effects of adaptation strategies to climate change on the effects of development.

2.5. Preparation of climate change scenarios

Future climate projection daily data for the two IPCC SRES scenarios (A2 and B2) provided by the SEA START Regional Centre were based on the ECHAM4[5] GCM from the Max Planck Institute for Meteorology, Germany and downscaled to the Mekong region using the PRECIS[6] system. The PRECIS data for the Baseline 1985 - 2000 were adjusted by comparing them with the available observed data in the DSF. Adjustment methods (see Appendix A) were applied in an effort to calibrate the models to match the flow regime outputted from the DSF for Scenario S2 with that from Scenario S1 using the available observed data. Such adjustment, called bias-correction by Fujihara et al. (2008) is needed to make the downscaled monthly values of the simulated climate for the past period match the observed monthly values. Daily climate data were compared using: (i) point-based data, i.e. observed data at climate stations and RCM data at the same coordinates; and (ii) surface-based data, i.e. observed precipitation data at stations aggregated to sub-basins by using MQUAD program in the DSF and RCM data aggregated to sub-basins from PRECIS grid cells with resolution of 0.2 degree x 0.2 degree.

The SWAT model was run to identify the suitable adjustment methods by comparing outputs from model runs with adjusted RCM data and with observed climate data for 1985 - 2000. The adjustment was necessary because the RCM data for this period includes some extreme values, for example, some daily precipitation RCM values are between 500 - 1,000 mm and some are even over 1,000 mm; values which were not recorded in the observed dataset. These values result in too high water yields and river flows in several catchments in the model outputs. The adjustment was first applied to the precipitation data, then for other parameters such as maximum and minimum temperatures, wind speed and solar radiation. After running the SWAT model for all sub-basins, the IQQM model was also run for the whole Basin. In addition, the ISIS model was run for the Tonle Sap and the Delta.

For Scenarios S4, S5 and S6, the same adjustment methods as used for Scenario S2 were applied for both A2 and B2 future projection climate in 2010 - 2050 to minimise the bias in the climate change modelling.

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[5] ECHAM climate model has been developed from the weather forecast model of the ‘European Centre for Medium Range Weather Forecast’

[6] Providing Regional Climate for Impact Studies (PRECIS), a regional climate model developed by Hadley Centre

2.6. BDP scenarios for climate change analysis

During the development of the DSF from 2000 - 2004, the Consultant provided the seven demonstration scenarios (Halcrow, 2004) as shown in Table 2.3.

Inputs to each of these scenarios included:

- hydrological conditions (climate, observed river flows, rainfall – runoff relationships);
- known or assumed water demands (for irrigation, municipal or other uses); and
- information about existing or proposed infrastructure or other interventions (such as dams, diversions, embankments etc.).

Outputs were simulations of how the magnitude and pattern of river flows[7], and related information, such as the areas inundated by floods or suffering saline intrusion, would change in each scenario. The climate change scenario was included by simply increasing or decreasing the temperature and rainfall of the observed data by a certain percentage for the whole Basin.

Table 2.3 Summary of existing development scenario formulations in the Mekong River Basin

WUP (MRC - Water Utilisation Programme)	WB (World Bank)	BDP1 (MRC - Basin Development Program, Phase 1)	IBFM3 (MRC – Integrated Basin Flow Management, Phase 3)
1) Baseline 2) Impact of climate change 3) Impact of catchment change 4) High irrigation growth 5) Impact of Chinese dams 6) Impact of LMB dams 7) Impact of flood embankments	1) Baseline 2) Chinese dams 3) Low development 4) Embankments 5) Agriculture 6) High development	1) Baseline 2) Upper dams 3) Low development 4) Irrigation 5) High development	1) Baseline 2) Flow regime 1 (BDP1-Low development) 3) Flow regime 2 (BDP1-Irrigation) 4) Flow regime 3 (BDP1-High development)

In 2004, the World Bank approached the MRCS and suggested the use of the DSF in the planning of a regional water resources development strategy and revised development scenarios (Table 2.3). The climate change scenario was dropped (TSD Modelling Team, 2007). Under the BDP1, the Embankments Scenario was eliminated leaving only five scenarios and the Agriculture Scenario was renamed the Irrigation Scenario. Under Phase 3 of the Integrated Basin Flow Management (IBFM) these Scenarios were referred to as Baseline, FR1 (Low Development), FR2 (Irrigation), and FR3 (High Development).

Under BDP Phase 2, these Scenarios were revised and new Scenarios were considered as presented in Table 2.4.

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[7] To avoid confusion between the wet season (May - October) and the dry season (November - April) based on precipitation distribution and the wet season (June - November) and the dry season (December - May) usually used in flow analysis, in this study the following terms are used:

- for climate analysis: rainy season (May - October) and dry season (November - April) – the wet season is also used as rainy season if this term was used in a cited reference.
- for flow analysis: high-flow season (June - November) and low-flow season (December - May).

Table 2.4 Basin-wide water resource development scenarios (MRC, 2009)

Baseline situation	Definite future situation	Foreseeable future situation	Longer-term future
1. Baseline line scenario	2. Chinese Dam Scenario 3. Definite Future Scenario	4. LMB 20-Year Development Plan Scenario 5. LMB 20-Year Plan Scenario without Mainstream Dams 6. LMB 20-Year Plan Scenario without Mainstream Dams in the Middle and Lower LMB 7. Mekong Delta Flood Management Scenario	8. LMB Long-term Development Scenario 9. LMB Very High Development Scenario

By the end of 2008, BDP Phase 2 had provided details of fast track scenarios (MRC, 2008) that included the baseline, definite future and foreseeable future. More studies and consultations with the Mekong Countries were implemented to revise the long-term future scenarios. In this first assessment, two scenarios, namely the Baseline Scenario and the LMB 20-Year Development Plan Scenario (numbered 4 in Table 2.4, hereafter called the Development Scenario) were selected for a comparison of the impacts of climate change on flow regime (Table 2.5). Details of sector development in these scenarios are presented in Tables 2.6-2.9.

The Baseline scenario represents the development conditions in the Basin in 2000 (MRC, 2009) and includes:

- physical conditions including climate; land use; public and industrial water demand; irrigated areas, cropping patterns, and delivery infrastructure; storage characteristics; and hydraulic conveyance and flood storage; and
- management conditions including operating rule curves for storages; water allocation policies; and operating rules for salinity barriers.

The Baseline Scenario is used as a “reference scenario” to which the flow changes in the Development Scenario can be compared. In this Baseline Scenario, the total live storage (Table 2.6) of current large reservoirs (Figure 2.5) is 9,638 MCM (million m^3), about 2% of the annual Mekong water (475,000 MCM). Irrigation in the wet and dry seasons, of areas of 5.3 million ha and 2.1 million ha respectively, provides an annual total irrigated area of 7.4 million ha (Figure 2.7).

The Development Scenario includes:

- the Chinese dams being developed in the UMB;
- the significant water resources developments on the LMB tributaries since 2000 such as Nam Theun 2, Nam Ngum 2 hydropower projects, and several irrigation projects;
- the current development plans of the LMB countries, including the 11 dams on the mainstream currently being studied, realistic diversions and other developments for irrigated agriculture, flood management and mitigation, domestic and industrial water supply planned for implementation during the coming 20 years in the various BDP sub-areas.

Table 2.5 Selected scenarios for the first assessment of climate change impacts on flow regime (MRC, 2009).

Scenario	Objective	Climatic condition	Demand	Intervention (Dam and Diversion)
Baseline	For use as the *"reference scenario"* representing the development conditions in 2000	1985 - 2000	Domestic and industrial - Lao 116 MCM - Thailand 935 MCM - Cambodia 126 MCM - Vietnam 443 MCM **Irrigation*** - Lao 324,000 ha - Thailand 1,422,000 ha - Cambodia 1,340,000 ha - Vietnam 4,295,000 ha	**Dams** - Lao 5 dams - Thailand 12 dams - Vietnam 1 dam
LMB 20 Year Development Plan	To ascertain flow regime change due to multi-sector water resource developments for next 20 years	1985 - 2000	Next 20 year plan **Domestic and industrial** - Lao 291 MCM - Thailand 1542 MCM - Cambodia 427 MCM - Vietnam 481 MCM **Irrigation*** - Lao 471,000 ha - Thailand 1,738,000 ha - Cambodia 1,644,000 ha - Vietnam 4,332,000 ha	**Total dams** - Upper Mekong 6 dams - Lao 47 dams - Lao-Thailand 2 dams - Thailand 12 dams - Cambodia 8 dams - Vietnam 12 dams **Diversions** - Thailand 2 projects

* These data are taken from the 'supplement note for 5th RTWG meeting on scenario formulation and assessment of hydrological changes' (MRC, 2009). This value includes supplementary irrigation in rainy season (see Table 2.8). However, the numbers look high particularly for Cambodia. We referred to data of MRC scenarios at basin level that were contributed by riparian countries, and we are not in a position to correct them.

In the Development Scenario, in addition to the storage in the Baseline Scenario, the total live storage of the Chinese reservoirs[8] is 22,189 MCM (4.7% of Mekong water) and that of the LMB reservoirs is 43,972 MCM (9.3% of Mekong water). In total, these reservoirs (Figure 2.5) provide live storage of 75,799 MCM (16% of Mekong water). Of the total hydropower capacity of the Mekong Basin of 48,807 MW (Table 2.6) Lao PDR will generate the highest percentage (36% + 7.2% shared with Thailand), higher than China (37.9%), Cambodia (12.2%), Vietnam (6.1%) and Thailand (0.6%). However, because hydropower capacity depends on water head as well as storage volume, of the total live storage to generate this capacity, Lao PDR needs over half (51.6% + 0.8 shared with Thailand), compared with China (29.3%), Cambodia (9.9%), Thailand and Vietnam (about 4.2% each). The expansion of the irrigated areas (see Figure 2.8 for the project locations) will provide an annual increase of 10.9% of which 8% and 18.3% will be in the rainy and dry season respectively. These percentages are percentages of the Baseline figures. Domestic and industrial water demand is minor, even though it is double under the Development Scenario (Table 2.9).

[8] The Manwan reservoir in Yunnan has been in operation since 1993, but its live storage is minor (250 MCM) therefore it is included with the other Chinese reservoirs

Table 2.6 Summary of hydropower development in the Mekong Basin under 20-year Development Plan (based on details in Table 2.7)

Country	Design discharge	Capacity	Annual energy	% Total capacity in Mekong Basin	Storage	% Total storage in Mekong Basin
	m^3/s	MW	GWh		MCM	
Existing						
China (in Mekong)		2,900		7.1	525	0.7
Lao PDR	583	575	3,027	1.4	5,603	7.4
Thailand	1,483	258	530	0.6	3,256	4.3
Vietnam	424	720	3,659	1.8	779	1.0
Definite future (under preparation or on-going)						
China (in Mekong)		12,550		30.8	21,664	28.6
Lao PDR	1,827	2,598	11,770	6.4	9,295	12.3
Vietnam	3,475	1,472	6,740	3.6	1,837	2.4
20 year plan – mainstream						
Cambodia	21,000	4,280	19,740	10.5	2,070	2.7
Lao PDR	28,292	6,848	30,137	16.8	2,222	2.9
Lao-Thailand	17,420	2,951	13,752	7.2	614	0.8
20 year plan – tributaries						
Cambodia	2,478	695	3,357	1.7	5,404	7.1
Lao PDR	8,205	4,661	21,786	11.4	21,993	29.0
Vietnam	112	299	1,238	0.7	536	0.7
Total by country						
Cambodia	23,478	4,975	23,097	12.2	7,474	9.9
China (in Mekong)		15,450		37.9	22,189	29.3
Lao PDR	38,907	14,682	66,720	36.0	39,113	51.6
Lao-Thailand	17,420	2,951	13,752	7.2	614	0.8
Thailand	1,483	258	530	0.6	3,256	4.3
Vietnam	4,011	2,491	11,636	6.1	3,153	4.2
Total for Mekong Basin	85,299	40,807	115,735	100.0	75,799	100.0

Table 2-7 List of hydropower projects in Baseline (BL) and LMB 20-year Development Plan scenarios (MRC, 2009)

Country	Project Name	Rated Head m	Plant Design Discharge m^3/s	Installed Capacity MW	Mean Annual Energy GWh	Full Supply Level mamsl	Low Supply Level mamsl	Live Storage MCM
Lao PDR (Baseline)	Nam Ngum 1	38.5	414.4	155.0	1,006.0	212.0	196.0	4,700.0
	Houayho	748.3	23.0	150.0	487.0	883.0	860.0	649.0
	Theun-Hinboun	225.5	106.0	210.0	1,327.0	400.0	395.0	15.0
	Nam Leuk	174.2	39.5	60.0	207.0	405.0	388.0	228.2
	Nam Song							11.2
Vietnam (Baseline)	Yali	190.0	424.0	720.0	3,658.6	515.0	490.0	779.0
Thailand (Baseline)	Chulabhorn	366.0	13.3	42.0	93.0	759.0	739.0	144.5
	Nam Pung	85.0	8.6	6.3	15.0	284.0	270.0	156.3
	Pak Mun	11.6	1,320.0	141.6	280.0	108.0	105.5	125.0
	Sirindhorn	30.3	141.0	42.0	86.0	142.2	137.2	1,135.0
	Ubol Ratana	16.0		26.3	56.0	182.0	175.5	1,695.0
Chinese	Manwan			1,550.0				250.0
	Dochashan			1,350.0				275.0
	Jinghong			1,750.0				309.0
	Xiaowan			4,200.0				9,895.0
	Nuozhadu			5,850.0				11,340.0
	Gongouqiao			750.0				120.0
Lao PDR	Nam Mang 3	513.2	9.1	40.0	138.0	750.0	742.0	45.0
	Nam Theun 2	356.6	334.0	1,075.0	5,936.0	538.0	525.5	3,378.4
	Xekaman 1	99.0	336.6	290.0	1,096.0	230.0	218.0	1,683.0
	Xekaman-Sanxay (Xekaman2)	12.2	378.0	32.0	123.0	122.0	122.0	0.0
	Xekaman 3	477.7	62.5	250.0	982.8	960.0	925.0	108.5
	Xeset 2	246.0	28.7	76.0	309.0	813.0	803.5	9.3
	Nam Ngum 2	146.5	448.0	615.0	2,218.0	375.0	345.0	2,994.0
	Nam Ngum 5	337.0	42.9	120.0	507.0	1,100.0	1,060.0	251.0
	Nam Lik 2	63.0	187.0	100.0	460.0	305.0	270.0	826.0
Vietnam	Plei Krong	43.0	367.6	100.0	417.2	570.0	537.0	948.0
	Se San 3	61.0	486.0	260.0	1,224.6	304.5	303.2	3.8
	Se San 3A	22.0	500.0	96.0	475.0	239.0	238.5	4.0
	Se San 4	56.0	719.0	360.0	1,420.1	215.0	210.0	264.2
	Se San 4A	0.0	0.0	0.0	0.0	155.2	150.0	7.5
	Buon Tua Srah	47.0	204.9	86.0	358.6	487.5	465.0	522.6
	Buon Kuop	99.0	316.0	280.0	1,455.2	412.0	409.0	14.7
	Sre Pok 3	60.0	412.8	220.0	1,060.2	272.0	268.0	62.6
	Sre Pok 4	17.1	468.9	70.0	329.3	207.0	204.0	10.1

Country	Project Name	Rated Head	Plant Design Discharge	Installed Capacity	Mean Annual Energy	Full Supply Level	Low Supply Level	Live Storage
Lao PDR	Mekong at Pakbeng	31.4	4,362.0	1,230.0	5,007.0	345.0	340.0	442.4
	Mekong at Luangprabang	40.0	3,812.0	1,410.0	6,268.0	320.0	310.0	936.7
	Mekong at Xayabuly	24.4	6,018.0	1,260.0	5,186.0	275.0	270.0	224.7
	Mekong at Paklay	25.7	5,782.0	1,320.0	5,785.0	248.0	245.0	316.5
	Mekong at Don sahong	17.0	2,400.0	360.0	2,375.0	74.5	72.0	115.0
	Mekong at Sanakham	25.0	5,918.0	1,268.0	5,516.0	220.0	215.0	186.7
Lao PDR - Thailand	Mekong at Sangthong-Pakchom	22.0	5,720.0	1,079.0	5,318.0	192.0	190.0	217.3
	Mekong at Ban Kum	18.6	11,700.0	1,872.0	8,434.0	115.0	115.0	397.0
Cambodia	Mekong at Sambor	32.9	13,000.0	3,300.0	14,870.0	40.0	38.0	2,000.0
	Mekong at Stung Treng	15.2	8,000.0	980.0	4,870.0	55.0	50.0	70.0
Lao PDR	Theun-Hinboun expansion	225.5	110.0	222.0	1,395.0	400.0	395.0	15.0
	Theun-Hinboun exp. (NG8)	47.0	88.4	60.0	294.0	455.0	420.0	2,262.0
	Nam Ngum 3	302.0	163.0	440.0	2,230.0	720.0	660.0	979.0
	Nam Theun1	140.0	404.0	523.0	1,840.0	292.0	260.0	2,549.2
	NamNgiep 1	136.2	230.0	260.0	1,327.0	320.0	296.0	1,191.8
	Nam Tha 1	65.5	289.5	168.0	759.4	455.0	442.5	675.5
	Xepian-Xenamnoy	642.0	70.0	390.0	1,748.0	786.5	760.0	885.0
	Nam Kong 1	186.0	44.5	75.0	469.0	320.0	287.0	505.0
	Xe Kong 3up	33.7	460.0	152.0	598.7	160.0	155.0	95.1
	Xe Kong 3d	17.2	568.0	96.0	375.7	117.0	111.0	168.4
	Xekong 4	140.0	240.0	300.0	1,901.0	290.0	270.0	3,100.0
	Xe Kong 5	188.1	146.0	248.0	1,201.0	500.0	470.0	1,355.5
	Nam Ou 1	20.5	1,045.0	180.0	829.0	305.0	300.0	10.0
	Nam Ou 2	11.0	932.0	90.0	413.0	320.0	316.0	8.4
	Nam Ou 3	43.0	831.0	300.0	1,337.0	375.0	370.0	13.5
	Nam Ou 4	16.0	558.0	75.0	337.0	400.0	395.0	9.2
	Nam Ou 5	25.0	514.0	108.0	496.0	430.0	425.0	11.2
	Nam Ou 6	68.0	368.0	210.0	840.0	510.0	490.0	363.0
	Nam Ou 7	90.0	238.0	180.0	725.0	630.0	600.0	1,134.0
	Nam Lik 1	19.5	300.0	54.0	255.0	195.0	191.0	6.8
	Nam San 3	831.6	6.7	48.0	366.0	1,470.0	1,445.0	121.7
	Nam Pha	111.0	142.3	150.0	577.0	550.0	515.0	2,738.0
	Nam Suang 1	32.0	129.0	40.0	187.1	325.0	314.5	87.6
	Nam Suang 2	122.8	119.6	134.0	617.6	460.0	435.0	2,014.7
	Nam Nga	97.3	107.9	100.0	434.3	440.0	407.0	1,565.1
	Nam Beng	75.4	43.2	30.0	120.0	430.0	410.0	97.9
	Nam Feuang 1	57.0	57.1	28.0	113.2	340.0	334.0	30.0

Country	Project Name	Rated Head	Plant Design Discharge	Installed Capacity	Mean Annual Energy	Full Supply Level	Low Supply Level	Live Storage
Vietnam	Upper Kontum	904.1	30.5	250.0	1,056.4	1,170.0	1,146.0	122.7
	Duc Xuyen	71.0	81.0	49.0	181.3	560.0	551.0	413.4
Cambodia	Lower Se San2 + Lower Sre Pok 2	26.2	2,119.2	480.0	2,311.8	75.0	74.0	379.4
	Battambang 1	34.0	52.0	24.0	123.2	76.0	58.0	1,040.0
	Battambang 2	450.0	5.8	36.0	187.0	670.0	658.0	110.0
	Pursat 1	115.0	99.2	100.0	442.9	200.0	185.0	690.0
	Pursat 2	23.0	57.0	17.0	91.0	50.0	41.0	295.0
	Stung Sen	19.0	145.0	38.0	201.0	43.5	35.0	2,890.0

Note: mamsl: metres above mean sea level

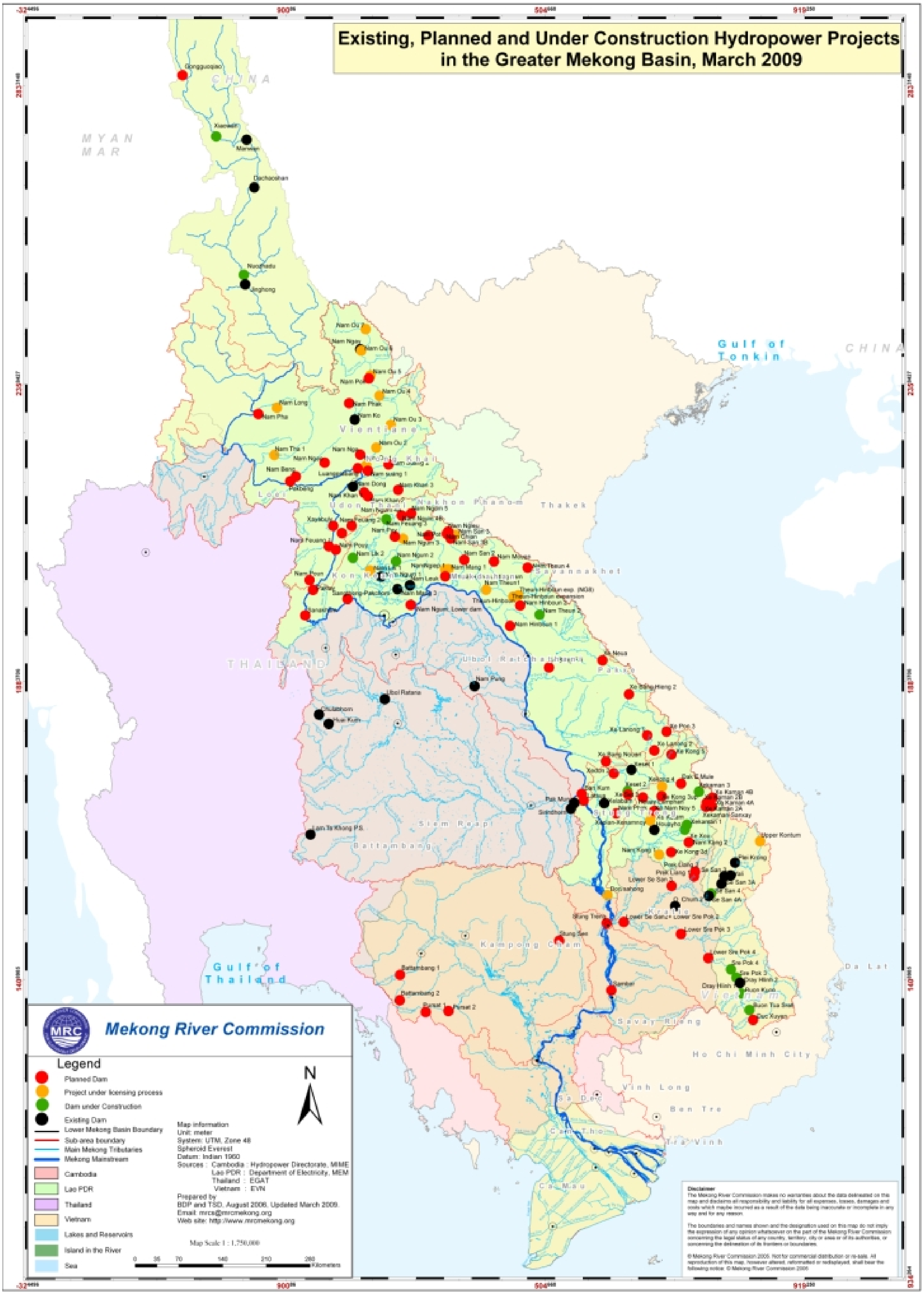


Figure 2.5 Location of hydropower dams (MRC, 2009)

Table 2.8 Irrigation area (x 1000 ha) in Baseline and LMB 20-year Development Plan (location of BDP sub-areas is shown in Figure 2.6)

BDP subarea	Baseline			LMB 20-year Plan Development			Percentage increase		
	Wet	Dry	Annual	Wet	Dry	Annual	Wet	Dry	Annual
Lao PDR									
1L+3L	22	14	36	32	20	52	45.5	42.9	44.4
4L	133	85	218	193	124	317	45.1	45.9	45.4
6L+7L	42	28	70	61	41	102	45.2	46.4	45.7
Country total	197	127	324	286	185	471	45.2	45.7	45.4
Thailand									
2T	148	13	161	180	38	218	21.6	192.3	35.4
3T	268	18	286	309	34	343	15.3	88.9	19.9
5T	850	125	975	985	192	1177	15.9	53.6	20.7
Country total	1266	156	1422	1474	264	1738	16.4	69.2	22.2
Cambodia[9]									
6+8C	16	4	20	20	10	30	25	150	50
7C	13	0	13	14	2	16	7.7		23.1
9C	451	44	495	491	103	594	8.9	134.1	20
10C	629	203	832	711	323	1034	13	59.1	24.3
Country total	1093	247	1340	1216	428	1644	11.3	73.3	22.7
Vietnam									
7V	123	44	167	126	78	204	2.4	77.3	22.2
10V	2,618	1,510	4128	2,618	1,510	4128	0	0	0
Country total	2,741	1,554	4,295	2,744	1,588	4,332	0.1	2.2	0.9
Basin total	5,297	2,084	7,381	5,720	2,465	8,185	8	18.3	10.9

Note: End of crop season BDP subarea irrigation (Beecham, R. and H. Cross (2005):

Lao PDR	Wet season: 31 October	Dry Season: 31 March
Thailand	Wet season: 31 October	Dry Season: 30 April
Cambodia	Wet season: 31 December	Dry Season: 30 March
Vietnam	Wet season: 31 October	Dry Season: 30 March

Table 2.9 Average annual domestic and industrial demands in Baseline and LMB 20-year Development Plan scenarios

Country	Baseline		LMB 20 year Development Plan	
	m^3/s	MCM	m^3/s	MCM
Lao PDR	3.7	116	9.7	305
Thailand	29.6	935	49.0	1,545
Cambodia	4.0	126	12.8	404
Vietnam	14.0	443	27.1	855
Total	51.4	1,620	98.6	3,109

[9] See the comments on the irrigated area at the bottom of the Table 2.5.

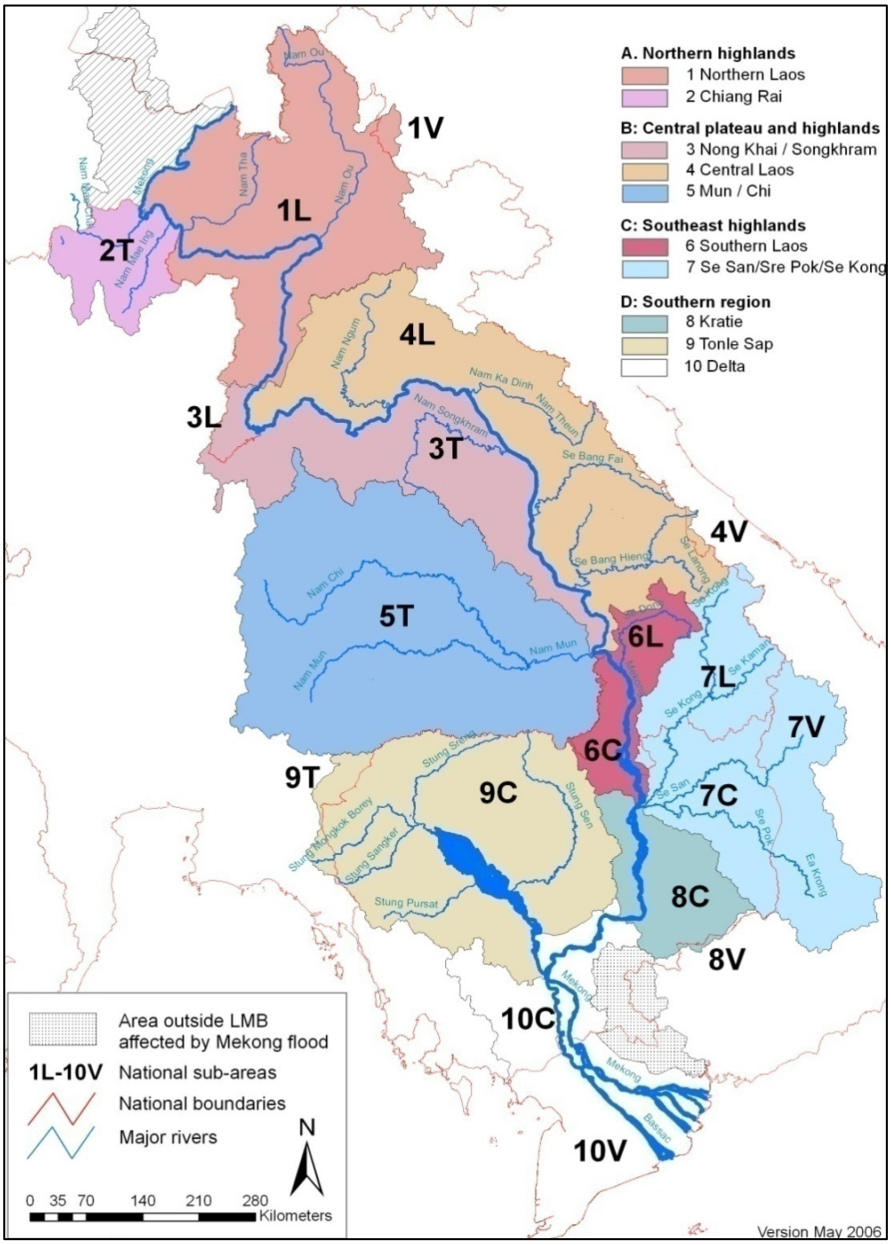


Figure 2.6 Location of BDP sub-areas

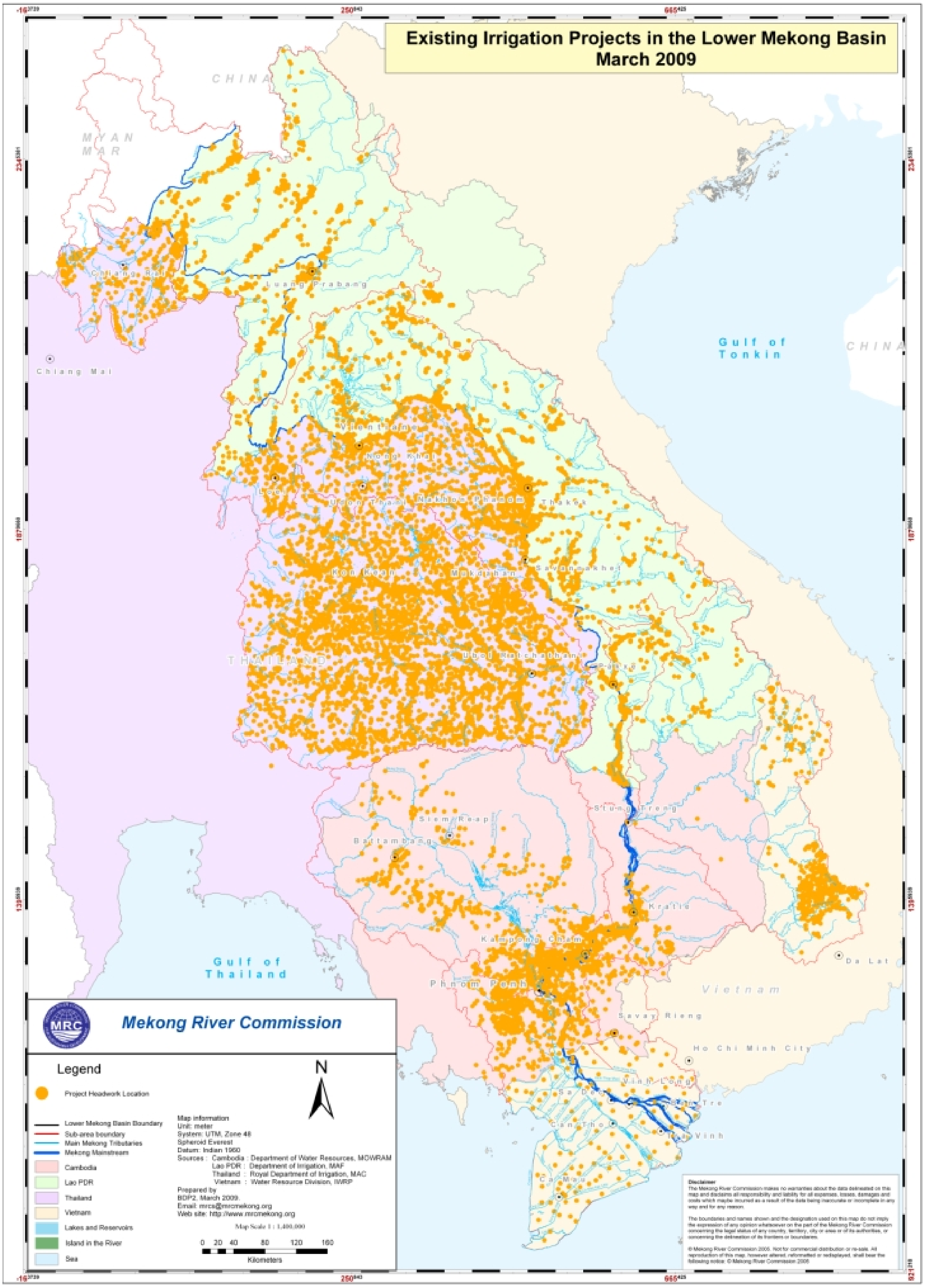


Figure 2.7 Existing irrigation projects[10] in the LMB (MRC, 2009)

[10] It is not clear in the original document what 'project' means – actually functioning schemes or schemes planned or rehabilitated in Cambodia. The information for this map were from the Department of Water Resources of Cambodia.

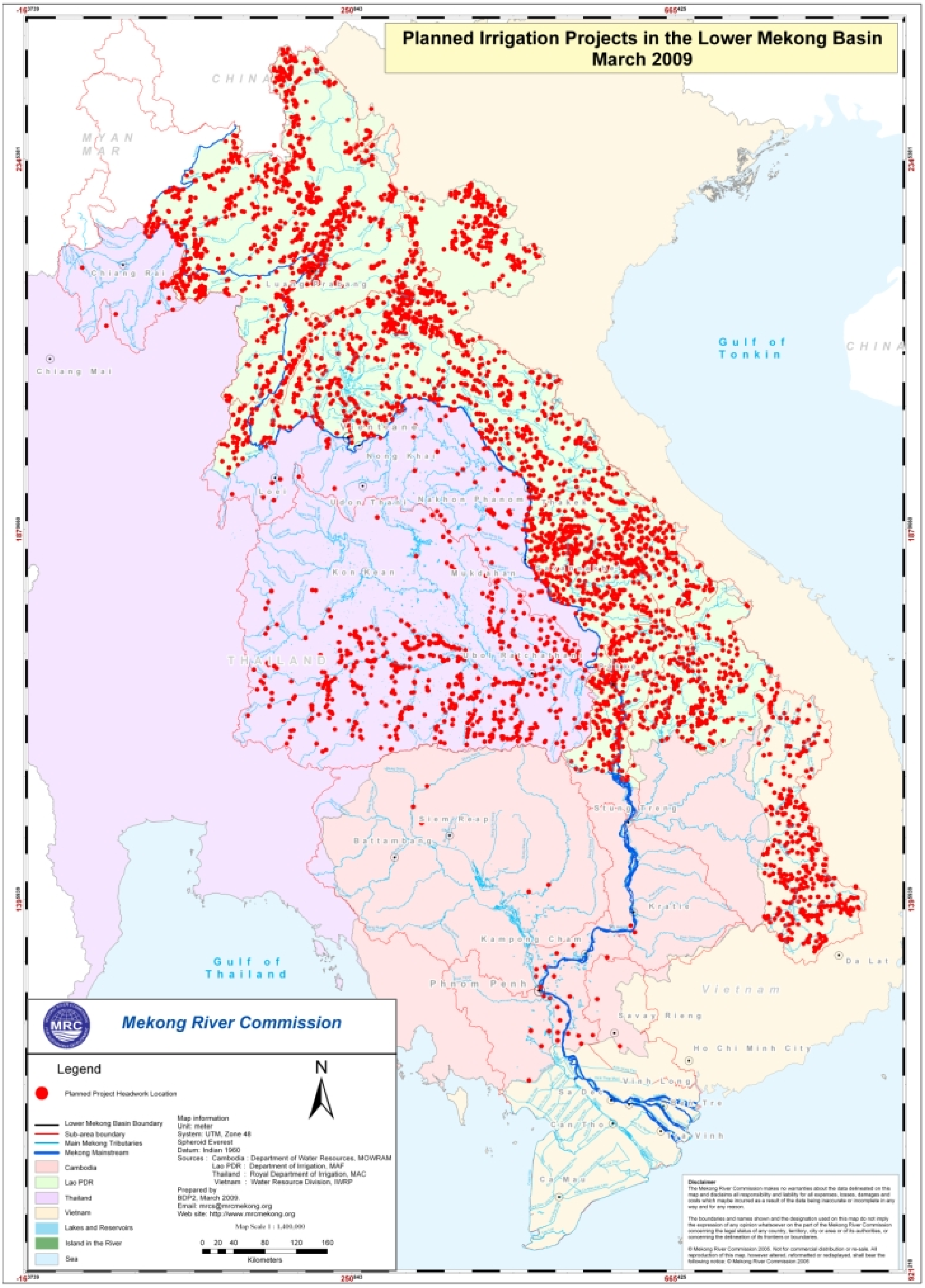


Figure 2.8 Planned irrigation projects in the LMB[11] (MRC, 2009)

[11] The map refers to MRC documents with information contributed by countries. Source of Cambodia data is Department of Water Resources. We don't have the details. BDP team of MRC is doing the revision and updating.

3. PRECIS DATA PROCESSING AND MODEL VERIFICATION

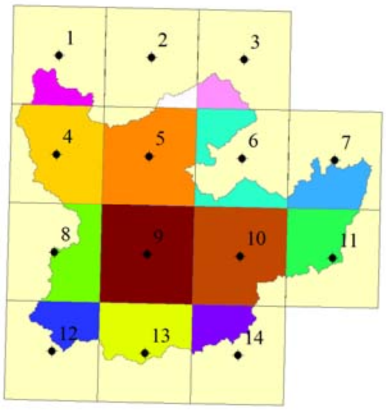
The PRECIS data were produced by the SEA START Regional Centre for 2,225 grid cells covering the entire Mekong River Basin with resolution of 0.2 degree x 0.2 degree (equivalent to about 22 km x 22 km). These data comprise the two data sets for ECHAM4 SRES Scenarios A2 and B2, each of which includes daily precipitation, maximum and minimum temperatures, solar radiation and wind speed. The data set for Scenario A2 scenario is for 1960 – 2004 and 2010 – 2050 while that for Scenario B2 is only for 2010 – 2050 since the data for 1960 – 2004 are identical to those for Scenario A2.

The three steps in processing the PRECIS data are: (i) aggregation of data from grid cells to sub-basins; (ii) adjustment of the simulated data to fit the observed data for 1985 - 2000; and (iii) application of the adjustment to the projected data for 2010 - 2050.

3.1. Aggregation of PRECIS data to sub-basins

For the SWAT model of the UMB, the area from Chinese–Lao border to Kratie and the Great Lake, sub-basin PRECIS data were obtained from grid-based data by using the grid area-weighted average. For example, precipitation of a SWAT sub-basin covering 14 PRECIS grid cells (Figure 3.1) is calculated by using the equation 3.1.

Sub-basin



$$CM_{sub} = \frac{\sum_{i=1}^{n}\left(A_{itsc,i} CM_i / A_i\right)}{\sum_{i=1}^{n}\left(A_{itsc,i} / A_i\right)} \qquad (3.1)$$

Where

CM_{sub}	=	SWAT sub-basin climate data
$A_{itsc,i}$	=	Area of grid i in the SWAT sub-basin
CM_i	=	Climate data of grid i
A_i	=	Area of grid cell varying by latitude of the cell
n	=	Number of overlaid grids, in this example n = 14

Figure 3.1 A SWAT sub-basin covers all or a part of 14 PRECIS grid cells

For the IQQM and ISIS models of the Great Lake and the Delta (downstream of Kratie), the PRECIS data for specific locations were assigned from the PRECIS data at the closest grid cell. However the PRECIS precipitation data were aggregated into 120 irrigation sub-areas of the Vietnam Delta IQQM model.

3.2. Adjustment of PRECIS data based on observed data

Although the PRECIS data were generated by dynamic downscaling methods that took into account the regional characteristics, when these are used for modelling at the sub-basin level, the outputs from the RCM should be compared with the observed data for any further adjustment to make sure that the model outputs from the PRECIS data will fit with those obtained from observed data for 1985 - 2000. Assuming that the same bias occurs for the whole dataset provided by the RCM, including future data, such adjustment, is also applied for 2010 - 2050 as illustrated in Figure 3.2.

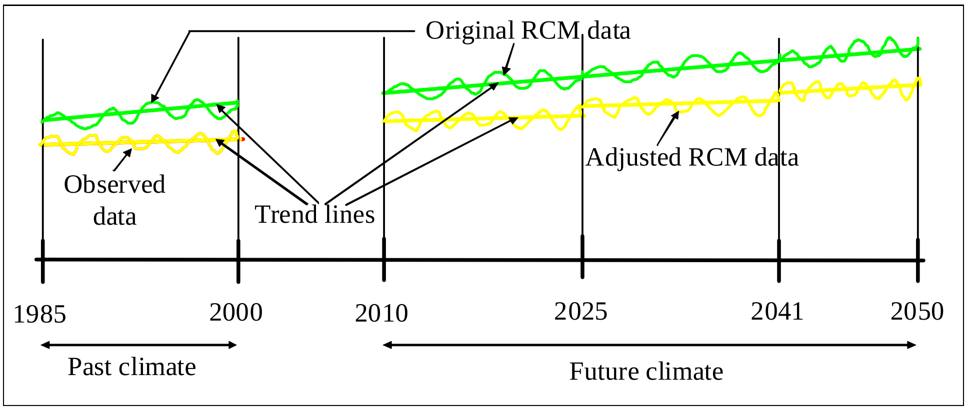


Figure 3.2 Conceptual schematization for adjustment of PRECIS data

3.2.1. Adjustment of precipitation data

In the DSF, observed sub-basin precipitation is generated by using the MQUAD, a tool for aggregating data at stations in or around the sub-basin to its areal precipitation. The PRECIS data of sub-basins for 1985 - 2000 were adjusted by comparison with the MQUAD data.

As shown in Table 3.1, in Scenario A2, the mean annual precipitation for 2010 – 2050 in the UMB, the LMB and throughout the entire Basin increases by 10.9%, 4.5% and 5.3% respectively, compared to that of 1985 – 2000. Under Scenario B2, these increases are smaller at 9.1%, 2.4% and 3.2% respectively. The percentage increases in the dry season from November to April (i.e. 27.5%, 7.9% and 10.7% in Scenario A2 respectively), are much higher than those in the wet season from May to October (7.7%, 4.0% and 4.5% respectively in Scenario A2). However, the total precipitation in the dry season is only about 11 - 13% of the annual precipitation. Figure 3.3 reveals that highest increase in the mean annual sub-basin precipitation may reach 44 - 45% in the UMB in Scenarios A2 and B2. In most of the LMB sub-basins, precipitation will increase from 1 - 10%, except in some sub-basins in northern Lao PDR and central Vietnam. On the other hand, precipitation will decrease, up to 8% in some water sectors in the Delta.

When these results are compared to the results from using data from 11 GCMs but selecting only one year (2030) as presented in Eastham et al. (2008), the adjusted PRECIS monthly data show larger variations in many months during 2010 - 2050 (Figure 3.4) but the highest value of 437 mm is less than that of 500 mm from the 11 GCMs for 2030. A possible explanation is that the GCM data used by Eastham et al. (2008) were not adjusted by comparison with the observed data in the past. The variation and the mean of the monthly data throughout the whole period are within the range and the mean of the 11 GCM data for 2030. However, the monthly PRECIS data for 2030 in both Scenarios A2 and B2 show that data in a single year may not give a good picture of the long-term trend of future climate change impacts.

Table 3.1 Mean annual, rainy (May-October) and dry (November-April) seasonal precipitation in Scenarios A2 and B2 compared to 1985 – 2000 for UMB, LMB and the entire Mekong Basin

Mekong Region	ECHAM4 Scenario	Mean Annual Precipitation (mm)					Change of Mean Annual Precipitation (mm)				Change of Mean Annual Precipitation (%)				Rate (mm/yr)
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	
Upper Mekong	A2	901	979	1,008	1,019	999	78	108	119	99	8.7	12.0	13.2	10.9	+2.56
Lower Mekong	A2	1,598	1,647	1,671	1,707	1,670	49	73	109	72	3.0	4.6	6.8	4.5	+1.86
Entire Mekong	A2	1,458	1,512	1,538	1,568	1,535	55	80	111	77	3.7	5.5	7.6	5.3	+2.00
Upper Mekong	B2	901	965	1,000	982	982	65	100	81	82	7.2	11.1	9.0	9.1	+2.12
Lower Mekong	B2	1,598	1,628	1,680	1,573	1,636	30	82	-25	38	1.8	5.1	-1.6	2.4	+0.98
Entire Mekong	B2	1,458	1,494	1,543	1,454	1,504	37	85	-4	47	2.5	5.8	-0.3	3.2	+1.21

Mekong Region	ECHAM4 Scenario	Mean Wet Season Precipitation (mm)					Change of Mean Wet Season Precipitation (mm)				Change of Mean Wet Season Precipitation (%)				Rate (mm/yr)
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	
Upper Mekong	A2	765	794	844	838	823	29	79	74	59	3.8	10.4	9.6	7.7	+1.52
Lower Mekong	A2	1,390	1,416	1,453	1,488	1,446	26	63	98	56	1.8	4.5	7.1	4.0	+1.46
Entire Mekong	A2	1,264	1,290	1,330	1,357	1,321	26	66	93	57	2.1	5.2	7.4	4.5	+1.47
Upper Mekong	B2	765	791	822	817	809	26	57	53	44	3.4	7.5	6.9	5.8	+1.14
Lower Mekong	B2	1,390	1,423	1,467	1,400	1,435	33	77	10	45	2.4	5.6	0.7	3.3	+1.18
Entire Mekong	B2	1,264	1,296	1,337	1,283	1,309	32	73	19	45	2.5	5.8	1.5	3.6	+1.17

Mekong Region	ECHAM4 Scenario	Mean Dry Season Precipitation (mm)					Change of Mean Dry Season Precipitation (mm)				Change of Mean Dry Season Precipitation (%)				Rate (mm/yr)
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	
Upper Mekong	A2	138	184	165	184	176	45	27	46	38	32.9	19.3	32.9	27.5	+0.99
Lower Mekong	A2	208	230	221	219	224	22	14	11	16	10.6	6.6	5.5	7.9	+0.43
Entire Mekong	A2	194	220	210	212	214	27	16	18	21	13.8	8.5	9.4	10.7	+0.54
Upper Mekong	B2	138	174	180	162	174	35	42	24	35	25.5	30.2	17.1	25.5	+0.92
Lower Mekong	B2	208	205	217	169	202	-2	9	-38	-6	-1.1	4.3	-18.4	-2.8	-0.15
Entire Mekong	B2	194	199	209	168	196	5	16	-26	2	2.7	8.1	-13.3	1.2	+0.06

Note: The rate of change (in mm/year) = difference between the 1985 - 2000 and the 2010 - 2050 periods/38.5 years from 1992.5 to 2030 as the mid-year of these two periods.

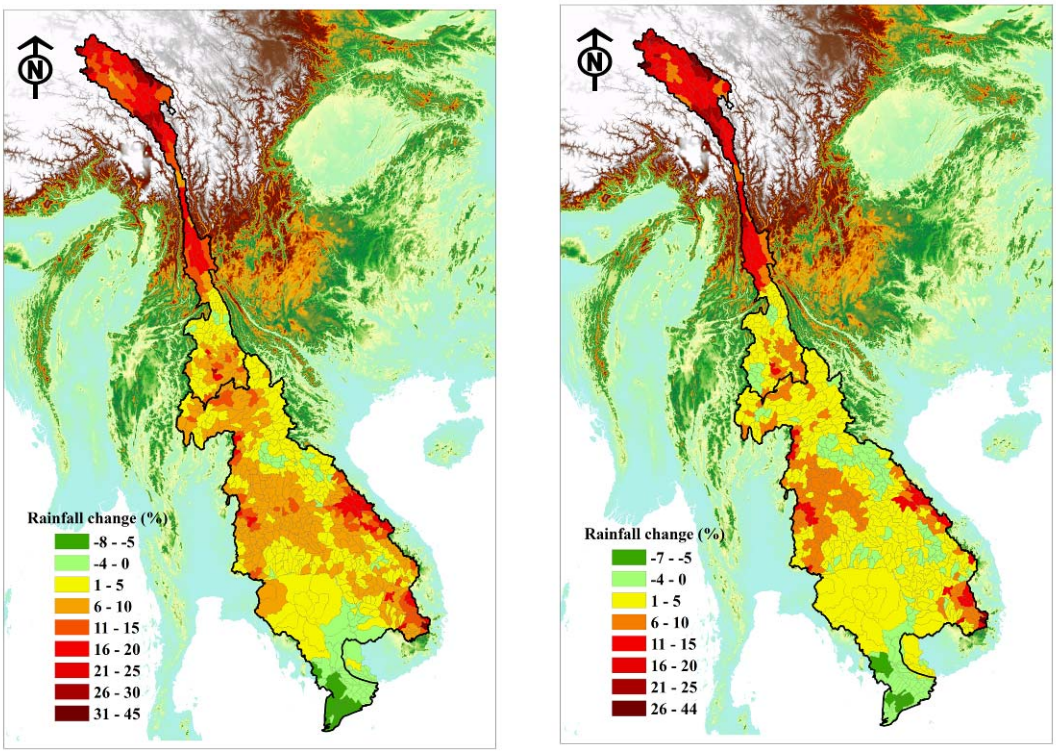


Figure 3.3 Change in mean annual sub-basin precipitation (%) during 2010 – 2050 compared to that for 1985 – 2000 for Scenario A2 (left) and Scenario B2 (right)

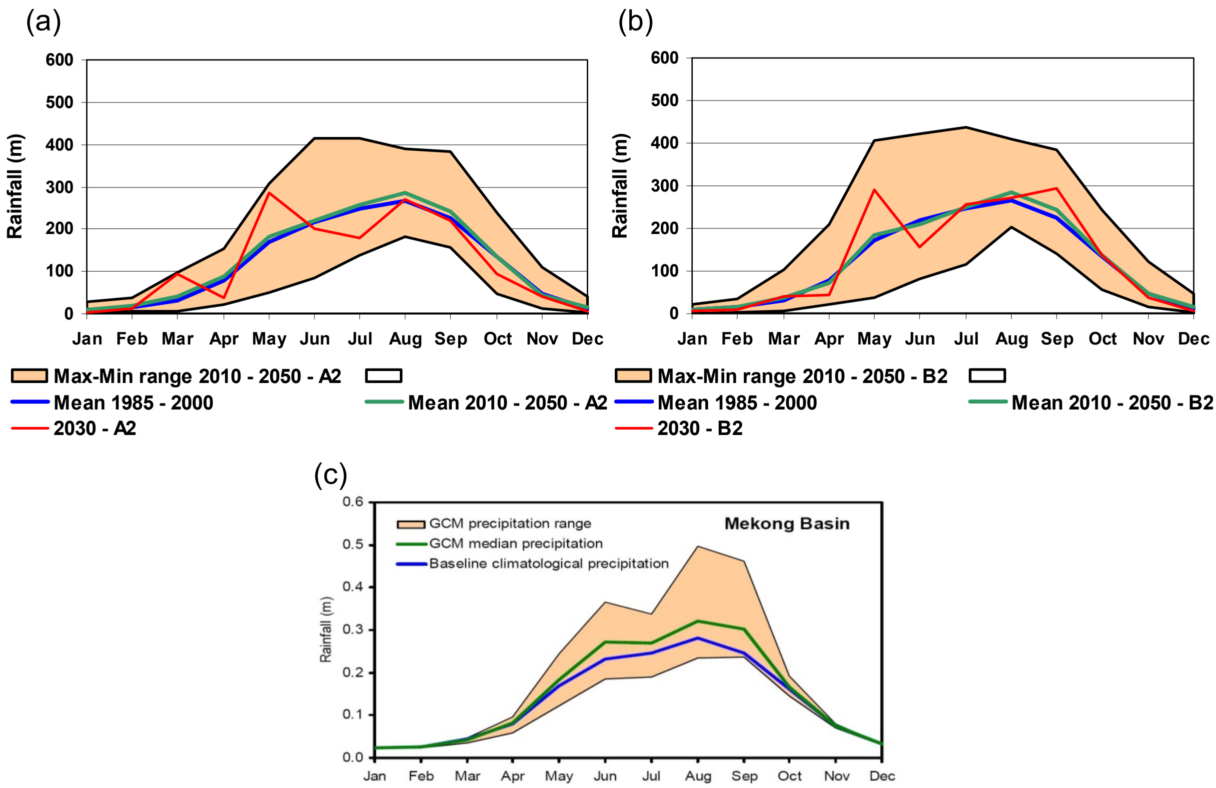


Figure 3.4 Changes in monthly precipitation in scenario A2 (a) and Scenario B2 (b) compared with change in 2030 (c) versus 1951 - 2000 indicated by Eastham et al. (2008)

3.2.2. Adjustment of temperature data

The sub-basin temperature was adjusted in the same way as the sub-basin precipitation. However, since in the current DSF, observed temperature data are limited in terms of stations and records, the data of one station in a certain year or period were assigned to many sub-basins. The results after adjustment (Table 3.2) show that the mean annual average temperature will increase 0.9°C, 0.7°C and 0.7°C for the UMB, LMB and the entire Mekong Basin respectively, in Scenario A2 and 1.0°C, 0.8°C and 0.8°C respectively, in scenario B2. Similar changes are also observed for the maximum and minimum temperatures. Figure 3.5 shows that highest temperature increase will be in the uppermost part of the UMB. The increase will be less in the LMB but slightly higher in the lower part of the LMB and the Delta.

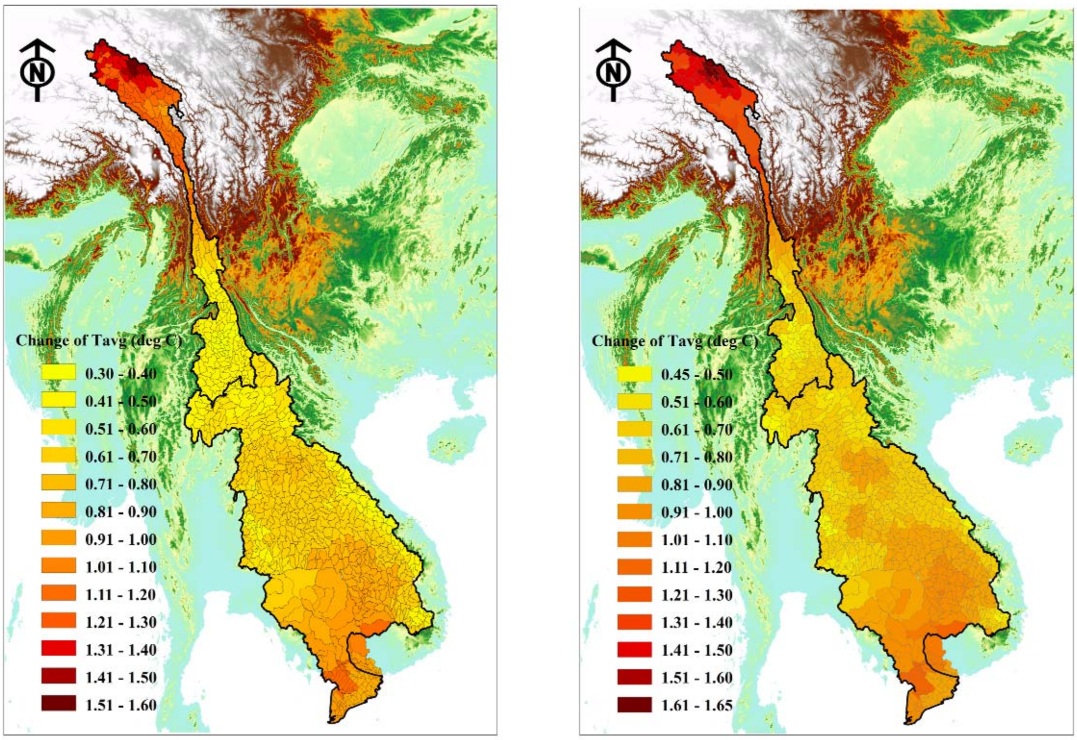


Figure 3.5 Increase in mean annual sub-basin average temperature during 2010 – 2050 compared to 1985 – 2000 for Scenario A2 (left) and Scenario B2 (right)

3.2.3. Adjustment of other climate parameters

An adjustment method similar to that for temperature was used for solar radiation and wind speed although the observed data for these parameters are very limited. However, model outputs are less sensitive to these parameters than they are to precipitation and temperature. Details of these parameters are not presented in this report.

3.2.4. Comparison of climate change projection with other studies

A comparison of changes in precipitation and temperature in the Mekong Basin in the future compared to the past are presented in Table 3.3. While most studies provide a common projected increase of temperature of about 0.020 - 0.023°C/year, the projected changes in precipitation vary. The annual and seasonal precipitation increases or decreases depending on the selection of the GCM or RCM models, the SRES scenarios, the duration of the past and future periods and the data (observed data in the basin, data from the global database or data from models). This comparison shows the high degree of uncertainty in projecting precipitation. This should be borne in mind when using results from any climate change scenario analysis.

Table 3.2 Mean annual maximum, minimum and average temperatures in 2010 - 2050 under Scenarios A2 and B2 compared to 1985 – 2000 for the UMB, the LMB and the entire Mekong Basin

Mekong Region	ECHAM4 Scenario	Mean Annual Maximum Temperature (°C)					Change of Mean Annual Maximum Temperature (°C)			
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050
Upper Mekong	A2	18.3	18.8	19.1	20.0	19.2	0.5	0.8	1.7	0.9
Lower Mekong	A2	30.7	31.0	31.5	32.0	31.4	0.3	0.7	1.3	0.7
Entire Mekong	A2	28.1	28.4	28.9	29.5	28.8	0.3	0.8	1.4	0.7
Upper Mekong	B2	18.3	18.9	19.3	20.2	19.3	0.6	1.0	1.9	1.0
Lower Mekong	B2	30.7	31.1	31.4	32.3	31.5	0.4	0.7	1.5	0.8
Entire Mekong	B2	28.1	28.5	28.9	29.7	28.9	0.4	0.8	1.6	0.8

Mekong Region	ECHAM4 Scenario	Mean Annual Minimum Temperature (°C)					Change of Mean Annual Minimum Temperature (°C)			
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050
Upper Mekong	A2	5.4	5.9	6.2	7.2	6.3	0.5	0.8	1.8	0.9
Lower Mekong	A2	21.5	21.7	22.2	22.8	22.1	0.2	0.7	1.3	0.6
Entire Mekong	A2	18.1	18.3	18.8	19.5	18.8	0.3	0.7	1.4	0.7
Upper Mekong	B2	5.4	6.0	6.4	7.4	6.4	0.6	1.0	2.0	1.0
Lower Mekong	B2	21.5	21.8	22.1	23.1	22.2	0.3	0.7	1.6	0.8
Entire Mekong	B2	18.1	18.4	18.8	19.8	18.9	0.4	0.7	1.7	0.8

Mekong Region	ECHAM4 Scenario	Mean Annual Average Temperature (°C)					Change of Mean Annual Average Temperature (°C)			
		1985 - 2000	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050	2010 - 2025	2026 - 2041	2042 - 2050	2010 - 2050
Upper Mekong	A2	11.9	12.4	12.7	13.6	12.8	0.5	0.8	1.8	0.9
Lower Mekong	A2	26.2	26.4	26.9	27.5	26.8	0.3	0.7	1.3	0.7
Entire Mekong	A2	23.3	23.6	24.0	24.7	24.0	0.3	0.8	1.4	0.7
Upper Mekong	B2	11.9	12.5	12.9	13.8	12.9	0.6	1.0	1.9	1.0
Lower Mekong	B2	26.2	26.6	26.9	27.8	27.0	0.4	0.7	1.6	0.8
Entire Mekong	B2	23.3	23.7	24.1	25.0	24.1	0.4	0.8	1.7	0.8

Table 3.3 Comparison of projected climate changes from different studies

Authors	Snidvongs et al. (2003)	Hoanh et al. (2003)	Ruosteenoja et al. (2003)	Water Development & Research Group of Helsinki University and START (2008)	Eastham et al. (2008)	Mac Sweeney et al. (2008a & 2008b)	ADB (2009a)	Johnston et al., (2009)	This study
Location	Lower Mekong catchment	Mekong Basin	Southeast Asia	Lower Mekong catchment	Lower Mekong catchment	Cambodia, Vietnam	Thailand, Vietnam	Greater Mekong Subregion	Mekong Basin
Models	CCAM	HADCM3	7 GCMs	ECHAM4-PRECIS	11 GCMs	15 GCMs	MAGICC (GCM)	PRECIS/ ECHAM4	PRECIS/ ECHAM4
Scenarios	No specific	A2, B2	A1F1, A2, B1, B2	A2	A1B	A2, A1B, B1	A1F1, B2	A2, B2	A2, B2
Period	From [1×CO_2] to [2×CO_2]	1960-2099	1961-2095	1960-2099	1951-2000 and 2030	1970-2090	1990-2100	1960-2049	1985-2050
Projected changes in annual rainfall	Not explicitly quantified	-1.64 to +4.36 mm/y	Either >0 or <0, depends on models and scenarios. Almost always insignificant	Increase (not explicitly quantified)	+0.1 to +9.9 mm/y	+0.3 to +0.6 mm/y	*1990-2050:* +1.26 to -1.62 mm/y (B2); 0.66 to -1.14 mm/y (A1F1) *1990-2100:* +3.27 to +4.91 mm/y (A1F1) and -1.63 to -2.45 mm/y (B2)	No significant change at the whole GMS scale	+ 1.2 (B2) to +2 (A2) mm/y
Changes in seasonal rainfall pattern	Dry season drier and longer 1-month delayed rainy season		Dry season drier and longer 1-month delayed rainy season	Dry season drier and longer 1-month delayed rainy season	Wetter rainy season (+1.7 to +6.1 mm/y) Drier dry season (-0.3 mm/y – not significant)	Wetter rainy season : +0.8 to +1.5 mm/y (KH); +0.4 to +1.5 mm/y (VN) Drier dry season: -0.7 to -0.1 mm/y (KH); -0.3 to -0.1 mm/y (VN)		Wetter rainy season in North Myanmar and Gulf of Thailand (From +0.2 to +0.6 mm/y) Drier dry season on both sides of Gulf of Thailand (-2.5 to -2.8 mm/y)	Wetter rainy season: +1.2 (B2) to +1.5 (A2) mm/y Wetter dry season in UMB +0.9 mm/y and insignificant change in LMB
Tempera-ture	+ 1 to +3°C (over 100 year period)	+0.026 to +0.036°C/y	+0.01 to +0.05°C/y	Increase (not explicitly quantified)	+0.012 to +0.014°C/y	0.00 to +0.06°C/y	+0.03 to +0.06°C/y	+0.023 to +0.024°C/y	+0.020 to +0.023°C/y

3.3. Baseline scenario with observed and PRECIS climate data

In the scenario analysis, outputs (such as water yield from sub-basins generated by the SWAT, simulated flow and irrigation extraction at key stations generated by the IQQM, water level and salinity generated by the ISIS) from the Development Scenarios with and without climate change are compared with outputs from the Baseline Scenario to analyse impacts of both development and climate change. Because PRECIS data are used for scenarios with future climate change, for a proper comparison simulated PRECIS data for 1985 - 2000 are also used to replace the observed data in providing the outputs of the Baseline Scenario, i.e. outputs in Scenario S2 are used in the comparison with the future projection instead of Scenario S1. Another objective of the model run of Scenario S2 for the Baseline with these PRECIS data is to identify the adjustment needed to make sure that the outputs from the DSF using simulated PRECIS data for 1985 - 2000 match the outputs from the same scenario using observed data.

The DSF models and data for the Baseline Scenario formulated and calibrated by IKMP (Information and Knowledge Management Programme) and BDP Teams were adopted for use in this climate change study. The DSF models include eight Lower Mekong SWAT Models upstream of Kratie, 16 Great Lake SWAT Models, three IQQM Models (upstream of Kratie, the Great Lake and the Vietnam Delta) and one ISIS model in downstream of Kratie. In addition a SWAT Model for the UMB was used.

The process of model runs for adjustment of RCM data by running the SWAT models is shown in Figure 3.6. First, water yield outputs from SWAT models for the Baseline with RCM data (model run Scenario S2) were compared with outputs for the Baseline with observed data and different adjustment methods (see Appendix A) were applied until the differences were minor and acceptable.

3.3.1. Verification of water yields from SWAT models

As examples of model outputs, daily and monthly discharges from the LMB SWAT Model 5 (river reach from Mukdahan to Pakse) are presented in Figures 3.7 and 3.8. These clearly demonstrate that the peaks of the daily and monthly river discharges using the unadjusted PRECIS climate data as inputs are much higher than those of either the observed discharges or those computed from the observed climate data. However the graph shows that both the daily and monthly river discharge hydrographs computed from the adjusted PRECIS climate data fit well with those from both the observed climate data and the observed discharge hydrographs.

In the same way, total daily and monthly water yields generated from Scenario S2 were also compared with those of Scenario S1. These are shown in Figures 3.9 and 3.10 which show that the daily and monthly water yields calculated by using unadjusted PRECIS data are much higher than those calculated from the observed data. After adjustment, the daily and monthly water yields using adjusted PRECIS data as inputs fit well with those from using observed data.

The evaluation results for all SWAT models upstream of Kratie and around the Great Lake are presented in Tables 3.4 and 3.5. In the model run with unadjusted PRECIS data, values of Coefficient of Efficiency (CE) are much lower than those values using observed data as inputs. The high values of Volume Ratio (VR) of all models (all over 100%) reflect an over-estimation of precipitation in the unadjusted PRECIS data. With the adjusted PRECIS data, the CE and VR values show that outputs are very close to those from the model run with observed data. Figure 3.11 shows a very similar spatial distribution of mean annual sub-basin water yields from model runs with observed and adjusted PRECIS data for the upstream area of Kratie.

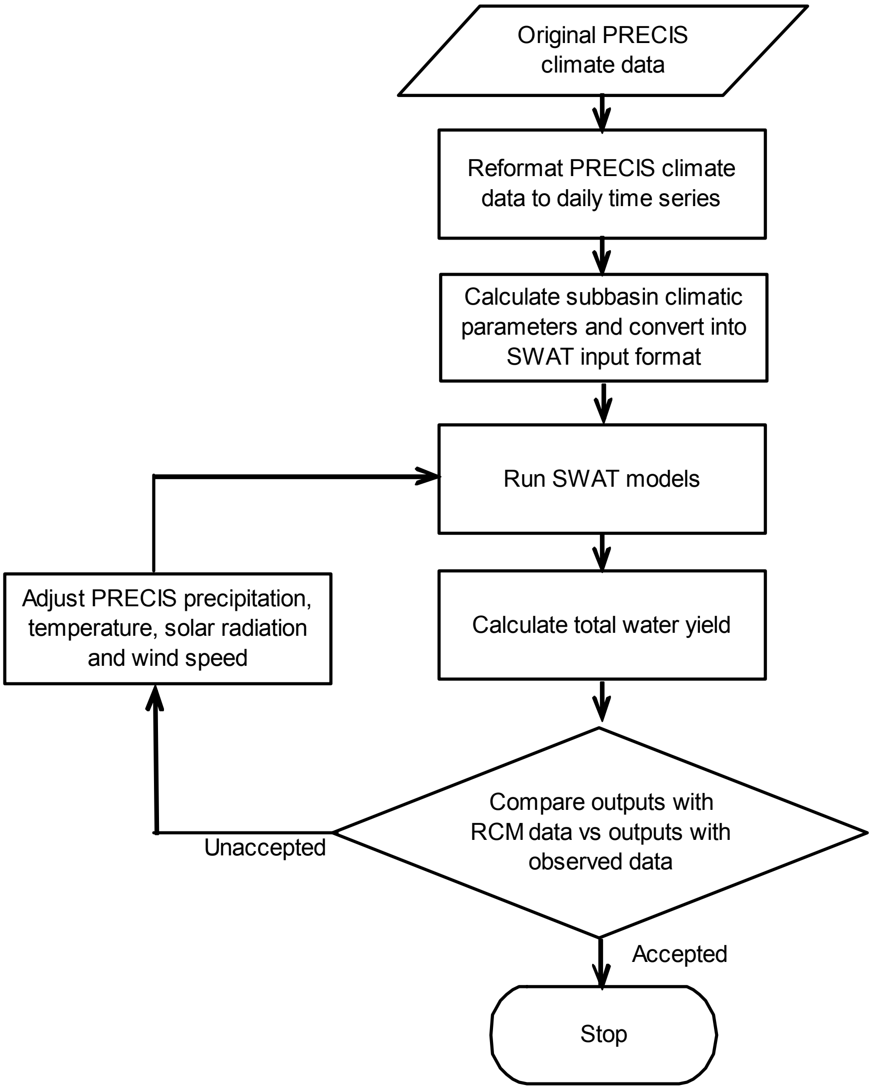


Figure 3.6 Flow chart for the adjustment of PRECIS data by running SWAT models

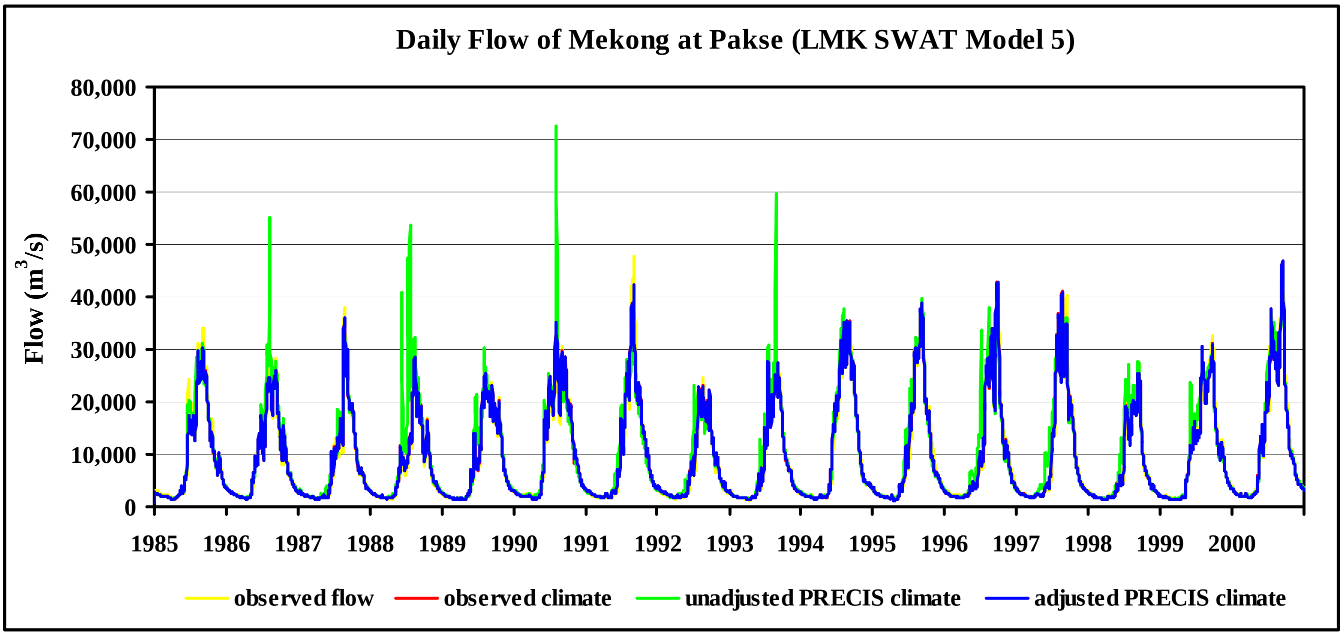


Figure 3.7 Comparison of daily observed discharge with outputs from model runs with observed climate data, unadjusted and adjusted PRECIS data for LMB SWAT Model 5

Note: In this figure and the following Figures 5-3, 5-4 and 5-5, outputs from the model run using the observed climate data cannot be seen clearly because they fit too well with the outputs from the model run using adjusted PRECIS data.

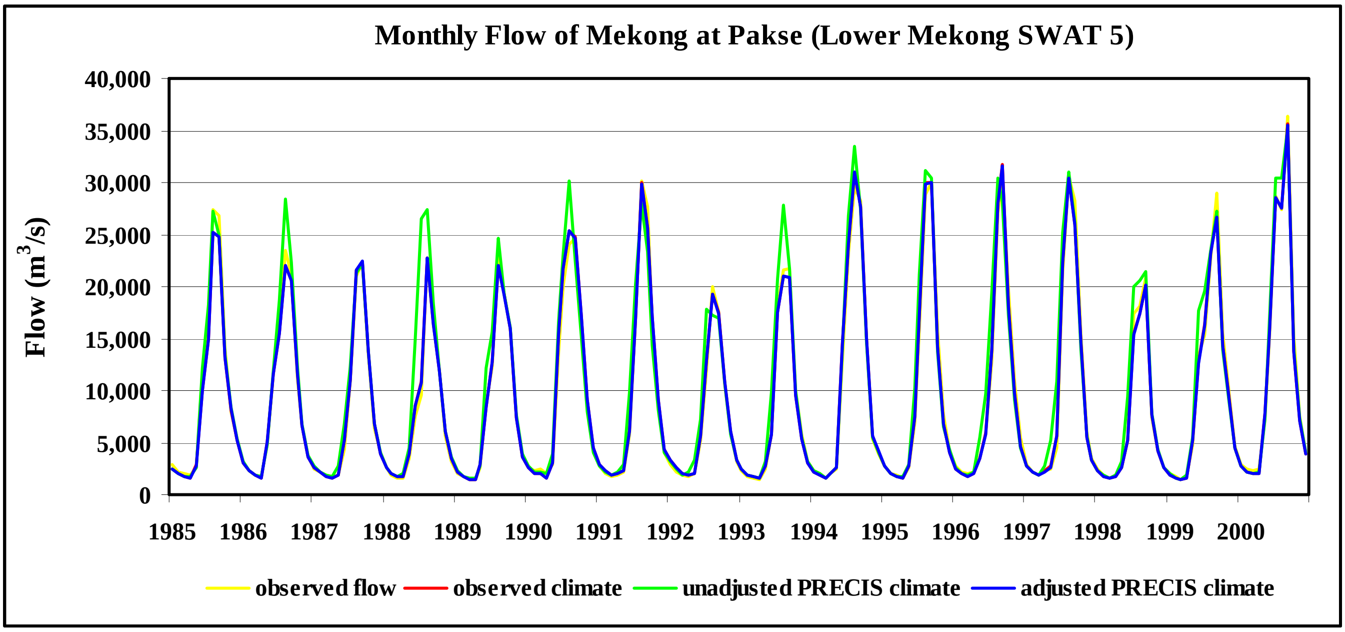


Figure 3.8 Comparison of monthly water yield from model runs with observed climate data, unadjusted and adjusted PRECIS data for LMB SWAT Model 5

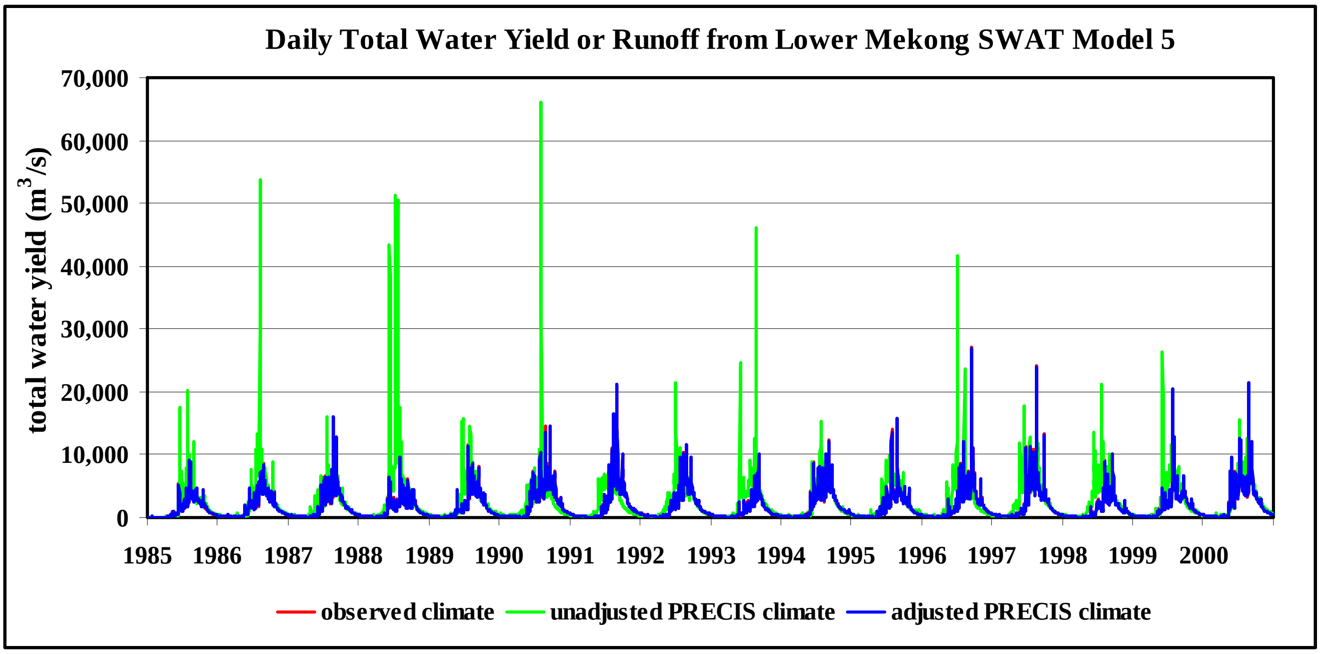


Figure 3.9 Comparison of daily water yields from model runs with observed climate data, unadjusted and adjusted PRECIS data for LMB SWAT Model 5

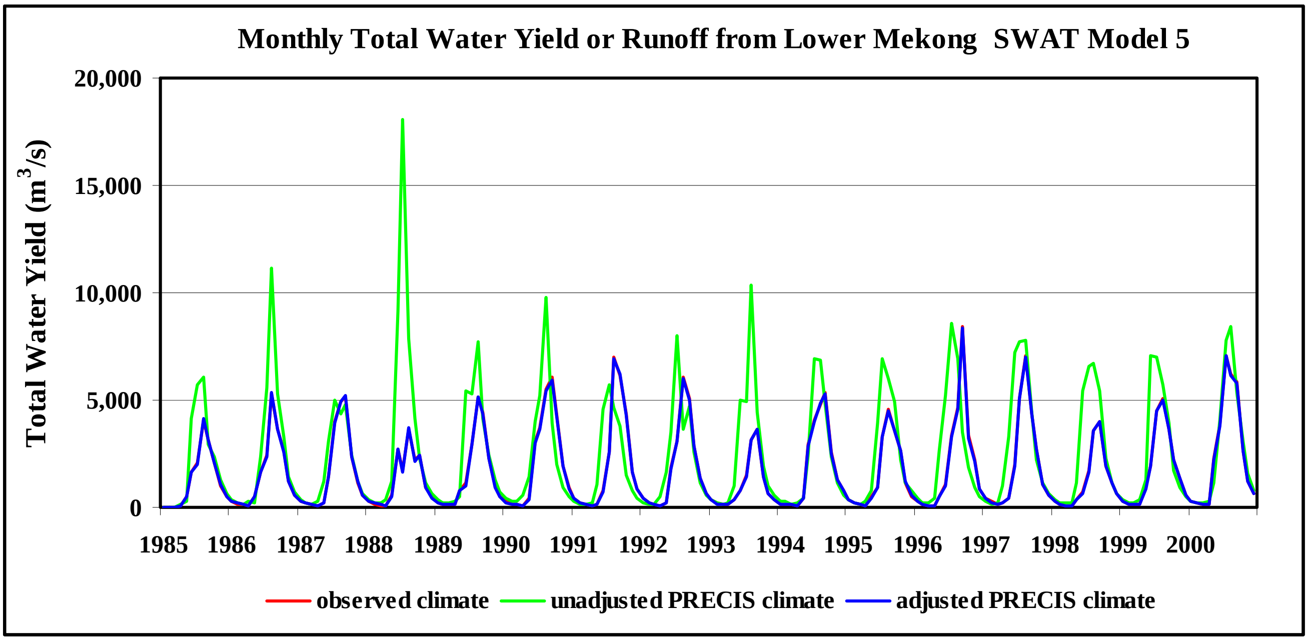


Figure 3.10 Comparison of monthly observed discharges with outputs from model runs with observed climate data, unadjusted and adjusted PRECIS data for LMB SWAT Model 5

Table 3.4 Comparison of results of SWAT models upstream of Kratie with different climate datasets

Model Code	Evaluation point	Observed data		Unadjusted PRECIS data				Adjusted PRECIS data				Mean Annual Precipitation (mm)		
		River discharge		River discharge		WYLD		River discharge		WYLD				
		CE	VR (%)	CE	VR (%)	CE	VR (%)	CE	VR (%)	CE	VR (%)	Observed	Unadjusted	Adjusted
UMB	Chiang Saen	0.68	101.8	0.50	120.2	0.50	122.1	0.63	98.8	0.98	96.9	901	986	901
LMB1	Chiang Saen	0.58	102.2	0.50	105.2	-0.76	113.3	0.58	101.9	1.00	98.7	1,474	1,634	1,474
LMB2	Luang Prabang	0.95	100.2	0.82	107.4	-0.24	123.5	0.94	99.4	1.00	97.9	1,576	1,724	1,576
LMB3	Vientiane	0.94	101.0	0.86	108.8	-3.02	164.9	0.94	100.8	1.00	98.5	1,361	1,674	1,361
LMB4	Mukdahan	0.94	104.5	0.84	107.1	0.50	102.1	0.94	104.1	1.00	99.2	2,140	2,130	2,140
LMB5	Pakse	0.98	99.6	0.89	107.9	-1.18	144.4	0.98	99.5	1.00	99.1	1,706	2,158	1,706
LMB6	Kratie	0.93	100.5	0.74	107.1	-1.82	124.0	0.93	100.6	1.00	100.3	1,875	2,351	1,875
LMB7	Yasothon	0.62	100.3	-1.70	150.7	-1.08	173.8	0.61	99.9	1.00	97.8	1,122	1,381	1,122
LMB8	Rasi Salai	0.38	99.9	-3.29	160.6	-2.22	159.7	0.41	98.1	0.99	98.4	1,049	1,315	1,072

Notes:

CE = Nash and Sutcliffe Coefficient of Efficiency, calculated as:

$$CE = 1 - \frac{\sum_{i=1}^{n}\left(O_i - P_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}$$

with n as number of values, *Oi* as observed, *Pi* as predicted values, $\overline{O}$ as mean of all *Oi* values

VR = Total Simulated Volume / Total Observed Volume for 16 years 1985-2000

WYLD = Water yield, SWAT terminology for runoff

Table 3.5 Evaluation of SWAT models with PRECIS data around the Great Lake

Model Code	SWAT Model Name	Unadjusted PRECIS data		Adjusted PRECIS data	
		WYLD		WYLD	
		CE	VR (%)	CE	VR (%)
GLK01	Stung Chinit	0.08	112.71	1.00	97.96
GLK02	Stung Sen	0.01	105.42	1.00	98.25
GLK03	Stung Staung	-0.53	101.55	0.99	96.41
GLK04	Stung Chikreng	-1.20	122.39	1.00	93.43
GLK05	Stung Siem Reap	-1.14	91.07	1.00	97.64
GLK06	Stung Sreng	-0.77	111.35	0.92	95.85
GLK08	Stung Mongkol Borey	-3.68	166.28	1.00	98.79
GLK10	Stung Battambang	-0.63	117.32	1.00	100.14
GLK11	Stung Dauntri	0.08	79.29	1.00	98.62
GLK12	Stung Pursat	-0.59	102.42	1.00	99.34
GLK13	Stung Boribo	-1.42	123.33	1.00	99.40
GLK14	Prek Thnot	-0.79	108.92	1.00	101.54
GLK15	Prek Te	-1.65	197.08	0.99	90.74
GLK16	Prek Chhlong	-6.92	236.16	1.00	97.98
GLK17	East Vaico	-0.87	201.30	1.00	99.44
GLK18	West Vaico	-0.14	118.89	1.00	98.36

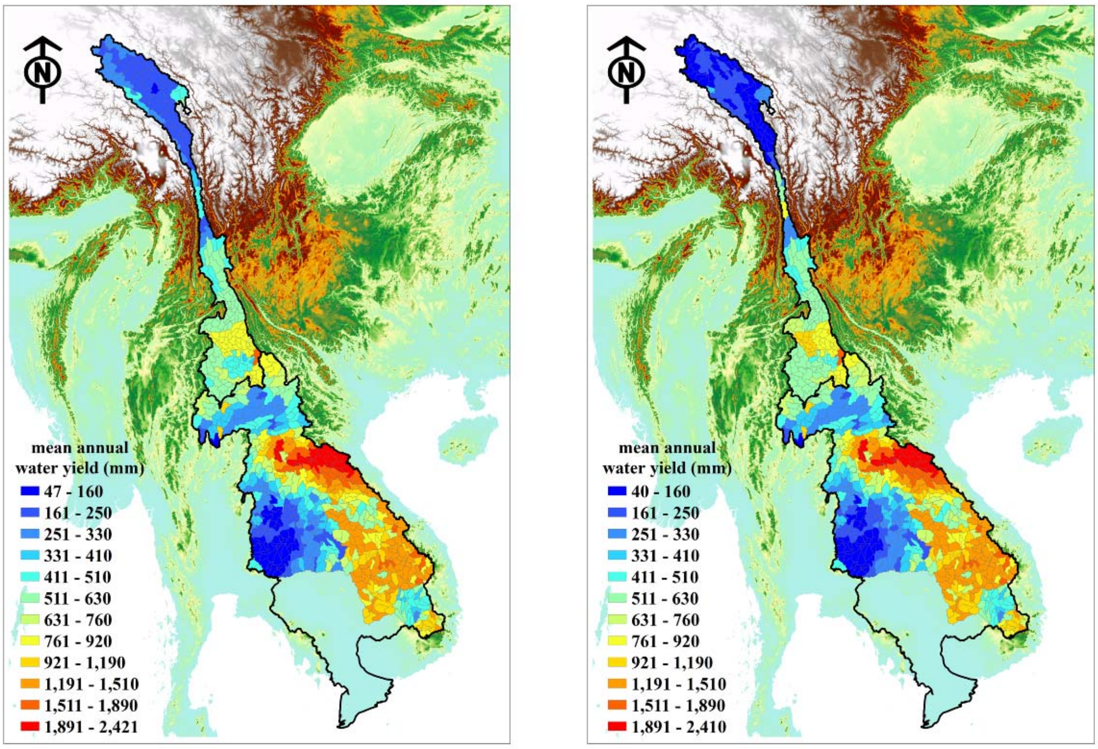


Figure 3.11 Mean annual sub-basin water yields during 1985 – 2000 from model runs with observed (left) and adjusted PRECIS (right) data

3.3.2. Verification of river discharge from IQQM model

In this verification, the daily total water yield from the SWAT model for the UMB was used as the inflow at Chinese–Lao border for the model run of Scenario S2 using PRECIS data, but for the model run of Scenario S1, using observed climate data, the observed inflow at Chiang Saen was used to rebuild the inflow at the Chinese–Lao border (as used in previous BDP studies). The influence of the China inflow on the Mekong mainstream discharge becomes smaller at locations further downstream. The verification of the model performance was carried out by comparing the daily river discharge computed from the model run of Scenarios S1 and S2. Table 3.6 presents the evaluation results at the key stations along the Mekong mainstream and at some selected points on the tributaries, while Figure 3.12 shows the comparison of the discharge at Kratie in Scenarios S1 and S2 as an example. With CE values close to 1.00 and VR values close to 100%, it can be concluded that the IQQM model using adjusted PRECIS data as inputs in Scenario S2 produced similar outputs to Scenario S1 using observed data.

3.3.3. Verification of flood and salinity from ISIS model

Because, over a long period, more attention is usually paid to the maximum levels of flooding and salinity intrusion than to their average levels, the comparison of flood and salinity conditions is based on a specific year when the flooding depth or salinity is the highest. Table 3.7 compares the flooded areas based on maximum flood depths at each river and canal node of a model run of Scenarios S1 and S2 in 2000 (a high flood year). The difference in the flooded areas in these two model runs is small, maximum -1.9% for the flooding depth > 3.0 m. Similarly Table 3.8 compares salinity intrusion areas based on maximum salinity at each river and canal node in these two models runs in 1998 (a high salinity year due to low river discharge). Most saline areas show increases of about 1 - 2%, except for those areas, with salinity > 32 g/l where the increase is 6.7%, but this is only in a narrow area along the coastline with high salinity. Therefore, it can be concluded that the ISIS model run for Scenario S2 using adjusted PRECIS data is able to produce similar results to the model run for Scenario S1 using observed data.

This verification of the SWAT, IQQM and ISIS outputs from Scenario S2 also helped with the conclusion that the adjustment methods applied to the PRECIS data are appropriate in making the RCM simulation for 1985 - 2000 match with the observed data, and these methods can be applied to the adjustment of PRECIS data for the future period of 2010 - 2050.

Table 3.6 Evaluation of IQQM model results upstream of Kratie in the model run of Scenario S2 using PRECIS data

Station Name	CE	VR (%)	Station Name	CE	VR (%)
Mekong at Chiang Saen	0.73	100.2	Se Bang Hieng at Ban Keng Done	1.00	97.9
Mekong Luang Prabang	0.90	99.4	Se Bang Hieng at Tchepon	1.00	99.8
Mekong at Chiang Khan	0.92	99.2	Se Done at Saravanne	1.00	100.6
Mekong at Vientiane	0.93	99.2	Se Done at Souvannakhili	1.00	99.0
Mekong at Nong Khai	0.93	99.2	Nam Mun at Ubon	0.99	96.9
Mekong at Nakhon Phanom	0.98	99.1	Nam Leak at Ban Hin Heup	1.00	99.2
Mekong at Mukdahan	0.98	99.2	Nam Ngum at Ban Pak Khanoung	1.00	99.0
Mekong at Pakse	0.99	99.2	Nam Oon at Ban Pok Yai	0.99	95.3
Mekong at Stung Treng	0.99	99.5	Nam Songkhram at Ban Tha Kok Daeng	1.00	99.2
Mekong at Kratie	0.99	99.5	Nam Ngiep at Muong Mai	1.00	98.9
Nam Mun at Rasi Salai	0.98	97.4	Se Bang Fai at Mahaxai	1.00	99.2
Nam Mun at Satuk	0.97	98.9	Nam Theun at Ban Signo	1.00	98.5
Lam Pao at Kamalasai	0.97	95.4	Nam Ou at Muong Ngoy	1.00	97.8
Nam Chi at Ban Chot	0.99	101.5	Nam Ing at Thoeng	1.00	99.1
Nam Chi at Yasothon	0.98	91.4	Nam Kok at Chiang Rai	0.99	95.8
Sre Pok at Lomphat	1.00	101.6	Nam Lao at Ban Tha Sai	0.99	98.0
Se Chomphone at Ban Keng Kok	1.00	96.3	Nam Khan at Ban Mout	1.00	97.4
Se Lanong at Muong Nong	1.00	99.3			

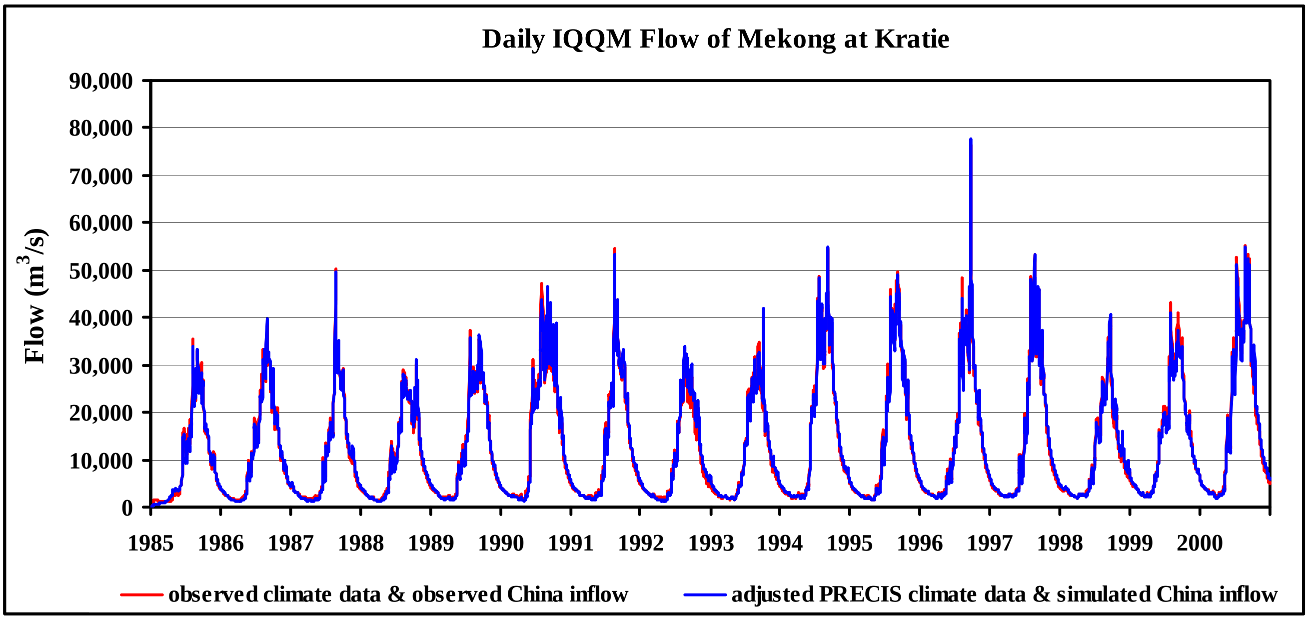


Figure 3.12 Comparison of the daily discharge at Kratie in two model runs of Scenarios S1 and S2

Table 3.7 Comparison of flooded areas in 2000 in two model runs of Scenarios S1 and S2

Maximum Depth	Flood Area of Maximum Flood Depth (km^2)		Difference in Flood Area (km^2)	
	Adjusted PRECIS Data	DSF Observed Climate	+/- (km^2)	+/- (%)
≥ 0.0 m	60,729	60,732	-3	0.0
> 0.5 m	41,317	40,939	378	0.9
> 1.0 m	36,393	36,211	182	0.5
> 1.5 m	30,923	31,132	-209	-0.7
> 2.0 m	26,347	26,769	-422	-1.6
> 2.5 m	21,971	22,352	-381	-1.7
> 3.0 m	17,977	18,328	-351	-1.9
> 3.5 m	15,198	15,384	-186	-1.2
> 4.0 m	13,570	13,749	-179	-1.3

Note: Area with >= 0.0 m includes non-flooded land.

Table 3.8 Comparison of salinity intrusion areas in 1998 in two model runs of Scenarios S1 and S2

Concentration (g/l)	Salinity Area for Maximum Concentration (km^2)		Difference in Saline Area (km^2)	
	Adjusted PRECIS Data	DSF Observed Climate	+/- (km^2)	+/- (%)
≥ 0 g/l	41,150	41,332	-182	-0.4
> 4 g/l	20,744	20,224	520	2.6
> 8 g/l	15,451	15,377	74	0.5
> 12 g/l	12,944	13,042	-98	-0.8
> 16 g/l	10,953	11,102	-149	-1.3
> 20 g/l	9,378	9,241	137	1.5
> 24 g/l	7,064	7,197	-133	-1.8
> 28 g/l	4,923	4,873	50	1.0
> 32 g/l	2,852	2,673	179	6.7

4. IMPACT OF DEVELOPMENT AND CLIMATE CHANGE ON THE FLOW REGIME

4.1. Mekong flow under development and climate change

Although water yield and river flow for many sub-basins and nodes can be generated from the SWAT, IQQM and ISIS models, this report deals with the changes in discharge at 11 key stations in the Mekong mainstream upstream of Kratie (see Table 2.1 and Figure 2.3 for the their locations). These discharges were generated by the IQQM model. The discharge at the three stations of Kampong Cham, Phnom Penh and Tan Chau downstream of Kratie, generated by the ISIS model were analysed. Discharge at these stations in the high-flow season is not a true reflection of all the water flowing in the Mekong mainstream because some water drains to the sea through the large tributary of the Bassac, and through many other smaller rivers and canals. Therefore values of high-flow season and annual discharges at these stations could be lower than those at Kratie.

The mean discharge in both the high- and low-flow seasons, and the annual discharges at these stations in Scenarios A2 and B2 are presented in Tables 4.1 to 4.6. The corresponding model runs of scenarios and years of simulation are also shown to indicate the development scenario and climate dataset used to generate the river flow. All climate data used in these scenarios are the adjusted PRECIS data, for either 1985 - 2000 or 2010-2050. For comparison, in addition to the mean value for 2010 - 2050, the mean value of each 16 year period (only 9 years in the last part of 2042 - 2050) were also calculated to show the possible future variations.

As previously described, since the PRECIS simulation data for 1985 – 2000 for Scenarios A2 and B2 are identical, the discharge outputs in the different tables are also identical. In general, climate change will result in higher discharge in both the high- and low-flow seasons at all stations in the future. The development of hydropower dams in the Development Scenario will result in a lower discharge in the high-flow season but the discharge will be higher in the low-flow season than that of the Baseline both without climate change (1985 - 2000) and with climate change (2010 - 2050). However, these changes will vary from year to year, as shown by the higher discharge during 2026 - 2041 than that in the other 16 year periods. Such variations in flow regime also imply that high climate variability, in particular the variability of precipitation, will continue in the future as shown in Table 3.1, and changes in the flow regime do not only depend on the total precipitation but also on its distribution throughout the year. Furthermore, there is also variation by space, development scenario and climate change scenario. For example, between 2010 and 2025 in the A2 Baseline Scenario, high-flow season discharge decreases at Nakhon Phanom, Mukdahan and Khong Chiam but increases at all other stations (Table 4.1) but in the B2 Baseline Scenario, high-flow season discharge increases at Pakse, Stung Treng, Kratie and Kompong Cham and decreases at all other stations. Such differences in the A2 and B2 Climate Scenarios are also found between 2042 and 2050 in the Development Scenario.

Despite these variations, the common trend in flow regime i.e. higher in both seasons due to climate change, and lower in high-flow season/higher in low-flow season due to development, can be observed at most stations. The detailed analysis of the flow changes by comparing different pairs of scenarios are discussed in the next Sections.

Table 4.1 Mean high-flow season discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change A2 Scenario

Station		Baseline Scenario: Mean high-flow season discharge (m^3/s)					Development Scenario: Mean high-flow season discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	4,127	4,213	4,668	4,498	4,453	3,412	3,616	4,080	3,936	3,867
2	Luang Prabang	6,008	6,087	6,861	6,400	6,458	4,912	5,138	5,891	5,471	5,505
3	Chiang Khan	6,636	6,798	7,624	7,344	7,240	5,536	5,848	6,652	6,410	6,285
4	Vientiane	6,837	7,021	7,861	7,653	7,488	5,734	6,067	6,885	6,711	6,527
5	Nong Khai	6,947	7,138	7,986	7,802	7,614	5,843	6,182	7,008	6,859	6,653
6	Nakhon Phanom	11,601	11,514	13,232	12,962	12,502	9,812	9,884	11,566	11,345	10,861
7	Mukdahan	12,522	12,425	14,392	14,137	13,568	10,939	10,992	12,940	12,723	12,132
8	Khong Chiam	14,444	14,223	16,434	16,457	15,610	12,656	12,808	14,972	15,035	14,141
9	Pakse	15,827	15,993	18,396	18,736	17,533	14,319	14,627	16,995	17,384	16,156
10	Stung Treng	20,827	21,353	24,297	24,286	23,146	19,055	19,738	22,603	22,677	21,501
11	Kratie	21,549	22,064	25,065	25,046	23,890	19,762	20,428	23,352	23,437	22,229
12	Kompong Cham	20,935	21,382	24,123	24,009	23,028	19,301	19,884	22,579	22,559	21,523
13	Phnom Penh	20,217	20,460	22,702	22,175	21,711	18,797	19,194	21,484	21,048	20,495
14	Tan Chau	14,435	14,511	15,823	15,618	15,266	13,614	13,793	15,156	14,997	14,589

Table 4.2 Mean low-flow season discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change A2 Scenario

Station		Baseline Scenario: Mean Low-flow season discharge (m^3/s)					Development Scenario: Mean Low-flow season discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	1,157	1,439	1,463	1,519	1,467	1,847	2,012	2,040	2,069	2,035
2	Luang Prabang	1,499	1,882	1,952	2,001	1,937	2,247	2,475	2,560	2,578	2,532
3	Chiang Khan	1,613	2,026	2,104	2,170	2,089	2,356	2,609	2,707	2,745	2,678
4	Vientiane	1,640	2,057	2,138	2,212	2,124	2,377	2,635	2,739	2,785	2,709
5	Nong Khai	1,668	2,091	2,174	2,252	2,160	2,403	2,668	2,773	2,823	2,744
6	Nakhon Phanom	2,172	2,637	2,757	2,855	2,733	2,771	3,068	3,204	3,269	3,166
7	Mukdahan	2,220	2,691	2,814	2,925	2,792	2,935	3,235	3,377	3,449	3,339
8	Khong Chiam	2,386	2,876	2,994	3,139	2,984	3,060	3,394	3,545	3,648	3,510
9	Pakse	2,506	3,112	3,201	3,430	3,218	3,333	3,769	3,882	4,063	3,879
10	Stung Treng	3,515	4,219	4,400	4,371	4,325	4,511	5,029	5,142	5,154	5,101
11	Kratie	3,622	4,323	4,497	4,446	4,420	4,621	5,143	5,259	5,212	5,204
12	Kompong Cham	3,650	4,328	4,501	4,447	4,423	4,643	5,159	5,264	5,192	5,208
13	Phnom Penh	3,718	4,391	4,577	4,514	4,492	4,708	5,226	5,336	5,267	5,279
14	Tan Chau	5,052	5,591	5,807	5,696	5,700	5,502	5,981	6,132	6,096	6,066

Table 4.3 Mean annual discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change A2 Scenario

Station		Baseline Scenario: Mean annual discharge (m^3/s)					Development Scenario: Mean annual discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	2,642	2,826	3,066	3,008	2,960	2,629	2,814	3,060	3,002	2,951
2	Luang Prabang	3,754	3,985	4,406	4,200	4,197	3,580	3,806	4,226	4,024	4,018
3	Chiang Khan	4,125	4,412	4,864	4,757	4,665	3,946	4,228	4,680	4,577	4,482
4	Vientiane	4,239	4,539	5,000	4,932	4,806	4,056	4,351	4,812	4,748	4,618
5	Nong Khai	4,308	4,615	5,080	5,027	4,887	4,123	4,425	4,890	4,841	4,698
6	Nakhon Phanom	6,887	7,075	7,995	7,909	7,618	6,292	6,476	7,385	7,307	7,014
7	Mukdahan	7,371	7,558	8,603	8,531	8,180	6,937	7,113	8,159	8,086	7,735
8	Khong Chiam	8,415	8,550	9,714	9,798	9,297	7,858	8,101	9,259	9,341	8,826
9	Pakse	9,167	9,553	10,799	11,083	10,376	8,826	9,198	10,439	10,723	10,018
10	Stung Treng	12,171	12,786	14,348	14,328	13,735	11,783	12,384	13,873	13,915	13,301
11	Kratie	12,585	13,193	14,781	14,746	14,155	12,192	12,786	14,305	14,325	13,717
12	Kompong Cham	12,292	12,855	14,312	14,228	13,726	11,972	12,521	13,921	13,875	13,365
13	Phnom Penh	11,967	12,426	13,639	13,345	13,102	11,753	12,210	13,410	13,158	12,887
14	Tan Chau	9,743	10,051	10,815	10,657	10,483	9,558	9,887	10,644	10,546	10,328

Table 4.4 Mean high-flow season discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change B2 Scenario

Station		Baseline Scenario: Mean high-flow season discharge (m^3/s)					Development Scenario: Mean high-flow season discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	4,127	4,042	4,479	4,157	4,238	3,412	3,435	3,914	3,513	3,639
2	Luang Prabang	6,008	5,804	6,767	5,800	6,179	4,912	4,855	5,808	4,807	5,216
3	Chiang Khan	6,636	6,488	7,623	6,538	6,942	5,536	5,536	6,659	5,542	5,976
4	Vientiane	6,837	6,706	7,894	6,768	7,183	5,734	5,750	6,924	5,765	6,211
5	Nong Khai	6,947	6,827	8,029	6,881	7,308	5,843	5,870	7,058	5,877	6,335
6	Nakhon Phanom	11,601	11,456	13,064	11,243	12,037	9,812	9,830	11,413	9,537	10,383
7	Mukdahan	12,522	12,428	14,089	12,181	13,022	10,939	10,998	12,648	10,678	11,571
8	Khong Chiam	14,444	14,198	15,981	14,029	14,857	12,656	12,760	14,530	12,515	13,397
9	Pakse	15,827	16,044	17,865	15,640	16,666	14,319	14,673	16,474	14,188	15,269
10	Stung Treng	20,827	21,185	23,247	20,663	21,875	19,055	19,560	21,623	18,927	20,226
11	Kratie	21,549	21,939	23,979	21,366	22,609	19,762	20,290	22,341	19,605	20,940
12	Kompong Cham	20,935	21,248	23,161	20,712	21,877	19,301	19,747	21,681	19,113	20,362
13	Phnom Penh	20,217	20,195	21,920	19,824	20,787	18,797	18,951	20,735	18,474	19,542
14	Tan Chau	14,435	14,392	15,391	14,047	14,706	13,614	13,702	14,687	13,310	14,000

Table 4.5 Mean low-flow season discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change B2 Scenario

	Station	Baseline Scenario: Mean low-flow season discharge (m^3/s)					Development Scenario: Mean low-flow season discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	1,157	1,383	1,522	1,332	1,426	1,847	1,966	2,073	1,959	2,007
2	Luang Prabang	1,499	1,770	2,038	1,713	1,862	2,247	2,382	2,613	2,387	2,474
3	Chiang Khan	1,613	1,903	2,214	1,848	2,013	2,356	2,509	2,786	2,518	2,619
4	Vientiane	1,640	1,935	2,255	1,879	2,048	2,377	2,536	2,824	2,547	2,652
5	Nong Khai	1,668	1,971	2,297	1,911	2,086	2,403	2,571	2,864	2,577	2,687
6	Nakhon Phanom	2,172	2,484	2,982	2,440	2,670	2,771	2,945	3,385	2,964	3,122
7	Mukdahan	2,220	2,536	3,055	2,489	2,729	2,935	3,104	3,578	3,131	3,296
8	Khong Chiam	2,386	2,693	3,276	2,652	2,912	3,060	3,246	3,786	3,281	3,465
9	Pakse	2,506	2,941	3,552	2,861	3,163	3,333	3,627	4,195	3,621	3,848
10	Stung Treng	3,515	3,933	4,716	3,741	4,197	4,511	4,772	5,497	4,667	5,033
11	Kratie	3,622	4,042	4,830	3,816	4,301	4,621	4,900	5,616	4,758	5,149
12	Kompong Cham	3,650	4,073	4,797	3,818	4,300	4,643	4,924	5,581	4,750	5,143
13	Phnom Penh	3,718	4,148	4,833	3,889	4,359	4,708	4,991	5,622	4,808	5,198
14	Tan Chau	5,052	5,401	5,970	5,225	5,586	5,502	5,725	6,336	5,497	5,914

Table 4.6 Mean annual discharge at 14 key stations along the Mekong River in the Baseline and Development Scenarios without and with climate change B2 Scenario

	Station	Baseline Scenario: Mean annual discharge (m^3/s)					Development Scenario: Mean annual discharge (m^3/s)				
		1985-2000	2010-2025	2026-2041	2042-2050	2010-2050	1985-2000	2010-2025	2026-2041	2042-2050	2010-2050
	Scenario	*S2*	*S4*	*S4*	*S4*	*S4*	*S3*	*S5*	*S5*	*S5*	*S5*
1	Chiang Saen	2,642	2,713	3,001	2,744	2,832	2,629	2,701	2,994	2,736	2,823
2	Luang Prabang	3,754	3,787	4,403	3,756	4,021	3,580	3,619	4,210	3,597	3,845
3	Chiang Khan	4,125	4,195	4,918	4,193	4,477	3,946	4,022	4,722	4,030	4,298
4	Vientiane	4,239	4,320	5,075	4,324	4,616	4,056	4,143	4,874	4,156	4,432
5	Nong Khai	4,308	4,399	5,163	4,396	4,697	4,123	4,221	4,961	4,227	4,511
6	Nakhon Phanom	6,887	6,970	8,023	6,842	7,353	6,292	6,387	7,399	6,250	6,753
7	Mukdahan	7,371	7,482	8,572	7,335	7,876	6,937	7,051	8,113	6,904	7,434
8	Khong Chiam	8,415	8,445	9,629	8,340	8,885	7,858	8,003	9,158	7,898	8,431
9	Pakse	9,167	9,492	10,708	9,251	9,914	8,826	9,150	10,334	8,905	9,559
10	Stung Treng	12,171	12,559	13,982	12,202	13,036	11,783	12,166	13,560	11,797	12,630
11	Kratie	12,585	12,991	14,404	12,591	13,455	12,192	12,595	13,979	12,181	13,045
12	Kompong Cham	12,292	12,661	13,979	12,265	13,089	11,972	12,335	13,631	11,932	12,753
13	Phnom Penh	11,967	12,172	13,376	11,856	12,573	11,753	11,971	13,178	11,641	12,370
14	Tan Chau	9,743	9,897	10,681	9,636	10,146	9,558	9,713	10,511	9,403	9,957

4.2. Impacts of development without climate change

As described in Chapter 2, a comparison of Scenarios S2 with S3 or S5 with S4, allows the analysis of the impacts of development on the flow regime under the same climate conditions, either with or without climate change.

To analyse the impacts of development assuming no future climate change, discharge at key stations in Scenario S3 (Development + PRECIS data for 1985 - 2000) was compared to that at the stations in Scenario S2 (Baseline + PRECIS data for 1985 - 2000) (see Table 4.7). In the high-flow season, discharge decreases at all stations. The amount of the decrease gradually increases with the downstream distance. The decrease at the upstream station of Chiang Saen is 715 m^3/s, whereas at the downstream station of Kratie it is 1,787 m^3/s. There are some variations at Mukdahan and Pakse because of the water use in these reaches. Downstream from Kratie, the values decrease again because, as previously described, these downstream stations do not reflect the total amount of the Mekong water.

In the low-flow season, the reverse is true, with discharge increasing at all stations but to a lesser extent than the corresponding decrease in the high-flow season. Thus the annual discharge, the sum of the high- and low-flow seasons, shows an overall decrease. This decrease in annual discharge reflects more water use in the Basin by new hydropower reservoirs and for irrigation in the future in the Development Scenario. When expressed as percentages, the decreases in the discharge in the high-flow season and increases in the low-flow season gradually reduce from upstream to downstream. These variations lead to variations in the decreases of the annual discharge, with the highest percentage decrease of 8.6% occurring at Nakhon Phanom, and smaller percentages at Mukdahan and Khong Chiam (5.9% and 6.6% respectively), and less than 5% at other stations.

Table 4.7 Flow changes resulting from development without climate change

Station		Flow Change (+/- m^3/s)			Flow Change (+/- %)		
		1985-2000	1985-2000	1985-2000	1985-2000	1985-2000	1985-2000
		High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual
	Scenario	*S3-S2*	*S3-S2*	*S3-S2*	*S3-S2*	*S3-S2*	*S3-S2*
1	Chiang Saen	-715	690	-12	-17	60	-0.5
2	Luang Prabang	-1,097	748	-174	-18	50	-4.6
3	Chiang Khan	-1,100	742	-179	-17	46	-4.3
4	Vientiane	-1,103	738	-183	-16	45	-4.3
5	Nong Khai	-1,104	736	-184	-16	44	-4.3
6	Nakhon Phanom	-1,789	599	-595	-15	28	-8.6
7	Mukdahan	-1,584	716	-434	-13	32	-5.9
8	Khong Chiam	-1,788	674	-557	-12	28	-6.6
9	Pakse	-1,508	826	-341	-10	33	-3.7
10	Stung Treng	-1,772	996	-388	-9	28	-3.2
11	Kratie	-1,787	1,000	-394	-8	28	-3.1
12	Kompong Cham	-1,634	994	-320	-8	27	-2.6
13	Phnom Penh	-1,419	990	-215	-7	27	-1.8
14	Tan Chau	-821	450	-185	-6	9	-1.9

4.3. Impacts of development under climate change

Table 4.8 presents the flow changes resulting from development under climate change in Scenarios A2 and B2 (S5) compared to those in the Baseline (S4) in 2010 - 2050. The changes are similar to the changes assuming no climate change i.e. decreases in discharge in the high-flow season greater than the increases in the low-flow season leading to the decreases in the annual flow between 5% and 8% at Nakhon Phanom, Mukdahan and Khong Chiam, and less than 4.5% at other stations.

Table 4.8 Flow changes due to development under climate change

Station		Flow Change (+/- m^3/s)						Flow Change (+/- %)					
		A2			B2			A2			B2		
		2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050
		High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual
	Scenario	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*	*S5-S4*
1	Chiang Saen	-586	569	-9	-599	580	-9	-13.2	38.8	-0.3	-14.1	40.7	-0.3
2	Luang Prabang	-953	595	-179	-962	611	-176	-14.8	30.7	-4.3	-15.6	32.8	-4.4
3	Chiang Khan	-955	589	-183	-966	607	-180	-13.2	28.2	-3.9	-13.9	30.1	-4.0
4	Vientiane	-960	585	-188	-972	603	-184	-12.8	27.6	-3.9	-13.5	29.5	-4.0
5	Nong Khai	-962	584	-189	-973	602	-186	-12.6	27.0	-3.9	-13.3	28.9	-4.0
6	Nakhon Phanom	-1,641	433	-604	-1,654	452	-601	-13.1	15.8	-7.9	-13.7	16.9	-8.2
7	Mukdahan	-1,436	547	-445	-1,451	567	-442	-10.6	19.6	-5.4	-11.1	20.8	-5.6
8	Khong Chiam	-1,469	526	-471	-1,460	553	-454	-9.4	17.6	-5.1	-9.8	19.0	-5.1
9	Pakse	-1,377	661	-358	-1,396	685	-356	-7.9	20.5	-3.5	-8.4	21.7	-3.6
10	Stung Treng	-1,644	777	-434	-1,649	836	-406	-7.1	18.0	-3.2	-7.5	19.9	-3.1
11	Kratie	-1,660	785	-438	-1,669	848	-410	-6.9	17.8	-3.1	-7.4	19.7	-3.1
12	Kompong Cham	-1,506	784	-361	-1,515	843	-336	-6.5	17.7	-2.6	-6.9	19.6	-2.6
13	Phnom Penh	-1,216	786	-215	-1,244	839	-203	-5.6	17.5	-1.6	-6.0	19.2	-1.6
14	Tan Chau	-677	366	-155	-706	329	-189	-4.4	6.4	-1.5	-4.8	5.9	-1.9

4.4. Impacts of climate change on flow regime

Assuming the Baseline Scenario will be continued for the future, the impacts of climate change on flow regime can be analysed by a comparison of Scenario S4 (Baseline + PRECIS data for 2010 -2050) with Scenario S2 (Baseline + PRECIS data for 1985 - 2000) as shown in Table 4.9. With climate change, the discharge increases in both seasons. The increases are about 2 – 3 times greater in the high-flow season than those in the low-flow season at downstream stations in Scenario A2 but less in Scenario B2. In Scenario A2, the percentage increase in discharge is between 20% and 30% in the low-flow season and 7% and 11% in the high-flow season, leading to an overall increase of 10 - 13% in the annual discharge at stations upstream of Kratie. In Scenario B2, the increase in the low-flow season is still high, between 19% and 25%, but much less, only 2 - 5%, than that in the high-flow season, therefore the overall increase, of only 5 - 9%, in the annual discharge is less than that in Scenario A2.

Table 4.9 Flow change resulting from climate change in the Baseline Scenario

	Station	Flow Change (+/- m^3/s)						Flow Change (+/- %)					
		A2			B2			A2			B2		
		2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050
		High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual
	Scenario	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*	*S4-S2*
1	Chiang Saen	326	310	318	111	270	190	7.9	26.8	12.0	2.7	23.3	7.2
2	Luang Prabang	449	438	443	170	364	267	7.5	29.2	11.8	2.8	24.3	7.1
3	Chiang Khan	604	476	540	305	399	352	9.1	29.5	13.1	4.6	24.8	8.5
4	Vientiane	650	484	567	346	408	377	9.5	29.5	13.4	5.1	24.9	8.9
5	Nong Khai	667	493	580	361	418	389	9.6	29.6	13.5	5.2	25.1	9.0
6	Nakhon Phanom	901	561	731	436	498	467	7.8	25.9	10.6	3.8	22.9	6.8
7	Mukdahan	1,046	572	809	500	509	504	8.4	25.8	11.0	4.0	22.9	6.8
8	Khong Chiam	1,166	598	882	413	526	469	8.1	25.1	10.5	2.9	22.0	5.6
9	Pakse	1,706	712	1,209	839	656	748	10.8	28.4	13.2	5.3	26.2	8.2
10	Stung Treng	2,318	810	1,564	1,048	682	865	11.1	23.0	12.8	5.0	19.4	7.1
11	Kratie	2,341	798	1,569	1,060	679	870	11.2	22.7	12.9	5.1	19.3	7.1
12	Kompong Cham	2,094	774	1,434	942	650	796	10.0	21.2	11.7	4.5	17.8	6.5
13	Phnom Penh	1,495	775	1,135	570	642	606	7.4	20.8	9.5	2.8	17.3	5.1
14	Tan Chau	832	648	740	272	534	403	5.8	12.8	7.6	1.9	10.6	4.1

A comparison of Scenario S5 (Development + PRECIS data for 2010 - 2050) with Scenario S3 (Development + PRECIS data for 1985 - 2000) reveals similar impacts of climate change on flow regime in the Development Scenario (Table 4.10). Although the increase of discharge in the low-flow season is less than that found in the Baseline because, in the Development Scenario more water is available in the sub-basins in the low-flow seasons and so more will be used. On the other hand, the greater increase in the discharge in the high-flow season in comparison to that in the Baseline Scenario shows that the water control measures in the Development Scenario have not taken into account the increase in water yield due to climate change. However, these two changes lead to a similar change in annual discharge in the Baseline Scenario at most stations. Once again, the annual discharge increase of 11 - 14% in Scenario A2 is slightly higher than that 7 - 9% in Scenario B2.

Table 4.10 Flow change due to climate change in the Development Scenario

Station		Flow Change (+/- m^3/s)						Flow Change (+/- %)					
		A2			B2			A2			B2		
		2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050
		High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual
	Scenario	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*	*S5-S3*
1	Chiang Saen	456	188	322	228	160	194	13.4	10.2	12.2	6.7	8.6	7.4
2	Luang Prabang	593	284	439	305	226	266	12.1	12.7	12.3	6.2	10.1	7.4
3	Chiang Khan	749	323	536	439	264	352	13.5	13.7	13.6	7.9	11.2	8.9
4	Vientiane	793	332	563	477	274	376	13.8	14.0	13.9	8.3	11.5	9.3
5	Nong Khai	810	341	575	492	284	388	13.9	14.2	14.0	8.4	11.8	9.4
6	Nakhon Phanom	1,049	395	722	571	351	461	10.7	14.3	11.5	5.8	12.7	7.3
7	Mukdahan	1,193	403	798	633	360	497	10.9	13.7	11.5	5.8	12.3	7.2
8	Khong Chiam	1,485	450	967	741	405	573	11.7	14.7	12.3	5.9	13.2	7.3
9	Pakse	1,838	546	1,192	951	515	733	12.8	16.4	13.5	6.6	15.5	8.3
10	Stung Treng	2,446	590	1,518	1,171	522	847	12.8	13.1	12.9	6.1	11.6	7.2
11	Kratie	2,468	583	1,525	1,178	528	853	12.5	12.6	12.5	6.0	11.4	7.0
12	Kompong Cham	2,222	564	1,393	1,062	500	781	11.8	12.0	11.9	5.6	10.6	6.6
13	Phnom Penh	1,698	571	1,134	745	490	617	9.0	12.1	9.6	4.0	10.4	5.3
14	Tan Chau	975	564	770	386	413	399	7.2	10.2	8.1	2.8	7.5	4.2

4.5. Comparison of development and climate change impacts

Impacts of both development and climate change on flow regime are analysed by comparing Scenario S5 (Development + PRECIS data 2010 - 2050) with Scenario S2 (Baseline + PRECIS data 1985 - 2000) as shown in Table 4.11. Discharge in the low-flow season increases significantly (by 40 - 70% at stations upstream of Kratie) in both Scenarios A2 and B2 because of the contribution of both development and climate change. On the other hand, flow change in the high-flow season varies with the climate change scenario. In Scenario A2, discharge in this season decreases at upstream stations, but increases downstream from Pakse. In Scenario B2, it decreases at all stations, but to a lesser extent than the increase in the low-flow season. Development and climate change together result in an increase in the annual discharge at all stations. The increase of 5 – 10% in Scenario A2 is greater than that of 0 – 7% in Scenario B2 with the exception of the slight decrease of 1.9% at Nakhon Phanom.

Table 4.11 Flow change due to both development and climate change

	Station	Flow Change (+/- m³/s)						Flow Change (+/- %)					
		A2			B2			A2			B2		
		2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050	2010-2050
		High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual	High-flow season	Low-flow season	Annual
	Scenario	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*	*S5-S2*
1	Chiang Saen	-260	879	310	-487	850	181	-6.3	76.0	11.7	-11.8	73.5	6.9
2	Luang Prabang	-503	1,033	265	-792	975	91	-8.4	68.9	7.0	-13.2	65.0	2.4
3	Chiang Khan	-351	1,065	357	-661	1,006	173	-5.3	66.0	8.6	-10.0	62.4	4.2
4	Vientiane	-310	1,069	380	-626	1,012	193	-4.5	65.2	9.0	-9.2	61.7	4.6
5	Nong Khai	-295	1,076	391	-612	1,020	204	-4.2	64.5	9.1	-8.8	61.1	4.7
6	Nakhon Phanom	-740	994	127	-1,218	950	-134	-6.4	45.8	1.8	-10.5	43.7	-1.9
7	Mukdahan	-390	1,119	364	-951	1,076	62	-3.1	50.4	4.9	-7.6	48.5	0.8
8	Khong Chiam	-303	1,124	411	-1,047	1,079	16	-2.1	47.1	4.9	-7.3	45.2	0.2
9	Pakse	329	1,372	851	-557	1,342	392	2.1	54.8	9.3	-3.5	53.5	4.3
10	Stung Treng	674	1,586	1,130	-601	1,518	458	3.2	45.1	9.3	-2.9	43.2	3.8
11	Kratie	681	1,582	1,132	-609	1,528	459	3.2	43.7	9.0	-2.8	42.2	3.6
12	Kompong Cham	588	1,558	1,073	-572	1,493	460	2.8	42.7	8.7	-2.7	40.9	3.7
13	Phnom Penh	278	1,561	920	-674	1,480	403	1.4	42.0	7.7	-3.3	39.8	3.4
14	Tan Chau	155	1,014	584	-435	862	214	1.1	20.1	6.0	-3.0	17.1	2.2

Figures 4.1 to 4.6 show comparisons of the impacts in the paired scenarios on the high- and low-flow seasons, and the annual discharges in Scenarios A2 and B2, while Figure 4.1 shows clearly the contrasting trends of development and climate change in the high-flow season. While development causes a decrease in discharge of between 5% and 18%, climate change causes an increase in discharge of between 5% and 14%. The effect of decreasing high-flow season discharge by development under non-climate change conditions (Scenario S3 - S2) is slightly higher than that under climate change conditions (Scenario S5 - S4). On the other hand, the effect of the increase in the high-flow season discharge by climate change under development (Scenario S5 - S3) is slightly higher than that in the Baseline (S4 - S2). This poses questions as to the efficiency of development, designed and operating in non-climate change conditions, in controlling the high-flow season discharge under climate change. More detailed analysis will be needed to identify suitable options in adapting to climate change. The combined effects of development and climate change lead to a 2 - 5% decrease (Scenario S5 - S2) in high-flow season discharge at stations upstream of Pakse, but a slightly smaller increase of 0 - 4% downstream from this station.

In contrast to the high-flow season, development (Scenario S5 - S4) and climate change (Scenario S4 - S2) result in a similar increase of 20 – 40% in the low-flow season discharge at all stations, with the exception of Tan Chau (Figure 4.2). The increase resulting from climate change is mainly explained by the increase of precipitation and snowmelt in the UMB discussed below. The combined effects of development and climate change (Scenario S5 - S2) lead to a 40 - 80% increase in discharge which is higher at upstream but gradually reduces downstream. The increase in the low-flow season discharge by development under non-climate change condition (Scenario S3 - S2) is higher than that under climate change condition (Scenario S5 - S4). In contrast, the increase in the low-flow season discharge by climate change under development (Scenario S5 - S3) is lower than that under Baseline (Scenario S4 - S2) since more water is used in the sub-basins in the low-flow season under the Development Scenario.

Development and climate change increase the total annual discharge at all stations by 2 - 12% (Scenario S5 - S2 in Figure 4.3). In this combination, the impact of climate change is stronger giving an 8 - 14% increase in the annual discharge while the impact of development is lower with 0 - 8% decrease. Interestingly, while there are large differences in effects of development on climate change impacts (Scenario S5 - S3 compared with Scenario S4 - S2) and of climate change on development impacts (Scenario S5 - S4 compared with Scenario S3 - S2) in the high- and low-flow seasons as already discussed (Figures 4.1 and 4.2), these differences in the effects on the annual discharge are minor. This implies that a seasonal analysis of impacts season should be made rather than one which only looks at the annual discharge.

Under Scenario B2, similar results for the high-flow season, low-flow season and annual discharges are presented in Figures 4.4, 4.5 and 4.6 respectively. The impact of climate change on the high-flow season discharge (Figure 4.4) is less at 2 - 8% than that at 5 - 14% in Scenario A2, while the impact of development is the same as that in Scenario A2. This results in their combined impacts bringing about a decrease in the high-flow season discharge at all stations, with a 7 - 13% decrease upstream of Pakse and a 3 - 4% decrease downstream from this station. In contrast, in Scenario B2, the impacts of both development and climate change on low-flow season discharge (Figure 4.5) are similar to those in Scenario A2 (Figure 4.2). The combined impacts in both seasons result in an increase in annual discharge, but the increase is smaller in Scenario B2 at 0 - 7% compared to 2 - 12% in Scenario A2. This is true of all stations, with the exception of a slight decrease of 2% at Nakhon Phanom.

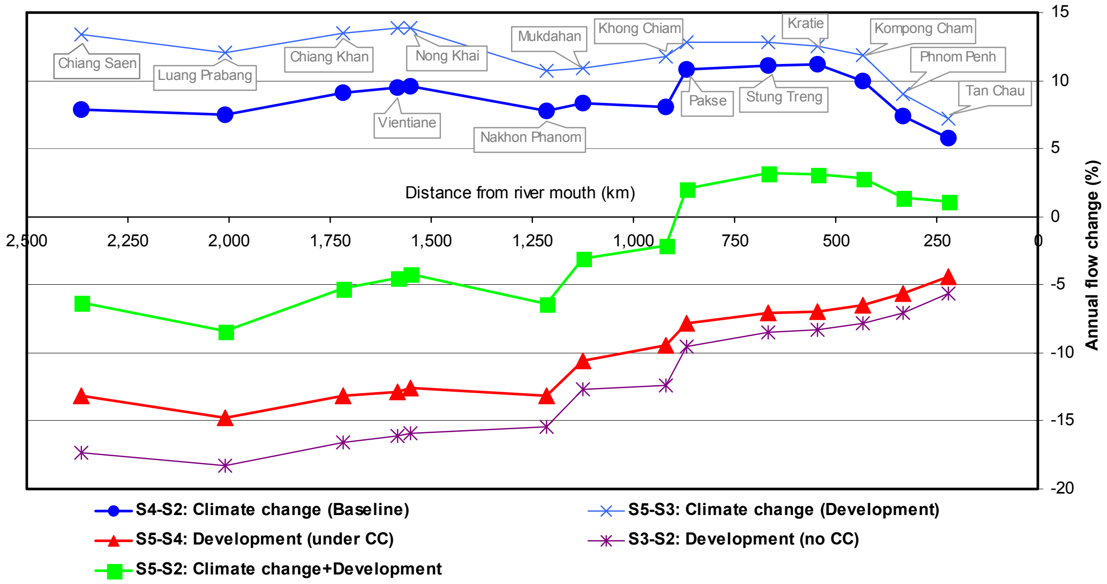


Figure 4.1 Impacts of development and climate change on high-flow season discharge under Scenario A2

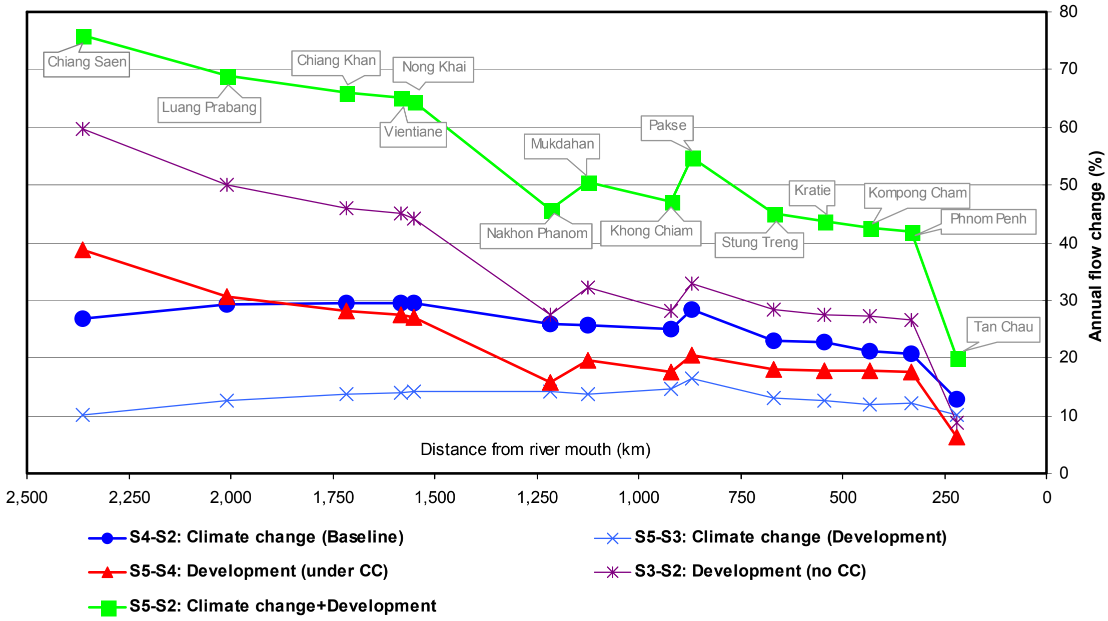


Figure 4.2 Impacts of development and climate change on low-flow season discharge under Scenario A2

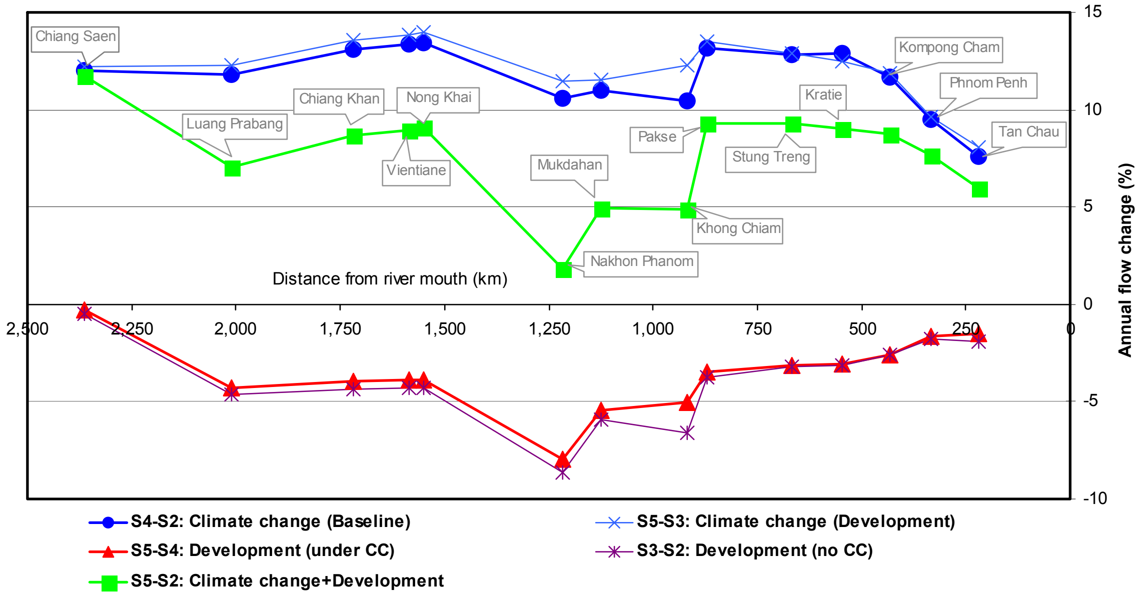


Figure 4.3 Impacts of development and climate change on annual discharge under Scenario A2

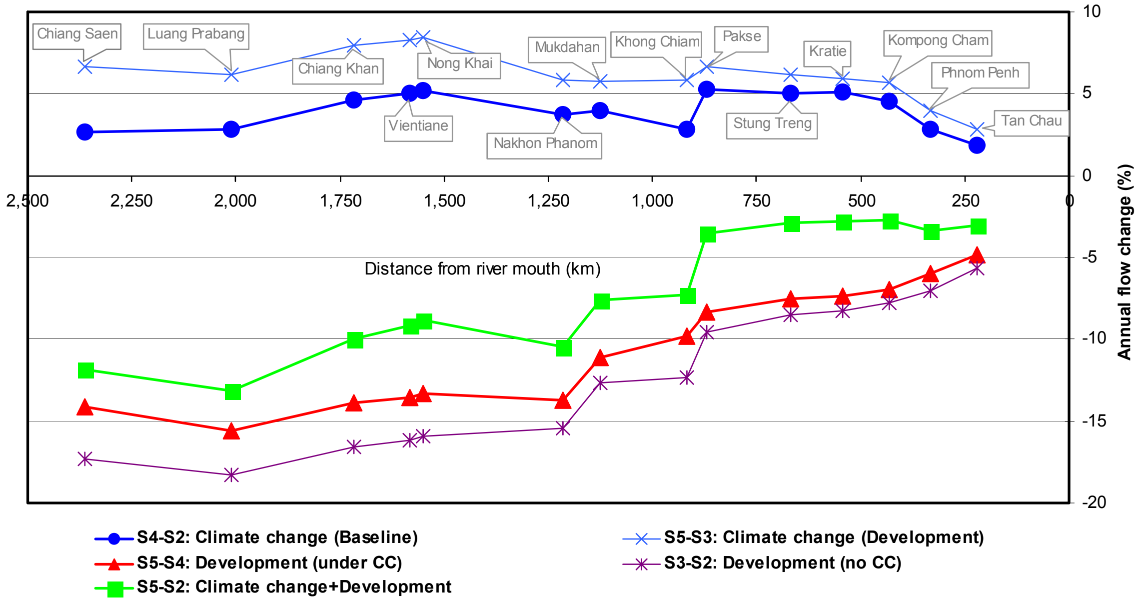


Figure 4.4 Impacts of development and climate change on high-flow season discharge under Scenario B2

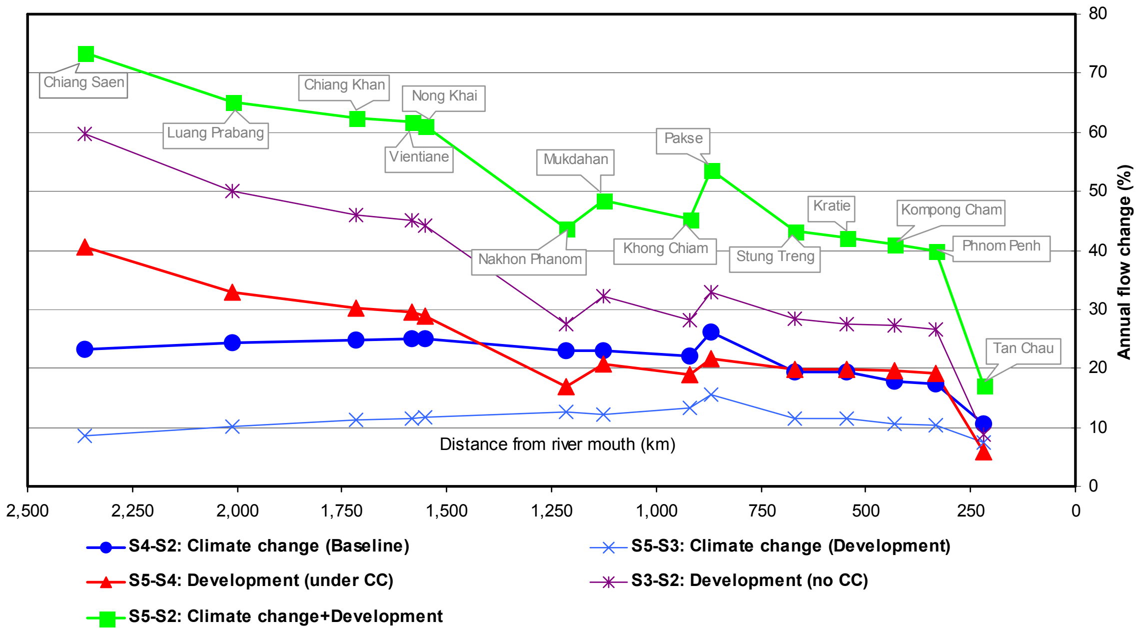


Figure 4.5 Impacts of development and climate change on low-flow season discharge under scenario B2

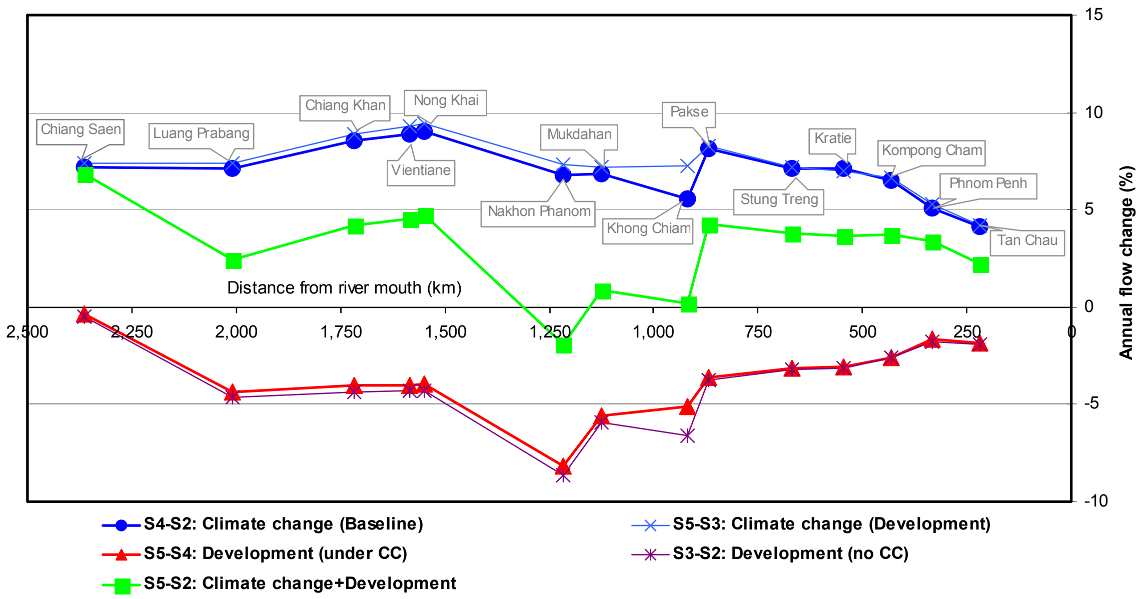


Figure 4.6 Impacts of development and climate change on annual discharge under Scenario B2

4.6. Contribution of snowmelt under climate change

Climate change and its effects on snowmelt in the UMB could result in changes in the flow regime of the Mekong River. The increased temperature will mean the earlier melting of snow in the UMB. This is not the same as the effects of climate change on the melting of glaciers. Within the Mekong catchment, the melted glaciers (about 17.3 km^3) and permafrost covering about 50,000 km^2 of the Tibetan part of the catchment (about 10 km^3) are equivalent to about 25,000 million m^3 of water, (Eastham et al., 2008). If future global warming were to melt all these glaciers and the permafrost, the annual amount of water produced would still be insignificant in comparison to the total Mekong water of 475,000 million m^3 per year (Eastham et al., 2008; Johnston et al., 2009).

The mean monthly and annual snowmelt depths in millimetres were calculated for all SWAT sub-basins of the UMB. Figure 4.7 presents the changes in the future (2010 – 2050) of the mean annual sub-basin snowmelt depths compared to those of 1985 – 2000. The maximum increase is around 40 mm in both Scenarios A2 and B2. The mean annual snowmelt depths over the entire UMB are 23.2, 39.9 (a 72% increase) and 37.5 (a 62% increase) mm/year for the baseline climate of 1985 – 2000, and the future climate of 2010 – 2050 under Scenarios A2 and B2, respectively.

Table 4.12 shows that snowmelt currently contributes around 5.5% to the total water yield at the Chinese–Lao border and this might increase to 8% in 2010 - 2050 in Scenarios A2 and B2. Snowmelt in the UMB contributes about 7% at Chiang Saen to the Mekong discharge, but the percentage gradually lowers further downstream, to about 1.5% at Kratie.

In 1985 - 2000, at the time of the greatest snowmelt in March, its contribution to river discharge is significant, contributing 68.2% and 22.2% at Chiang Saen and Kratie, respectively. With the temperature and precipitation increase under the climate change scenario, the amount of March snowmelt will change, but the percentage contribution to the river discharge will not differ by much, because the river discharge also changes

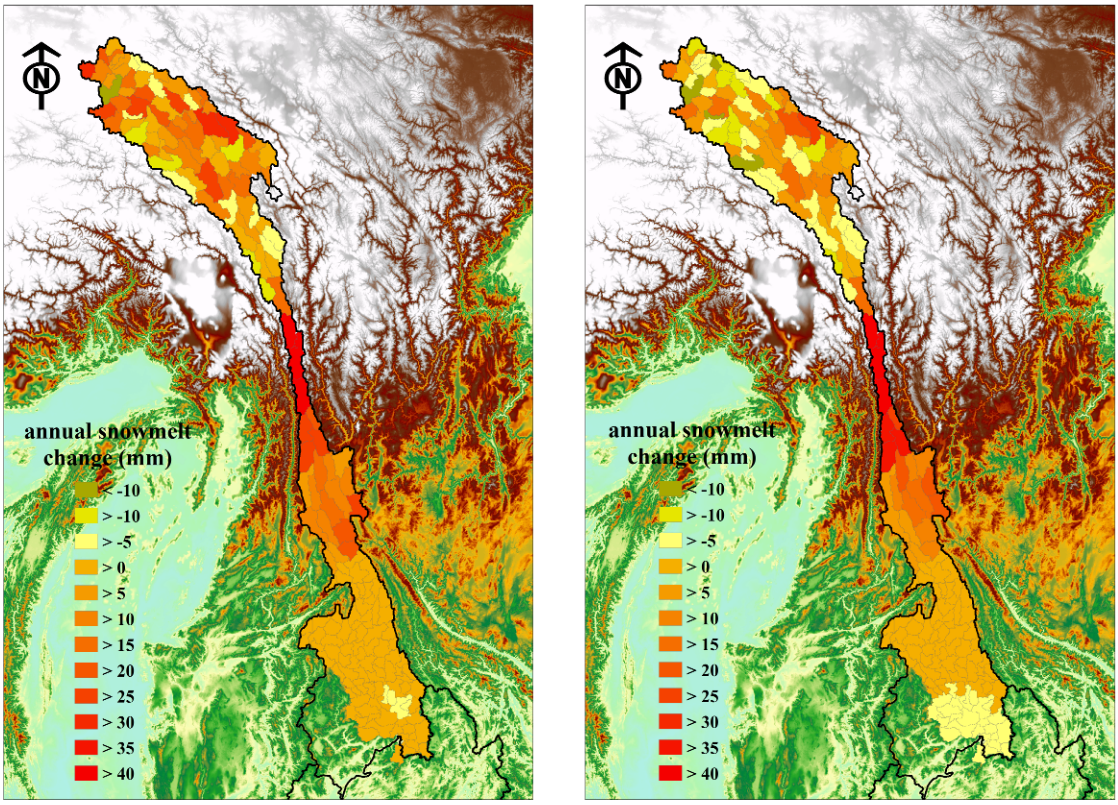


Figure 4.7 Changes of mean annual snowmelt depths in 2010 – 2050 of Scenario A2 (left) and B2 (right) relative to the mean depth of 1985 – 2000

Table 4.12 Mean annual snowmelt contribution to water yield in the UMB under Scenarios A2 (upper part) and B2 (lower part)

Period	Mean Annual Water Yield or Runoff (mm)	Mean Annual Snowmelt (mm)	Snowmelt Contribution to Water Yield (%)	Snowmelt Increase Relative to 1985 - 2000	
				(mm)	(%)
1985 - 2000	417.8	23.2	5.5		
2010 - 2025	443.6	43.4	9.8	20.2	87.3
2026 - 2041	487.6	39.5	8.1	16.4	70.6
2042 - 2050	483.6	34.8	7.2	11.7	50.3
2010 - 2050	469.5	39.9	8.5	16.7	72.3

Period	Mean Annual Water Yield or Runoff (mm)	Mean Annual Snowmelt (mm)	Snowmelt Contribution to Water Yield (%)	Snowmelt Increase Relative to 1985 - 2000	
				(mm)	(%)
1985 - 2000	417.8	23.2	5.5		
2010 - 2025	432.1	41.1	9.5	17.9	77.2
2026 - 2041	473.5	36.6	7.7	13.5	58.2
2042 - 2050	446.5	33.0	7.4	9.8	42.4
2010 - 2050	451.4	37.5	8.3	14.3	61.8

4.7. Irrigation extraction under development and climate change

In comparison with 1985 - 2000, the higher temperatures in 2010 – 2050 are likely to lead to increased demands for water for agriculture which in turn led to the projection of more water diversions for irrigation. This increase could also be due to the expansion of crop areas in the dry season with higher river discharge. Another reason could be the change in the precipitation pattern making more supplementary irrigation necessary in the wet season. More detailed analysis will be needed to confirm these assumptions.

Table 4.13 summarises changes in the total diversions for irrigation in the different scenarios. The current demand of 36,074 million m^3 in Scenario S2 (Baseline + PRECIS data for 1985 - 2000), diversions in Scenarios S3 (Development + PRECIS data for 1985 - 2000) or S4 (Baseline with A2 and B2 PRECIS data for 2010 -2 050) increases to about 40,000 million m^3 (an 11 - 12% increase). In both development and climate change scenarios, about 45,000 million m^3 (a 24 - 25% increase) more water is diverted for irrigation. However, this increase depends to a large extent on the assumptions of the way in which irrigation schemes will be implemented in different sub-areas (Table 4.13). For example, in the sub-area 10V (Vietnam Delta), no irrigation expansion is assumed in the Development Scenario (Table 2.8), therefore irrigation in Scenarios S2 and S3 remains the same under the same climate conditions. However, in the climate change scenarios, diversions for irrigation in this sub-area increase significantly by about 2,600 - 2,900 million m^3 (about 60% of the total increase in the basin) due to increase in water requirement for crops under projected climate conditions.

Table 4.13 Changes in net irrigation diversions of BDP subarea due to development and climate change (in million m^3, BDP sub areas as shown in Fig., 2.6)

BDP Subarea	Past period 1985-2000			A2: 2010-2050				B2: 2010-2050			
	Base line	Develop-ment	+/- (%)	Base line	Develop-ment	+/- (%)	+/- (%)	Base line	Develop-ment	+/- (%)	+/- (%)
Scenario	*S2*	*S3*	*S3-S2*	*S4*	*S5*	*S5-S4*	*S5-S2*	*S4*	*S5*	*S5-S4*	*S5-S2*
1L	243	357	46.5	280	406	45.0	66.8	288	419	45.2	71.9
2T	543	742	36.8	538	739	37.4	36.2	557	761	36.5	40.1
3L	25	37	44.9	31	46	46.0	80.8	31	46	45.8	81.8
3T	947	1,291	36.3	1,153	1,546	34.0	63.2	1,104	1,498	35.7	58.1
4L	1,669	2,438	46.1	1,918	2,809	46.5	68.3	1,946	2,854	46.7	71.0
5T	5,823	8,044	38.1	5,878	8,218	39.8	41.1	5,546	7,845	41.4	34.7
6C	200	288	44.3	233	335	43.9	67.8	242	348	44.0	74.4
6L	147	216	46.2	166	241	45.0	63.2	174	253	45.4	71.4
7C	122	151	24.6	160	195	21.6	60.6	167	204	21.8	67.6
7L	139	204	46.8	161	235	46.0	69.5	170	249	46.0	79.1
7V	625	1,008	61.4	699	1,100	57.5	76.2	725	1,124	55.0	80.0
8C	219	296	34.9	267	353	32.3	61.0	265	352	32.9	60.5
9C	2,009	2,015	0.3	2,261	2,268	0.3	12.9	2,133	2,145	0.5	6.7
10C	3,634[12]	3,634	0.0	3,931	3,931	0.0	8.2	3,989	3,989	0.0	9.8
10V	19,728	19,795	0.3	22,858	22,889	0.1	16.0	22,657	22,694	0.2	15.0
Total	36,074	40,515	12.3	40,533	45,311	11.8	25.6	39,995	44,779	12.0	24.1

[12] This include supplementary irrigation in wet season. See the note at the bottom of Table 2.5.

4.8. Impacts of development and climate change on flood and salinity intrusion

Change in flood frequencies will require detailed analysis at the sub-basin level. At the basin-wide level, change is analyzed by simply comparing the change in the number of days with discharge higher than the mean in the high-flow season under development and climate change scenarios (Table 4.14). In the Development Scenario (S3), in comparison with the Baseline with the climate conditions of 1985 – 2000 (Scenario S2), the number of days with high discharge at Chiang Saen decreases by 52% but this percentage gradually decreases to about 12% at Tan Chau. However in the Baseline, climate change (Table 4.14, column S4 - S2) increases the number of days with high discharge by about 5 - 19% in Scenario A2, but by about only 0 – 10% in Scenario B2. The decrease in the number of days with high discharge in the Development Scenario is smaller with climate change, of about 34% and 41% at Chiang Saen under Scenarios A2 and B2 respectively. This percentage gradually decreases at the downstream stations. The percentage variations by station and by climate change scenario indicates that the current development plan has not yet been adapted for climate change, as shown by the input data and the reservoir rules and regulation used in the current DSF models.

Table 4.14 Average number of days per year with discharge higher than mean discharge in high-flow season

Station		Mean discharge in high-flow season 1985-2000	Average number of days per year with discharge higher than mean discharge in high-flow season.						Change (%)				
			No CC		A2		B2		No CC	A2		B2	
			1985-2000	1985-2000	2010-2050	2010-2050	2010-2050	2010-2050	1985-2000	2010-2050	2010-2050	2010-2050	2010-2050
	Scenario		*S2 – Base line*	*S3 - Dev*	*S4 – Base line*	*S5 - Dev*	*S4 – Base line*	*S5 - Dev*	*S3-S2*	*S4-S2*	*S5-S2*	*S4-S2*	*S5-S2*
1	Chiang Saen	4,127	97	47	106	68	97	57	-52.1	9.6	-30.4	-0.2	-41.3
2	Luang Prabang	6,008	89	43	102	67	96	59	-51.1	15.1	-24.3	7.6	-34.0
3	Chiang Khan	6,636	89	46	105	74	97	65	-48.6	17.9	-17.4	9.1	-27.6
4	Vientiane	6,837	89	48	105	76	97	66	-46.6	18.6	-14.6	9.6	-25.3
5	Nong Khai	6,947	89	48	106	76	98	68	-45.9	19.1	-13.9	10.4	-23.6
6	Nakhon Phanom	11,601	87	59	94	71	90	68	-31.4	8.1	-17.6	4.0	-21.2
7	Mukdahan	12,522	86	66	93	76	90	73	-23.7	7.6	-12.2	3.8	-15.3
8	Khong Chiam	14,444	86	68	91	77	86	74	-20.3	6.1	-10.5	0.9	-13.3
9	Pakse	15,827	86	72	92	81	88	78	-16.5	6.5	-6.7	2.2	-10.3
10	Stung Treng	20,827	88	72	93	83	89	79	-18.5	5.0	-6.3	0.4	-10.6
11	Kratie	21,549	88	73	93	83	89	80	-17.4	5.5	-5.4	1.1	-9.0
12	Kompong Cham	20,935	91	76	95	85	91	83	-16.4	4.4	-6.4	-0.3	-8.9
13	Phnom Penh	20,217	93	79	98	88	93	85	-14.7	5.3	-5.3	0.1	-8.5
14	Tan Chau	14,435	105	93	118	106	111	100	-11.9	12.0	1.0	5.6	-4.7

Attention is commonly paid to areas of the Mekong Delta which are flooded or suffer saline intrusion in extreme years, therefore in 1985 - 2000, 1998 was selected since it was a low discharge year with high salinity intrusion and 2000 was selected since it was a year of high floods. The selection of the extreme years for 2010 - 2050 is based on the daily flow at Kratie. The years of 2048 and 2047 in Scenarios A2 and B2 respectively, were selected for flood analysis because of the high daily discharge in the high-flow season. For the salinity analysis the years of 2021 and 2022 were selected for Scenarios A2 and B2 respectively.

In Baseline Scenario S2 in 2000 the total flooded area was about 45,000 km^2 (Table 4.15), while in Development Scenario S3 with the same climate data of 2000, this area was reduced to 43,000 km^2 (-3.4%) because the peak flow was lower. However, under climate change with the Baseline (Scenario S4), the total flooded area increased to 49,000 km^2 (+8.8%) in Scenario A2 and to 46,000 km^2 (+3.1%) in Scenario B2, corresponding to very high peak flows. The difference in the two climate change scenarios implies that the area of flooding depends, to a large extent, on the highly uncertain future distribution of the daily precipitation throughout the wet season (Figure 4.8). Water control under Development Scenario S5 can reduce the total flooded area by only less than 1% of the total flooded area in Scenarios A2 and B2 (comparing Scenario S5 - S2 with Scenario S4 - S2) because of the limited decrease in peak flows (Figure 4.8). In all the Scenarios, the percentage increase (Scenario S4 - S2, and Scenario S5 - S2) or decrease (Scenario S3 - S2) is higher at higher flood depth levels (except some at depths of > 3 m), but the absolute values of flooded areas are lower.

Table 4.16 shows a comparison of the duration of flooding in areas with flood depths higher than 0.5 m in the different Scenarios. The climate conditions of 1985 - 2000 and development reduced the duration of flooding by about 6 - 9% (see column S3-S2), while the impacts of climate change vary a great deal from one Scenario to another with an increase of 14 - 23% at different duration levels in Scenario A2 but either a decrease or increase of 0 - 5% in Scenario B2 because the peak flow in Scenario B2 is very high, and the high flow period is short compared with that of the year 2000 and Scenario A2. The effects of development on the duration of flooding under climate change also vary depending on the different Scenarios and duration levels (columns S5-S2).

Changes in the salinity intrusion in the different scenarios are shown in Table 4.17. In the Development Scenario the increased discharge in the low-flow season reduces the salt intrusion area for salinity concentrations > 4 g/l by about 14% (column S3-S2). However, under climate change, although, over a long period, the mean discharge will increase, the annual variation is rather large, hence low-flow seasonal discharges may be lower than in the certain past years, although the long term average discharge in the low-flow season may increase as previously discussed. This variation is shown by the 16 - 17% increase of those areas of salinity > 4 g/l) in Scenario S4 (Baseline + PRECIS data for 2010 - 2050) in the years of 2021 and 2022 for Scenarios A2 and B2, respectively. Development can compensate for climate variability causing low minimum monthly discharges as shown in column S5-S2. However, salinity intrusion in the Delta also depends on the water volume stored in the Great Lake during the high-flow season in the previous year and the tidal regime in the sea, therefore the saline area does not always correspond to the minimum monthly discharge at Kratie, as shown in the cases of Scenarios A2 and B2 of Scenario S5.

Table 4.15 Flooded areas under different development and climate change scenarios

Maximum Flood Depth (m)	Flood Area based on Maximum Flood Depth (km^2)						Difference in Flooded Area (+/- km^2)					Difference in Flooded Area (+/- %)				
	Baseline 2000	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2
	S2	S4	S4	S3	S5	S5	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2
Peak daily discharge at Kratie (m^3/s)	*54,922**	*95,293*	*90,117*	*50,807*	*92,922*	*92,569*	*40,370*	*35,195*	*-4,116*	*38,000*	*37,647*	*73.5*	*64.1*	*-7.5*	*69.2*	*68.5*
> 0.0 m	44,654	48,579	46,037	43,121	48,295	45,753	3,925	1,383	-1,533	3,642	1,099	8.8	3.1	-3.4	8.2	2.5
> 0.5 m	41,317	46,915	42,657	39,541	46,599	42,253	5,598	1,340	-1,776	5,282	936	13.5	3.2	-4.3	12.8	2.3
> 1.0 m	36,393	43,917	38,311	33,352	43,457	37,620	7,524	1,918	-3,041	7,065	1,227	20.7	5.3	-8.4	19.4	3.4
> 1.5 m	30,923	40,563	33,061	27,946	40,003	32,355	9,641	2,138	-2,976	9,081	1,432	31.2	6.9	-9.6	29.4	4.6
> 2.0 m	26,347	36,459	28,993	22,975	35,703	28,334	10,112	2,645	-3,372	9,356	1,987	38.4	10.0	-12.8	35.5	7.5
> 2.5 m	21,971	32,783	24,924	19,060	31,951	24,212	10,812	2,953	-2,912	9,980	2,241	49.2	13.4	-13.3	45.4	10.2
> 3.0 m	17,977	29,006	20,934	15,767	28,211	20,275	11,028	2,957	-2,210	10,234	2,298	61.3	16.4	-12.3	56.9	12.8
> 3.5 m	15,198	25,501	17,439	13,897	24,588	17,136	10,302	2,241	-1,301	9,390	1,938	67.8	14.7	-8.6	61.8	12.7
> 4.0 m	13,570	21,422	15,656	12,152	20,424	15,433	7,852	2,086	-1,418	6,854	1,863	57.9	15.4	-10.5	50.5	13.7

Note: * Observed daily peak discharge at Kratie in 2000 was 56,273 m^3/s, slightly higher than the simulated value.

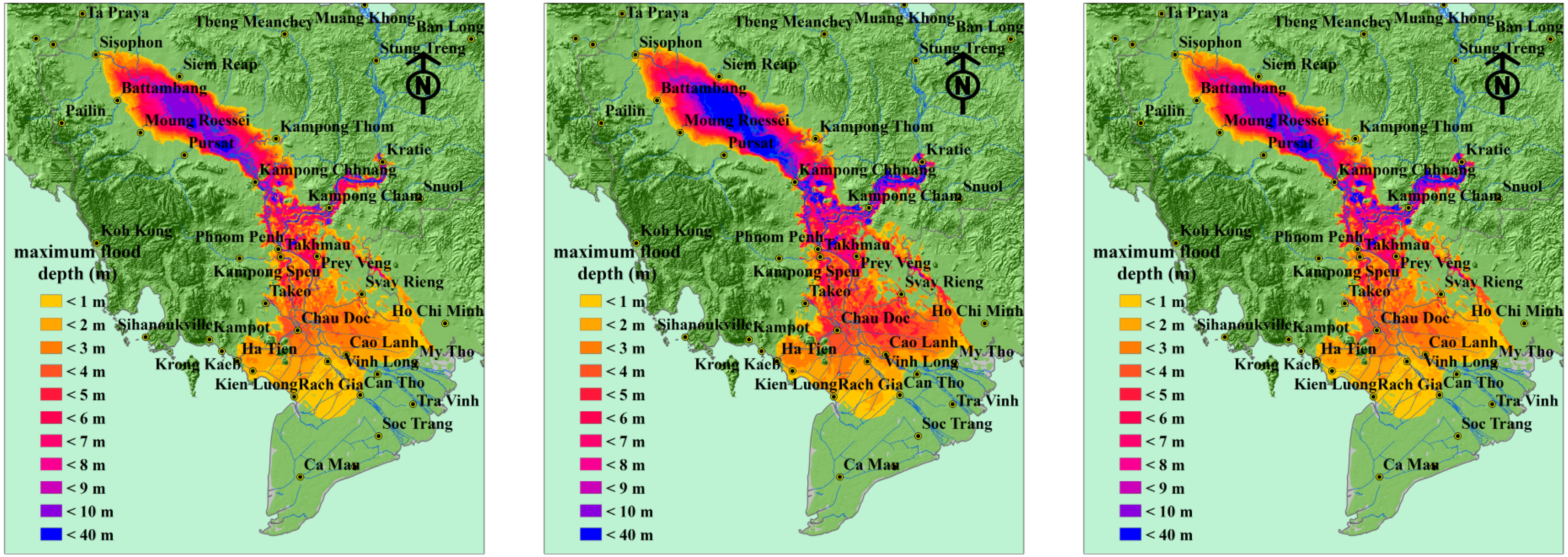


Figure 4.8 Flooded areas in 2000 under Scenario S2 (left), in 2048 under Scenario S5 A2 (middle) and in 2047 under Scenario S5 B2 (right)

Table 4.16 Flood duration under different development and climate change scenarios

Flood duration (months)	Flood duration based on flood depth > 0.5 m (km²)						Difference in flooded area (+/- km²)					Difference in flooded area (+/- %)				
	Baseline 2000	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2	Baseline 2048 A2	Baseline 2047 B2	Dev 2000	Dev 2048 A2	Dev 2047 B2
	S2	S4	S4	S3	S5	S5	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2
< 1 month	41,317	46,915	42,657	39,541	46,599	42,253	5,598	1,340	-1,776	5,282	936	13.5	3.2	-4.3	12.8	2.3
>= 1 month	38,166	44,640	36,568	35,933	43,998	35,506	6,474	-1,598	-2,233	5,832	-2,660	17.0	-4.2	-5.9	15.3	-7.0
>= 2 months	34,434	42,536	32,464	32,341	41,927	30,812	8,102	-1,970	-2,093	7,493	-3,621	23.5	-5.7	-6.1	21.8	-10.5
>= 3 months	30,087	37,797	29,544	27,592	36,953	27,346	7,709	-544	-2,496	6,866	-2,741	25.6	-1.8	-8.3	22.8	-9.1
>= 4 months	25,907	30,690	25,892	24,030	29,546	24,210	4,784	-15	-1,876	3,640	-1,696	18.5	-0.1	-7.2	14.0	-6.5
>= 5 months	19,173	22,302	19,923	17,640	20,354	18,213	3,129	750	-1,533	1,181	-960	16.3	3.9	-8.0	6.2	-5.0
>= 6 months	12,287	14,002	12,496	11,172	12,109	10,852	1,715	209	-1,115	-178	-1,435	14.0	1.7	-9.1	-1.4	-11.7

Table 4.17 Saline area under different development and climate change scenarios

Maximum salinity (g/l)	Saline area (km^2)						Difference in saline area (+/- km^2)					Difference in saline area (+/- %)				
	Baseline 1998	Baseline 2021 A2	Baseline 2022 B2	Dev 1998	Dev 2021 A2	Dev 2022 B2	Baseline 2021 A2	Baseline 2022 B2	Dev 1998	Dev 2021 A2	Dev 2022 B2	Baseline 2021 A2	Baseline 2022 B2	Dev 1998	Dev 2021 A2	Dev 2022 B2
	S2	S4	S4	S3	S5	S5	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2	S4-S2	S4-S2	S3-S2	S5-S2	S5-S2
	Minimum monthly discharge at Kratie (m^3/s)															
	*2,263**	*477*	*1,510*	*3,433*	*2,529*	*3,314*	*-1,786*	*-753*	*1,170*	*266*	*1,051*	*-78.9*	*-33.3*	*51.7*	*11.8*	*46.4*
> 0 g/l	20,744	24,152	24,270	17,852	18,101	19,734	3,409	3,526	-2,892	-2,643	-1,009	16.4	17.0	-13.9	-12.7	-4.9
> 4 g/l	20,744	24,152	24,270	17,852	18,101	19,734	3,409	3,526	-2,892	-2,643	-1,009	16.4	17.0	-13.9	-12.7	-4.9
> 8 g/l	15,451	17,555	18,231	14,288	14,395	15,552	2,104	2,780	-1,163	-1,056	101	13.6	18.0	-7.5	-6.8	0.7
> 12 g/l	12,944	13,668	13,755	12,117	11,967	12,583	724	811	-826	-977	-361	5.6	6.3	-6.4	-7.5	-2.8
> 16 g/l	10,953	11,258	11,075	10,289	10,114	10,387	305	122	-664	-839	-566	2.8	1.1	-6.1	-7.7	-5.2
> 20 g/l	9,378	9,206	9,164	8,874	8,213	8,713	-172	-214	-504	-1,165	-665	-1.8	-2.3	-5.4	-12.4	-7.1
> 24 g/l	7,064	6,735	6,597	6,666	5,986	6,441	-329	-468	-398	-1,078	-623	-4.7	-6.6	-5.6	-15.3	-8.8
> 28 g/l	4,923	4,406	5,006	4,732	4,144	4,768	-517	83	-190	-778	-155	-10.5	1.7	-3.9	-15.8	-3.1
> 32 g/l	2,852	2,633	2,967	2,797	2,563	2,992	-219	115	-56	-289	140	-7.7	4.0	-1.9	-10.1	4.9

Note: * Observed monthly lowest discharge at Kratie in 1998 was 2,190 m^3/s, slightly lower than the simulated value.

5. IMPACT OF CLIMATE CHANGE ON FLOODS AND FISHERIES

5.1. Introduction

A recent global review by Allison et al. (2009) ranked the vulnerability of national economies to the impacts of climate change on their fisheries using indices of exposure, sensitivity and adaptive capacity. The study ranked Vietnam and Cambodia as two of the most vulnerable countries in tropical Asia (ranking 27 and 30 respectively), along with Bangladesh, Pakistan and the Yemen. Their vulnerabilities arise from the combined effect of predicted warming, the economic and dietary importance of their fisheries and their comparatively limited capacity to adapt. Lao PDR was also found to be vulnerable but its ranking at 37 may underestimate its true relative vulnerability because its fisheries are likely to be grossly underestimated in the statistics employed for the study. Thailand ranked 82 in the study because despite the significance of its fisheries, it is better able to cope with climate change impacts having a higher gross domestic product, a more diversified economy, and lower rates of poverty.

The Tonle-Sap Great Lake (TS-GL) is the largest wetland in Southeast Asia with a maximum area in excess of 15,000 km^2 and is one of the most productive ecosystems on earth (Baran, 2005; MRC, 2005; Kummu et al., 2008). This system supports highly productive fisheries and dependent livelihoods both locally and regionally due to the migratory nature of the species of fish that seasonally inhabit the system. Annual fish landings have been estimated to be in the order of 230,000 to 240,000 tonnes, forming approximately 60% of the total inland fish production in Cambodia (Baran, 2005). The review described above clearly demonstrates the vulnerability of the fisheries of the LMB to climate change but what might be the nature and scale of climate change impacts on the fisheries resources in a warming basin with increasing, but more variable, precipitation?

5.2. Current knowledge about impact of climate change on fish ecology

Impacts of climate change on fisheries resources are likely to arise through complex behavioural, physiological and habitat change-related responses which may be exacerbated by the effects of adaptive coping strategies pursued by other sectors, particularly those that compete for water (Easterling et al., 2007; FAO, 2008; Allison et al., 2009; Brander, 2010). Whilst there is a large and growing literature on climate change impacts associated with marine systems, far fewer studies have examined impacts on freshwater systems and their fisheries, particularly in tropical regions.

Expected higher temperatures in the future have the potential to reduce oxygen solubility in water but can raise the oxygen and food intake demand of fish as their metabolic rates are raised (Ficke et al., 2007). Temperature also interacts with declining pH and increasing nitrogen and ammonia to raise metabolic rates, but the consequences of the interactions are speculative and complex (Easterling et al., 2007; Brander, 2007). Higher water temperatures, particularly during the winter months, can also favour the survival and poleward spread of parasites and bacteria. Combined, these responses have the potential to reduce fish growth in food limited environments, as well as their rates of survival. For example, Salmon in the Fraser River, Canada suffered elevated rates of mortality during the summer of 2004 when water temperatures were the highest ever recorded (Brander, 2007). Rises in gill ventilation rates in warmer, less oxygenated water can potentially lead to increased uptake of aquatic pollutants potentially rendering the flesh unfit for human consumption (Ficke et al., 2007). When food and oxygen are not limiting factors to growth under higher temperatures, fish growth responds positively to temperature as observed for cod stocks over their entire geographic range, although the effects of raised temperatures may vary seasonally in some species. Growth may be enhanced during the winter months and suppressed during the summer months as experimentally demonstrated for Rainbow trout (*Oncorhynchus mykiss*) (Brander, 2010). Under laboratory conditions, Vass et al. (2009) report increasing rates of growth for *labeo rohita* with increasing temperature from 29^o C to 34^o C, but with decline in growth thereafter, suggesting a thermal optimum for growth of approximately 34^o C for this particular species. This temperature-dependent growth response is typical of most species (Ficke et al., 2007).

Although temperature is not thought to be an important cue for gamete development and spawning behaviour in tropical fishes, studies have shown that the reproductive success of tropical species, measured in terms of output and survival of offspring, can decline under elevated temperatures (Ficke et al., 2007).

Populations inhabiting regions where temperatures already exceed their thermal optima, and stenothermal species with narrow thermal tolerances, are therefore most at risk of impact from rising temperatures. Stenothermal species may therefore be displaced to regions where water temperatures more closely match their relatively narrow thermal optima and be replaced by more temperature tolerant eurythermal species such as common carp (*Cyprinus carpio*) (Ficke et al., 2007; FAO, 2008; Brander, 2010). The effects of increasing temperature on marine and freshwater ecosystems are already evident with rapid poleward shifts in the distributions of fish and plankton and the occurrence of local extinctions at the extreme ranges of freshwater and diadromous species such as salmon and sturgeon (Brander, 2007).

Vass et al. (2009) report a geographic shift in some warm water species including *Mastacembelus armatus*, *Glossogobius guiris* and *Xenentodon cancila* from the middle and lower Ganga River, to the upper sections of the river that have experienced warming in recent decades. The same authors postulate that observed changes to predator-prey ratios in the river have been caused by rising water temperatures although the mechanisms responsible for these changes are not clear. The warmer temperatures have also brought forward the start and extended the duration of breeding programmes in aquaculture hatcheries by some 45 to 60 days.

Expected higher temperatures in the future also have the potential to reduce the productivity of large lakes and reservoirs by thermal stratification and stabilisation of the water column reducing the availability of nutrients in the surface layers. This process also creates cold anoxic deep waters. Sudden overturn of these anoxic waters can cause fish mortalities (Brander, 2007; Ficke et al., 2007).

Changes to river flow in response to changing spatial and temporal patterns of precipitation are expected to impact on fish stocks inhabiting river systems (FAO, 2008; Brander, 2010). Flows affect habitat availability, system productivity, and also fish population processes i.e. growth, survival and reproduction (Junk et al., 1989; Welcomme, 1985; Welcomme and Halls, 2004; Ficke et al., 2007).

A seasonal decline in precipitation and river discharge during the spawning season (May- August) has been hypothesised to be the cause of declining recruitment in populations of Indian major carps in the Ganga River, India as well as overall yields of this group of carps (Vass et al., 2009).

In the LMB, lower flows combined with sea level rise could change salinity profiles in the Vietnamese delta and lead to greater upstream salinity intrusion. These changes could displace stenohaline species further upstream and increase the upstream range and biomass of euryhaline species inhabiting the basin including those that depend upon brackish water environments to complete their life-cycles such as the giant river prawn (*Macrobracium rosenbergii*). Changes in species composition might therefore be significant but the net effect on wild fish production and fishing opportunities in the LMB is expected to be small (Bates et al., 2008; Barlow and Burnhill, undated). The expansion of existing aquaculture systems based upon species such as *M. rosenbergii* may become an important adaptive strategy option for farmers inhabiting the delta if river flows diminish in the future. Vass et al. (2009) report an almost 300 % increase in landings of marine and euryhaline fish and prawn species in the Hooghly estuary of the Ganga River basin, mostly during the winter months, corresponding to four decades of declines in discharge rates. However, it is uncertain if these yield increases have arisen from changes in flow and salinity or some other factors such as fishing effort. Salinity has also been reported to effect spermatozoa activity and buoyancy-related survival of eggs in Cod (*Gadus morhua*) and therefore changes to salinity may have the potential to influence reproductive success (Brander, 2007).

It has been suggested that changes in primary production and transfer will have a key impact on fisheries (Easterling et al., 2007). Increasing flows during the flood season translate to more extensive and prolonged floodplain inundation potentially increasing overall system productivity in river systems including the fish component (Junk et al., 1989; Welcomme, 1985). In Bangladesh, for example, it has been predicted that a 20% to 40 % increase in flooded areas could raise total annual yields by 60,000 to 130,000 tonnes (FAO, 2007a).

Halls et al. (2008) illustrate how the growth of fish in the Tonle-Sap Great Lake (TS-GL) system is strongly correlated with flood extent and duration. Longer, more extensive floods are likely to provide greater and more prolonged feeding opportunities for fish. It follows that improved growth should also favour survival and reproductive potential (fecundity). Changes in growth rates therefore provide valuable advance warning of changes to surplus production and stock biomass, particularly in long-lived species (Brander, 2010).

However, not all species may benefit. Increasing river flows may hamper upstream spawning migrations, erode spawning beds or sweep eggs and juveniles past downstream nursery and feeding habitat. Overly-rapid changes in water level can also lead to diminished reproductive success of channel margin spawning phytophil and nest-building species. Changes to the timing of flows also have the potential to disrupt spawning behaviour (Welcomme and Halls, 2001).

The dry season is a period of great stress to many river fish species arising from diminished feeding opportunities and water quality, and elevated risk of predation or capture. Fish survival during this period is therefore likely to be density-dependent (Welcomme and Hagborg, 1977). Increased precipitation and water availability during this period might favour fish survival and ultimately exploitable biomass, whilst drier conditions would have the converse effects (Halls and Welcomme, 2004). However, increasing dry season water levels also have the potential to diminish primary production and habitat diversity within the system by permanently inundating fringing forests and vegetation leading to permanent die-back and by effectively reducing the size of the flood margin or 'aquatic-terrestrial-transition-zone' (ATTZ) for nutrient re-cycling (Junk et al., 1989).

Increasing hydrologic variability in river systems could select for generalist species that are able to exploit a wide range of resources and tolerate to a wide range of environmental conditions leading to the loss of locally adapted or specialist species (Ficke et al., 2007).

No mechanistic (explanatory) models currently exist with which to predict the net effects of these potential responses and their interactions making the task of understanding the impacts of climate change on fisheries production very daunting (Brander, 2010). However, empirical models aimed at describing behaviour at a higher level (e.g. fish community) might offer a practical alternative (Brander, 2010; Jennings and Brander, 2010).

As a contribution to the CCAI, this report adopts this type of approach to examine how predicted precipitation and evapotranspiration-driven changes to flow indicated by extent and duration of flooding under different climate change and basin development scenarios may affect exploitable fish biomass in the Tonle Sap-Great Lake (TS-GL) system.

5.3. General study approach

The approach adopted assumes that the historical response of fish biomass to variation in the system's hydrology will provide a reliable forecast of how fish biomass is likely to respond to flooding patterns under future climatic conditions (and basin development). Furthermore, it is assumed that the same response can be expected in other parts of the basin, particularly in the lower part of the basin below the Great Fault Line.

Empirical models describing the response of indicators of fish biomass to variation in hydrological conditions have been described for several tropical and European river systems from as early as 1910. These typically take the form of linear regression models using indices of flood extent and duration to describe inter-annual variation in catch or some other index of fish biomass such as catch per unit of effort, CPUE (see Welcomme, 1985 for review).

Several workers including Lieng et al. (1995), Baran et al. (2001), and van Zalinge et al. (2004) have described models of this type for the TS-GL system based upon annual catch estimates for the Cambodian *dai* (stationary trawl net) fishery and maximum annual water level as a proxy of flood extent. The dai fishery is located along the Tonle Sap River and targets the seasonal migrations of fish as they migrate from the Lake to the Mekong mainstream with the receding flood waters each year. The most recent model (Halls et al., in prep.) employs the daily catch rate of a *dai* unit as the biomass index. A flood index (FI) is used to combine the extent and duration of the flood each year, *y*:

$$FI_y = \sum_d FA_{y,d} \tag{5.1}$$

Where $FA_{y,d}$ is the flooded area of the TS-GL system in year *y* on day *d*, measured above the mean flooded area for the model period 01/01/97 to 31/03/2009. Using deviations above the mean flooded area to define the flood period aims to capture the potential effects of changes to dry season (and flood season) water levels on system production driven by the area of the ATTZ described above. Estimates of $FA_{y,d}$ were derived from daily observations of water level ($WL_{y,d}$) at Kampong Luong gauging station in the Great Lake (Figure 5.1) and the following second-order polynomial provided by John Forsius, MRC:

$$FA_{y,d} = 716.64 + 1094.19WL_{y,d} + 30.05WL^2{}_{y,d} \tag{5.2}$$

Other hydrological indices were also considered during model fitting including indices to account for variation arising from potential dry season (survival-related), and rate of flood rise and fall related effects (see Halls et al in prep). However, the FI alone provided the best-fitting and parsimonious model. Fixed factors in the General Linear Model (GLM) account for spatial (*dai* row) and intra-annual (month and lunar cycle) variation in the daily catch rates. Overall the model explains almost 70 % of the variation in the observed catch rates (Figure 5.2).

The model predicts that fish biomass, indicated by the mean daily catch rate of a *dai* unit during the fishing season (Oct-Mar), increases exponentially with the FI (Figure 5.3) as follows:

$$CPUE = 83.96.e^{1.595E-06FI} \qquad (5.3)$$

Figure 5.1 The location of the Kampong Luong gauging station in the GL

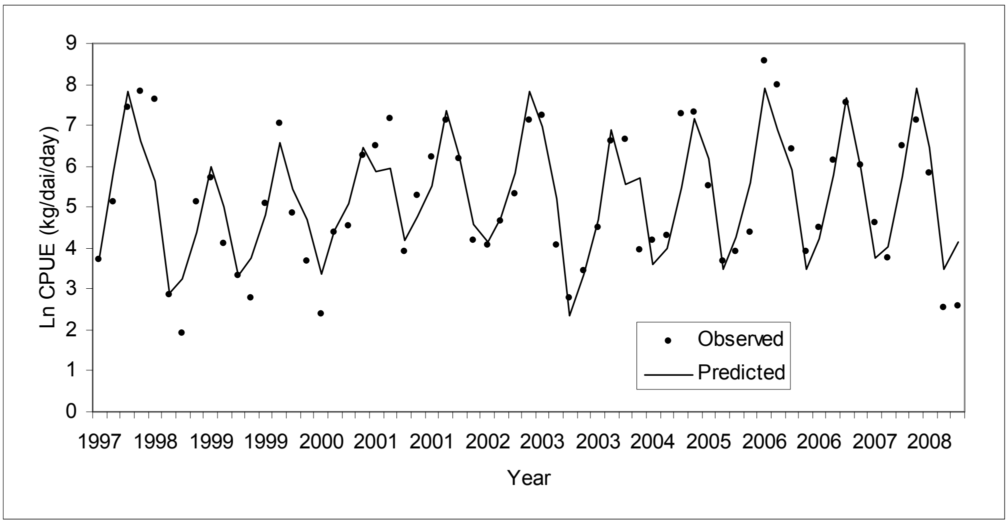


Figure 5.2 The GLM observed and predicted mean catch rates 1997-2009.

For the purposes of illustration, mean monthly, instead of daily, catch rates are illustrated.

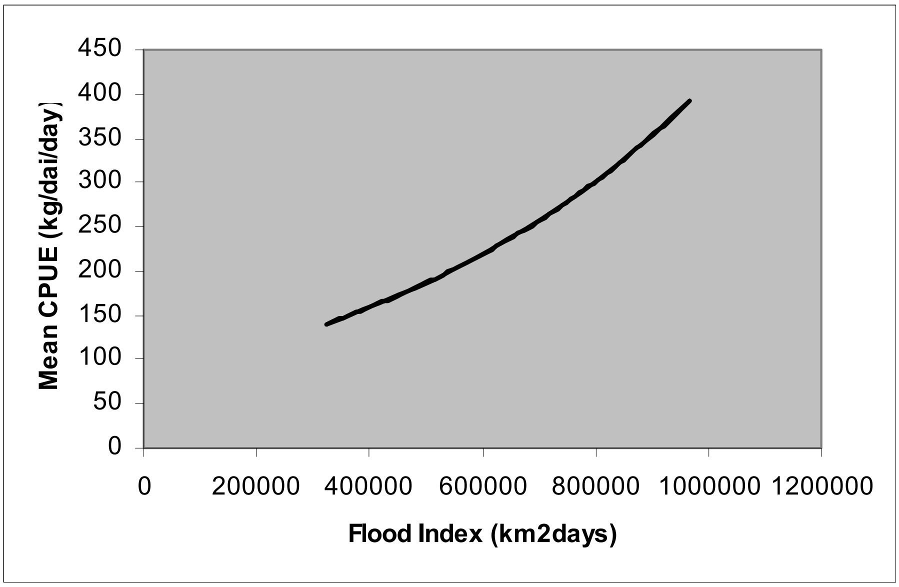


Figure 5.3 The relationship between the mean predicted daily catch rate of a dai unit during the fishing season and the flood index (FI) for the TS-GL System

5.4. Materials and methods

The model illustrated in Figure 5.3 was used to predict how fish biomass in the TS-GL may respond to future climate and basin development-induced changes to the annual flood index. Six climate change and basin development scenarios were examined (Table 5.1). The 20 year Future Development Scenario includes the construction of 31 tributary and 11 mainstream dams and the expansion of irrigation projects by some 2 million hectares. This development has the potential to modify the hydrology of the basin through storage and abstraction effects. Future precipitation in the basin was predicted under future emissions scenarios A2 and B2 (IPCC 2000). The forecasted changes to precipitation, water storage and abstraction were combined in the iSIS hydrological model of the LMB (MRC, 2005) to generate daily water level estimates at Kampong Luong for each scenario (Figure 5.4).

Table 5.1 Climate change and basin development scenarios examined. CC – climate change effects; Development – basin development project effects; ✓ - included in scenario; × - not included in scenario.

Scenario[13]	Title	Development	CC	Description/Comments
S1	Baseline Scenario 1985-2000	×	×	
S2	Baseline Scenario A2 2010-2050	×	✓	A2 Future Emissions
S3	Baseline Scenario B2 2010-2050	×	✓	B2 Future Emissions
S4	20 Year Future Development 1985-2000	✓	×	
S5	20 Year Future Development A2 2010-2050	✓	✓	A2 Future Emissions
S6	20 Year Future Development B2	✓	✓	B2 Future Emissions

[13] S1 and S4 in this Table is corresponding to S2 and S3 in flow analysis. S2 & S3, and S5 & S6 in this Table are corresponding to sub-scenarios S4-A2 & S4-B2, and S5-A2 & S5-B2 in flow analysis, respectively.

	2010-2050			

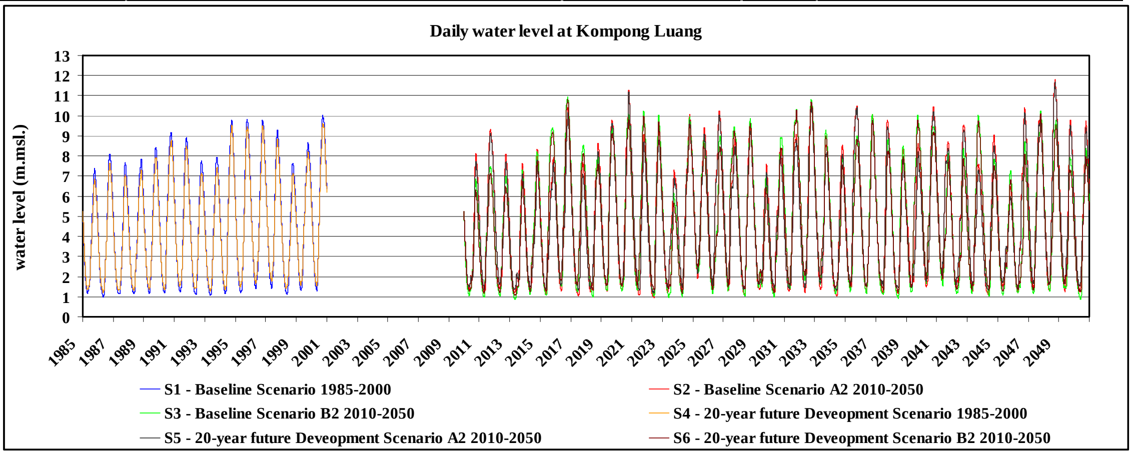


Figure 5.4 Observed and predicted water level above mean sea level for the six climate and basin development scenarios

Two alternative time series of annual flood indices (Equation 5.1) were estimated for each scenario. The first (FI1) was calculated using the mean flooded area for period (i.e. 1985-2000 or 2010-2050) of each scenario. The second series (FI2) was calculated using the same mean flooded (6883 km^2) area used to derive the model illustrated in Figure 5.3 described by Halls et al. (in prep).

The FI1 series attempts to account for the effects of changes to the size of the ATTZ on system productivity (and fish biomass) arising from long-term or permanent increases in dry season water levels, or disproportionate increases or decreases to wet and dry season water levels. The FI2 series on the other hand, assumes that variation in system productivity is dependent upon only the area (and duration) of flooding exceeding an area of 6338 km^2 regardless of changes to dry season water levels and areas. Neither series accounts for potential changes to density-dependent fish survival arising from changes to dry season water availability.

Time series of the fish biomass index (mean daily catch rate of a dai unit during the fishing season) corresponding to the two alternative FI time series for each scenario were predicted using Equation 5.3. Significant differences in the estimates of the mean biomass index over the time series of each scenario were tested for using ANOVA and Tukey post hoc pairwise tests with SPSS v11. The variance ratio test (Zar, 1984, p123) was used to test for equality of variance in the flood indices between the baseline and each emission scenario, with and without development. The biomass index (CPUE) was first $\log_e$-transformed to meet the normality assumptions of the test. Whilst ANOVA is generally robust to the assumptions of homoscedasticity and normality (Zar, 1984), nonparametric tests (Kruskal-Wallis and Mann-Whitney) were also performed. The results of these tests are however, not reported below because they were consistent with those of the parametric tests.

5.5. Results

The time series of daily water levels at Kampong Luong used to develop the fisheries model illustrated in Figure 5.4 compare well with those estimated for scenario 1. The series used to develop the model contains greater variability and marginally lower water levels during flood of 1998/99 and the converse for the following year, but there is no difference in the average water level over the period of comparison (01/01/1997 to 31/12/2000).

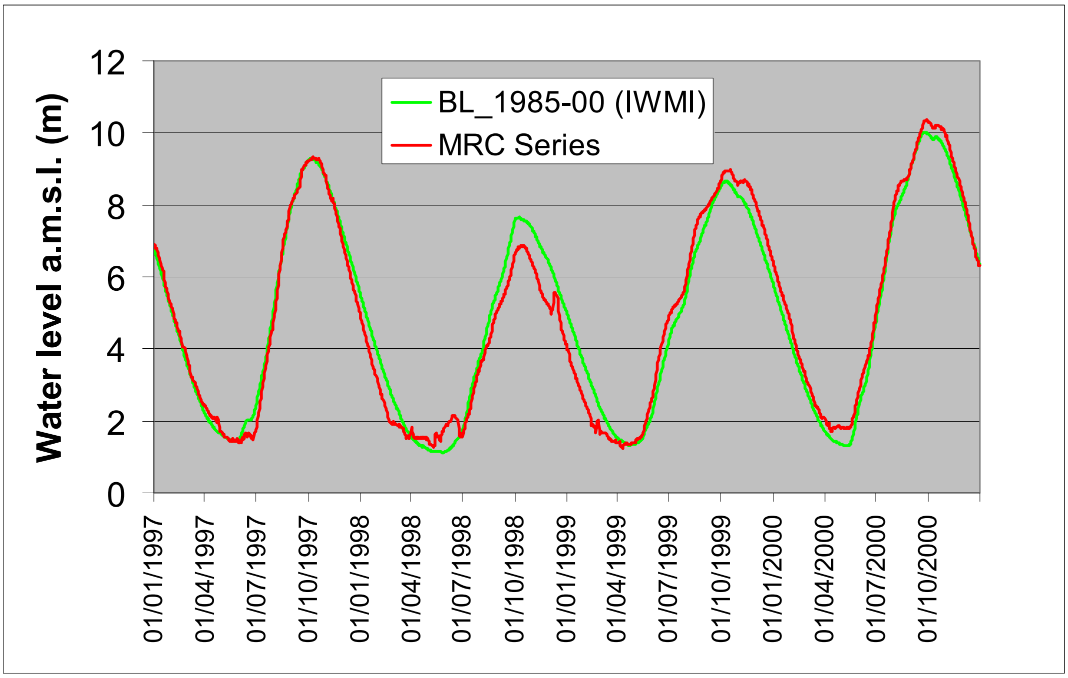


Figure 5.5 Comparison of water level data at Kompong Luong provided by the MRC and IWMI

Mean minimum water levels were significantly different ($p < 0.001$) among the scenarios with two homogenous subsets corresponding to scenarios with and without basin-development (Figure 5.6 left). With and without basin development, mean minimum water levels were predicted to be higher under future climate conditions for both emission scenarios but not significantly ($p > 0.05$) different from the baseline. Increases in mean minimum water levels are predicted to be greater (but not significantly) under the A2 compared to the B2 emissions scenario. Therefore, whilst climate change effects on minimum water levels could not be detected, minimum water levels are predicted to be on average almost 30 cm higher under the three basin development scenarios compared to the three climate change-only scenarios (Figure 5.7).

Maximum water levels are predicted to be on average lower with basin development than without (Figure 5.6 right, Table B.2, Appendix B) but no significant differences ($p = 0.056$) in the estimates of mean maximum water levels were detected among the six scenarios. Mean maximum water levels were also predicted to be higher under future climate conditions for both emissions scenarios but were also not significantly different from the baseline ($p > 0.05$).

The variance ratio tests revealed no evidence to suggest that that the variance of either flood index increases under either emission scenario, with or without basin development. Furthermore, no significant differences in the mean values of either flood index (FI1 or FI2) and therefore in the corresponding estimates of fish biomass were detected ($p = 0.75$ and $p = 0.12$, respectively) among the six scenarios (Figure 5.8 and Figure 5.9). Whilst not significantly different from the baseline scenario, fish biomass is predicted to be higher under future climatic conditions both with and without basin development for both flood indices (Figure 5.9).

Differences in mean values among scenarios were more discernable for the FI2 flood index and corresponding biomass index. Estimates of the back transformed mean fish biomass index for each scenario and flood index are given in Table B.2 in Appendix B. For the FI1 flood index, mean *dai* catch rates are predicted to increase from 210 kg/day to approximately 230 kg/day without basin development or only very marginally with basin development (212 - 214 kg/day). For the FI2 Flood Index, mean catch rates are predicted to increase from 194 kg/day to between 241 and 224 kg/day without basin development to between 199 and 213 kg/day with basin development.

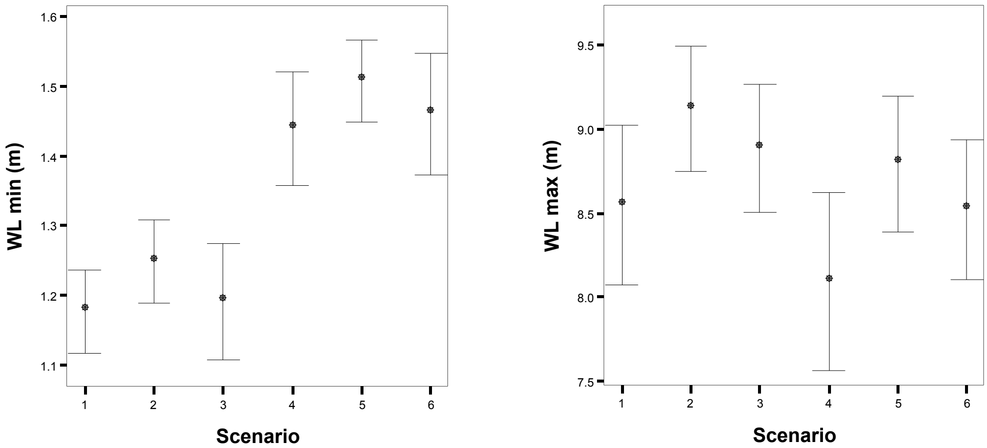


Figure 5.6 Estimates of mean minimum (left) and maximum (right) water level for the six scenarios. Error bars give 95% confidence intervals around the mean.

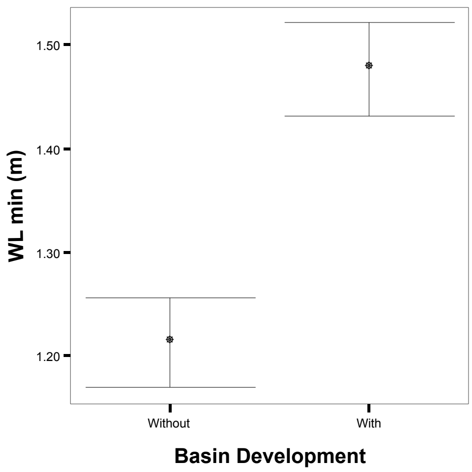


Figure 5.7 Estimates of the mean minimum water level for the scenarios without (scenarios 1-3) and with (Scenarios 4-6) basin development. Error bars give 95% confidence intervals around the mean.

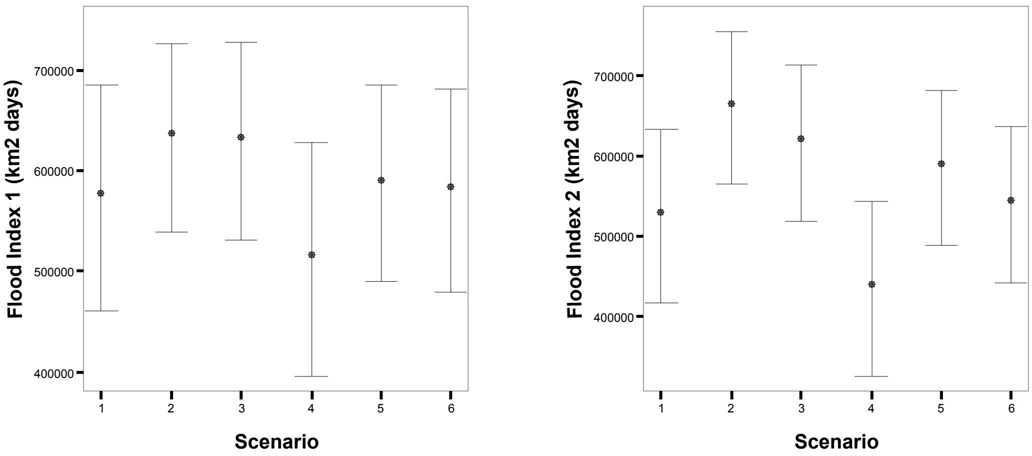


Figure 5.8 Estimates of the Flood Index 1 (left) and Flood Index 2 (right) for the six scenarios. Error bars give 95% confidence intervals around the mean.

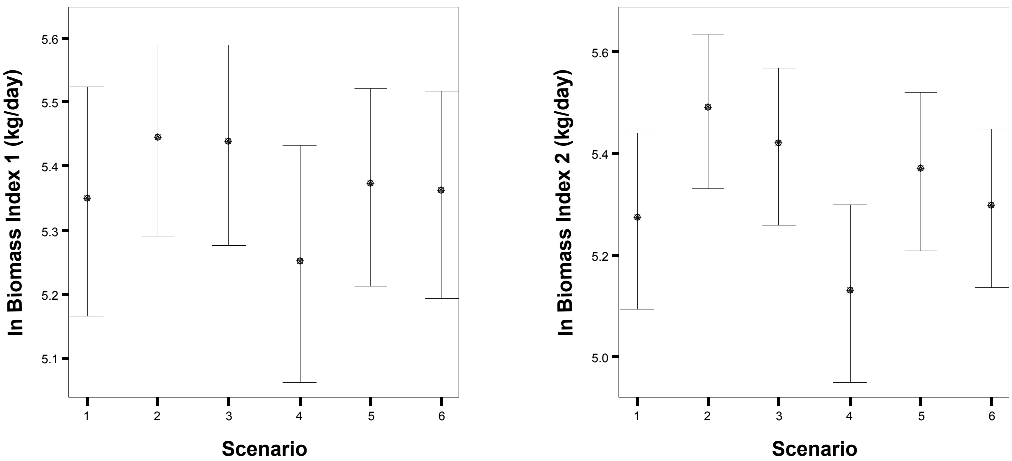


Figure 5.9 Estimates of the mean $\log_e$-transformed fish biomass index for the TS-GL System corresponding to Flood Index 1 (left) and Flood Index 2 (right) for the six scenarios. Error bars give 95% confidence intervals around the mean.

5.6. Conclusions

An empirical model has been applied to predict how fish biomass in the LMB might respond to future flooding patterns under different scenarios of climate change and basin development. The model assumes that the catch rates of the *dai* fishery of the Tonle Sap provide a reliable index of fish biomass in the TS-GL system and that the model predictions are generally applicable across the basin. The assumption that catch rates provide an index of fish abundance is common practice in fisheries science although the relationship between catch rates and biomass may not always be linear (see Hilborn and Walters, 1992). Without supporting data from other parts of the basin it is difficult to comment on the applicability of the model beyond the TS-GL system. However, many of the species of the fish that seasonally inhabit the TS-GL system that are the target of the *dai* fishery are highly migratory often over distances of more than 600 km (Poulsen et al., 2004; Adamson et al., 2009).

Therefore changes to fish biomass in the TS-GL system are likely to propagate over a large distances effecting fisheries and piscivorous fish populations beyond the TS-GL system.

No attempt was made to quantify the potential impacts on fish biomass caused by changes to water temperature in the basin, or salinity changes in the delta caused by changes to flow. Predicting these impacts demands greater knowledge and understanding of the physiological responses, tolerances and behavioural adaptations of the species of fish inhabiting the Mekong and the likely response of the ecosystem as a whole.

However, given the plasticity in their reproductive strategies to changes in temperature, their typical high critical thermal maxima, and the small temperature increases predicted for the tropics, the effects of altered flow regimes are anticipated to have greater detrimental effects on tropical species than changes in temperature (Ficke, 2007).

Without further basin development over the next 20 years, both minimum and maximum water levels, and the flood indices described here are predicted to increase over the next 40 years as a consequence of climate change, but not significantly at the 5 % level. These increases will be greater under the A2 compared to the B2 emissions scenario. A similar response to climate change is predicted under the basin development scenarios (Scenarios 4-6), but again, climate change effects are not detectable at the 5 % significance level.

Without climate change, basin development is predicted to lower maximum (wet-season) water levels and the flood indices, but not significantly. With climate change, maximum water levels and flood indices are predicted to rise only marginally (but not significantly) above the baseline (i.e. no further development or climate change). The mean values of maximum water levels and flood indices are however lower than those predicted for the two climate change-only scenarios (Scenarios 2 & 3) implying that planned basin development activities will counteract the effects on fish biomass of increasing flood indices predicted under both climate change scenarios.

The homogeneity of variance test results suggest that there the flood indices and therefore fish biomass will not be more variable under the future climate change and basin development scenarios compared to the baseline.

Given the extent of natural variability in the system combined with the predicted marginal changes in the flood indices, particularly under the 20 year future development scenarios, the effects of climate change on fish biomass in the TS-GL system during the next 40 years are unlikely to be detectable.

Further investigations revealed that the minimum changes in the mean estimates of the flood indices between the baseline (S1) and the climate change only (S2) Scenarios would need to exceed 27 % - 29 % for the FI1 and FI2 indices respectively to have statistically detectable (α = 5%, β = 10 %) impacts on predicted fish biomass, compared to the 10 % - 26 % increase in the flood indices currently predicted.

Basin development activities are however predicted to have a significant effect on minimum (dry-season) water levels, raising them by approximately 30 cm depending upon the climate change scenario. The effects of raised dry season water levels on system productivity and growth-related effects on fish biomass were theoretically accounted for in the FI1 flood index. Halls et al. (in prep) found that indices describing wet season hydrological conditions explained more of the variation in the fish biomass index than indices of dry season conditions and dry and wet season conditions tend to be correlated i.e. large floods follow above average dry season water levels. Halls and Welcomme, (2004) used a population dynamics approach to examine the relative importance of different flooding patterns on exploitable fish biomass under different assumptions of density-dependent population processes. They found that fish biomass increased almost asymptotically with dry season water availability (area). In other words, biomass becomes relatively insensitive to increasing dry season water levels above some threshold. In their model simulations, this threshold corresponded to dry season water areas equivalent to approximately 10 % - 15 % of the maximum flooded area. Using a biomass dynamics approach, Lorenzen et al. (2002) found the same form of response and threshold (approximately 10 %). Examination of the baseline data for the TS-GL system (S1) indicates that dry season water levels in this habitat vary from approximately 15 % to 28 % of the maximum flood area, with a mean of approximately 17 %. If these proportions are indicative of the wider conditions in the basin, then it would suggest that existing dry season water levels are above the threshold where further increases have little effect on biomass. Further increases in dry season water levels under future basin development or climatic conditions would therefore have little discernable benefit to fish survival and ultimately biomass.

It is important to recognise that this investigation has considered only flow-mediated impacts on fisheries arising from climate change and planned basin development activities. No attempt was made to include other potentially important pathways of impact caused by these basin development activities. Most notably, we have not considered the barrier impacts of dams on fish migrations between critical habitat, and the effects of dams on fish population survival rates arising from fish passage through turbines, spillways or via other dam structures. Indeed, these impacts may overshadow those arising from flow changes caused by dams and climate change, leading to species extinctions and significant reductions in fish yield (Halls & Kshatriya, 2009).

These barrier impacts of dams on fish migrations may become more important in a warming basin because they will diminish opportunities for fish to migrate to areas with appropriate thermal conditions. Even if opportunities for migration could be maintained with fish ladders or passes, fish would have to cope with a new physical environment and compete for space potentially bringing about changes in species composition if favour of generalist species and altering ecosystems (Ficke et al., 2007).

We therefore urge caution when interpreting the results of this investigation and recommend that predictions concerning the fisheries resources of the LMB account for these additional impact pathways alongside those arising from flow change.

6. IMPACT OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTIVITY

6.1. Introduction

Here, we examine the impact of climate change on the productivity of the major crops grown in the Lower Mekong Basin (LMB). Nearly 85% of the Mekong's population is employed in agriculture, fisheries and forestry (MRC, 2003). Offsetting the adverse impact of climate change and further improving agricultural productivity is critical to raising the incomes of poor rural communities which ultimately helps alleviate poverty. Food security is strongly dependent on agricultural productivity of the basin. Growth in productivity can increase and stabilize food supplies, as well as increase the ability to purchase food (Block, 1995). However, variability in the water cycle driven by climate change, as discussed in the previous Chapters, is considered to significantly impact food production in the near future (Toritani et al. 2007). According to the Intergovernmental Panel on Climate Change (IPCC, 2001) such change will have both beneficial and adverse effects on both environmental and socio-economic systems, but the larger the change and the rate of change in climate, the more adverse effects predominate.

The population of the Mekong is expected to increase from the current (2010) 67 million to more than 88 million in 2050 (based on medium variant projection, UN Population Division, 2006), and the proportion of urban dwellers from about 20% to about 40% or about 40 million. Economic growth is around 4.5% per annum. These three factors will drive great change in the Mekong Basin. Total food demand will increase at a rate greater than that of population alone, due to rising incomes and changing diet preferences with urbanisation.

Thus, agriculture faces greatly increased demands for food on the one hand, and several threats to production due to climate change on the other. Against this background, it is important to examine the potential impact of climate change on agricultural productivity of the basin. This will help prepare adaptation strategy and its costs can be reduced by anticipation, analysis and planning.

6.2. Literature review

Studies on the impact of climate change on agricultural productivity of the Mekong are very limited. Most probably the earliest study on the impact of climate change on rice production in the Southeast Asian regions was reported by Matthews et al. (1995, 1997). Matthews et al. (1997) simulated potential rice yield in South and Southeast Asian countries including Thailand using two crop simulation models, ORYZA1 (Kropff et al., 1994) and SIMRIW (Horie, 1987).

Kono et al. (2001) developed a GIS-based crop modelling method for evaluating the productivity of rainfed agriculture at the regional level and applied the model to lowland paddy in Northeast Thailand. They have estimated and mapped the potential yields and attainable yields under water limitations. Hoanh et al. (2003) assessed the impacts of climate change and climate variability on food production, food security and the environment (ecological and social) and developed adaptation strategies to alleviate the negative impacts on food and environment for the Mekong River Basin.

Chinvanno (2004), Chinvanno and Snidvongs (2005) and SEA START RC (2006) simulated the yield of rice, maize, sugarcane and cassava by MRB-rice shell and DSSAT model using simulated weather data from the CCAM (Conformal Cubic Atmospheric Model) climate model, which cover three periods (year 1980-89, 2040-49 and 2066-75) in various locations in Laos and northeast Thailand. Toritani et al.

(2007) evaluated the variability in the water cycle and its impact on food production on a regional scale by constructing and developing a hydrological process and crop yield estimation model. The model has been applied to the North-eastern region of Thailand and the Mekong Delta of Vietnam.

Sawano et al. (2008) modelled the dependence of the crop calendar on rainfall patterns based on a survey of the region's farmers as part of an effort to provide stronger basis for regional yield estimates. Coupling this model with a simple crop model Hasegawa et al. (2008) estimated the regional yields of rainfed lowland rice in Northeast Thailand. Eastham et al. (2008) assessed all 24 GCMs and selected 11 out of them based on their capacity to represent seasonal temperature and precipitation in the basin to generate climate data for 2030. The generated data were then used to assess the impact of climate change on crop yield at sub-basin level (Kirby et al., 2010) using FAO (Doorenbos and Kassam, 1979) yield response function. Ministry of Environment of Cambodia (Ministry of Environment, 2002 cited in ICEM, 2009) attempted to assess the potential impacts of climate change on rice productivity which shows the increases in wet season crops in some areas and decreases in others.

Most of the studies discussed above were limited to a part of the basin mostly in northeast Thailand and did not study the impact comprehensively at the basin level using a consistent approach. The studies of Matthews et al. (1995, 1997) are at the regional level (for Asia) which include only Thailand among the riparian countries of the lower Mekong Basin. The models developed by Kono et al. (2001), Sawano et al. (2008), Hasegawa et al. (2008), and Toritani et al. (2007) demonstrated the potential to use models as a tool to assess the impact of climate change on agricultural productivity. But none of these used generated climatic data for future to assess the impact. The impact assessment of Chinvanno (2004), Chinvanno and Snidvongs (2005), SEA START RC (2006), and Hoanh et al. (2003) are based on field scale models applied to very few locations in the basin except Cambodia. The recent study by Eastham et al. (2008) is very comprehensive in terms of climatic data used (analysed all 24 GCM models and 11 of them were chosen to generate data) and its spatial extent (considered whole lower basin) but the impact assessment was done using the FAO crop-water production function (not a crop growth model) which does not take into account the impact of temperature and CO_2 directly on plant growth (Raes et al., 2009a).

In this study, we divide the lower basin into agro-climatic zones, select the study sites to represent each zone, and examined the impact of climate change on the productivity of the major crops grown using same model to facilitate spatial comparison within the basin. So far, this appears to be the most comprehensive and consistent study for the whole lower Mekong Basin.

6.3. Site selection

The lower Mekong Basin comprises the areas in Laos (198,750 Km^2), Thailand (182,850 Km^2), Cambodia (159,100 Km^2) and Vietnam (63,600 Km^2). The climate of the lower Mekong Basin is classified as tropical monsoonal, almost always hot and seasonally excessively moist; with a minimum average monthly temperature never lower than 20°C (MRC, 2010). The distribution of mean annual rainfall over the basin shows a distinct east to west gradient with high spatial variability of tropical monsoon rainfall (MRC, 2010). Regional mean annual rates of evaporation vary between 1000 and 2000 mm. The highest figures occur over the Khorat Plateau of northeast Thailand but falling to as little as 1000 mm in the Central Highlands of Vietnam (MRC, 2010). Over the major part of the basin, annual evaporation and rainfall are roughly equal. Towards the north (Chiang Saen) a considerable moisture surplus develops as a result of higher rainfall and lower evaporation. The major regional feature, however, is the very high moisture deficits that characterise northeast Thailand, where evaporation exceeds rainfall by almost 700 mm in an average year (MRC, 2010).

Mainuddin et al. (2008) estimated spatial average provincial rainfall and potential evapotranspiration (PET) from the generated surfaces of monthly rainfall and PET using global surface data at 30 arcminutes resolution from the Climate Research Unit (CRU) of the University of East Anglia (http://www.cru.uea.ac.uk/cru/data/) for 1981-1995, and using global surface summary of daily data produced by the National Climatic Data Centre (NCDC) of National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov) and data of the meteorological stations within the Basin available from IWMI (www.iwmi.org) for 1996-2005.The variation in rainfall is much higher than the variation in potential evapotranspiration in the LMB and even within the country. Spatial average (1981-2005) provincial rainfall varies from 1174 to 1797 mm in Laos, 983 to 1689 mm in the provinces of Thailand, 1319 to 2087 mm in Cambodia, 1621 to 1828 mm in the provinces of Central Highlands of Vietnam, and 1683 to 2088 mm in the Mekong Delta. Corresponding potential evapotranspiration are 1259 to 1528 mm in Laos, 1517 to 1683 mm in Thailand, 1482 to 1691 mm in Cambodia, 1275 to 1373 mm in Central Highlands, and 1427 to 1536 mm in the Mekong Delta. Therefore based on the spatial average provincial rainfall, provinces within the basin have been divided into zones. As shown in Fig. 6.1, there are 3 zones in Laos (<1300 mm, 1300-1700 mm), >1700 mm), 4 zones in Thailand (<1200 mm, 1200-1400 mm, 1400-1600 mm, >1600 mm) , 4 zones in Cambodia (<1500 mm, 1500 – 1700 mm, 1700-1900 mm, >1900 mm) and 3 zones in Vietnam (2 in the Mekong Delta, <1900 mm and > 1900 mm) and 1 in Central Highlands, 1621-1828 mm).

The name of the country, in this chapter, indicates the areas within the Mekong River Basin, not the whole country unless otherwise mentioned. There are 18 provinces in Laos, 22 provinces in Thailand, 20 provinces in Cambodia, 4 provinces in the Central Highland of Vietnam and 12 provinces in the Mekong River Delta of Vietnam within the basin area (either fully or a major portion). Table 6.1 shows the name of the provinces of the countries within each zone. The ratio of average PET to average rainfall (moisture deficit or gain) results in almost similar zoning and grouping of provinces. One province (showed in bold in Table 6.1) from each zone (Figure 6.1) is selected to represent the group for simulation analysis considering the following information:

- Harvested area of the crop
- Geographic distribution through GIS map (so that the selected provinces are more or less evenly spaced)
- Presence of irrigated area
- Rainfall and PET in the provinces in the group.

6.4. Data sources

Provincial time-series data of planted and harvested area and production of different crops for Laos and Cambodia were obtained from the Regional Data Exchange System on food and agricultural statistics in Asia and Pacific countries maintained by the FAO Regional Office for the Asia Pacific Region (http://faorap-apcas.org/index.htm). Data for Thailand were collected from the Statistical Year Books published by the Office of Agricultural Economics of the Ministry of Agriculture and Cooperative of the Royal Thai Government (http://www.oae.go.th/main.php?filename=index___EN). Data for Vietnam were available from the website of the General Statistical Office of Vietnam (http://www.gso.gov.vn/default_en.aspx?tabid=491). General crop planting time and growing periods are based on the cropping pattern used by the Mekong River Commission (Nesbitt, 2005). Soil related information required for modelling were taken from the detailed soil classification map with physical and hydraulic properties for the whole basin used in SWAT model (Neitsch et al., 2002) of the MRC Decision Support Framework (Halcrow, 2004). The soil classification map of LMB is consists of about 10,500 polygons of varying sizes ranging from the maximum of 22,800 km^2 to minimum of 0.25 km^2 in area. The average size of the polygon is 59.8 km^2 and the median size is 7.1 km^2. The soil properties within each polygon are considered homogeneous having single value.

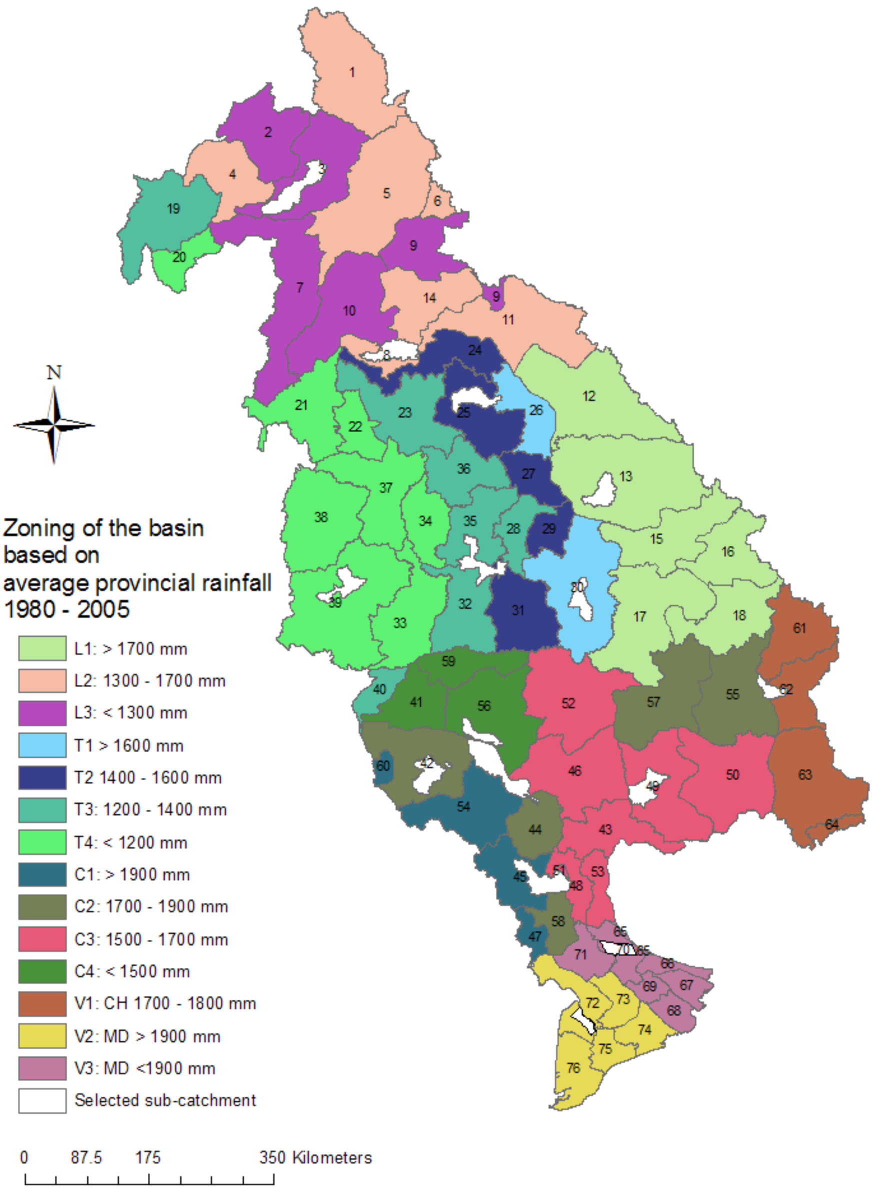


Figure 6.1 Zoning of the basin based on average provincial rainfall. Number shown inside a polygon is the province id. Provinces 1 to 18 are in Laos, 19 to 40 are in Thailand, 41 to 60 are in Cambodia, 61 to 64 are in Central Highlands of Vietnam and 65 to 76 are in the Mekong Delta of Vietnam. White polygons represent the selected cases study districts.

Table 6.1 Grouping of provinces within a country based on spatial average provincial rainfall

Zone No.	Laos	Thailand	Cambodia	Vietnam
1	Khammuane **Savannakhet (L1*)** Saravane Sekong Champasack Attapeu	Nakhon Phanom **Ubon Ratchathani (T1)**	**Kampong Speu (C1)** Kampot Pursat Krong Pailin	Kon Tum **Gia Lai (V1)** Đắk Lắk Lâm Đồng
2	Borikhamxay **Vientiane M. (L2)** Bokeo Luangprabang Huaphanh Phongsaly Xaysomboun	Nong Khai **Sakon Nakhon (T2)** Mukdahan Amnat Charoen Si Sa Ket	**Battambang (C2)** Kampong Chhnang Ratana Kiri Stung Treng Takeo	**Kiên Giang (V2)** Cần Thơ Sóc Trăng Bạc Liêu Cà Mau
3	Luangnamtha **Oudomxay (L3)** Xayabury Xiengkhuang Vientiane	Chiang Rai Udon Thani Yasothon Surin **Roi Et (T3)** Kalasin Sa Kaeo	Kandal Kampong Thom **Kratie (C3)** Phnom Penh Kampong Cham Mondul Kiri Preah Vihear Prey Veng	Long An Tiền Giang Bến Tre Trà Vinh Vĩnh Long **Đồng Tháp (V3)** An Giang
4		Phayao Loei Nong Bua Lam Phu Buri Ram Maha Sarakham Khon Kaen Chaiyaphum **Nakhon Ratchasima (T4)**	Banteay Meanchey **Siem Reap (C4)** Otdar Meanchey	

*Indicate the site code

6.5. Selection of an appropriate model: the AquaCrop Model

There are several crop models now available for the same crop that can be employed for impact assessment of climate change. These models have often large differences in their structure and data requirements (Aggarwal and Mall, 2002). Some of the widely used models are APSIM (McCown et al., 1996; Keating et al., 2003), DSSAT (Jones et al., 2003), ORYZA2000 (Bouman et al., 2001), WOFOST (van Diepen et al., 1989; Boogaard et al., 1998), INFOCROP (Aggarwal et al., 2004), CropSyst (Stockle et al., 2003), and CERES (Jones and Kiniry, 1986; Singh et al., 1993), etc. These models, however, present substantial complexity for the majority of the targeted users, such as other researchers, extension personnel, water user associations, consulting engineers, irrigation and farm managers, and economist (Steduto et al., 2009). Furthermore, they require an extended number of variables and input parameters (often available through field experiments and familiar to crop scientists) not easily available for the diverse range of crops and sites around the world (Steduto et al., 2009). Lastly, insufficient transparency and simplicity of model structure for the end user are considered a strong constraint (Steduto et al., 2009). To address all these concerns, and in trying to achieve an optimum balance between accuracy, simplicity and robustness, a new crop model, named AquaCrop, has been developed by FAO (Raes et al., 2009a; Raes et al., 2009b; Steduto et al., 2009).

The purpose of this study is to have a regional assessment of the impact of climate change on agricultural productivity and food security, and does not include any field experimental work in the scope of the study. Detail data such as crop physiological parameters, genotypes, water and nutrient management, with corresponding yield and biomass etc. are not available to us for any crop in the basin. Hence, AquaCrop was found to be very suitable for this study.

AquaCrop is a water-driven simulation model that requires a relatively low number of parameters and input data to simulate the yield response to water of most of the major field and vegetable crops cultivated worldwide. Its parameters are explicit and mostly intuitive and the model maintains sufficient balance between accuracy, simplicity and robustness. Several features distinguish AquaCrop from other crop growth models, achieving a new level of simplicity, robustness and accuracy (Raes et al., 2009a; Raes et al., 2009b; Steduto et al., 2009).

The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration that confer the model an extended extrapolation capacity to diverse locations and seasons, including future climate scenarios (Raes et al., 2009a). Details of AquaCrop including free downloading of the software can be found at AquaCrop website (http://www.fao.org/nr/water/aquacrop.html).

AquaCrop is mainly intended for practitioners such as those working for extension services, governmental agencies, NGOs and various kinds of farmers associations. It is useful for developing irrigation strategies under water deficit, finding the most suitable crop calendar under rainfed agriculture and obtaining yield estimates for field crops under a variety of environmental conditions. It is suited for perspective studies such as those under future climate change scenarios. Its performance has been tested for several crops with very satisfactory results (Hsiao et al., 2009; Farahani et al., 2009; García-Vila, et al., 2009; Heng, et al., 2009; Geerts, et al., 2009; Todorovic, et al., 2009). Todorovic et al. (2009) compared the performance of AquaCrop with that of two well established models, CropSyst and WOFOST, in simulating sunflower growth under different water regimes in a Mediterranean environment. Although AquaCrop required less input information than CropSyst and WOFOST, it performed similarly to them in simulating both biomass and yield at harvesting. The use of different numbers of parameters and crop growth modules by the tested models did not influence substantially the simulation results. Therefore, Todorovic et al. (2009) concluded that for management purposes and in conditions of limited input information, the use of simpler models should be encouraged.

6.6. Selection of crop for simulation

There are two cropping periods in the basin; based on climate (rainfall and evapotranspiration), the dry season is November to April and the wet season is May to October. Rice is the predominant crop in the basin (Table 6.2). Generally, three types of rice are grown. These are ‘lowland rainfed rice’ grown in lowland areas in the wet season, ‘upland rice’ grown in the upland areas, also in the wet season but usually planted few weeks earlier (depending on the location) than the lowland rainfed rice and ‘irrigated rice’ grown in the dry season. However, they are named differently in different riparian countries. Lowland rainfed rice, upland rice and irrigated rice are called lowland rice, upland rice and dry season rice, respectively, in Laos and Cambodia. In Vietnam, they are called summer-autumn rice, spring-summer rice and winter-spring rice, respectively (Nesbitt, 2005). Summer-autumn rice or 'lowland rainfed rice' is not grown in Central Highlands of Vietnam. Upland rice or spring-summer rice is the main rainfed rice in that area. Lowland rainfed rice is called major rice and irrigated rice is called 2nd rice in Thailand. Upland rice is not grown in Thailand. Lowland rainfed rice covered 79% of the annual rice harvested rice area of the basin in 2003; upland rice and irrigated rice covered 8% and 13% respectively (Mainuddin et al., 2008 and Mainuddin and Kirby, 2009). In this study, we have considered both rainfed (lowland and upland) and irrigated rice for simulation.

Table 6.2 Harvested area of different crops grown in the basin as percentage of the total harvested area, 1995-2003 [Mainuddin et al., 2008]

Crop	1995	1996	1997	1998	1999	2000	2001	2002	2003
Lowland rainfed rice	63.9	63.8	63.3	63.9	64.6	64.1	64.0	64.7	64.6
Irrigated rice	8.3	7.6	8.0	7.6	7.4	7.2	6.8	6.4	6.3
Upland	9.3	10.0	10.4	11.0	11.4	11.9	11.9	11.7	11.1
Maize	4.7	5.0	5.2	5.4	4.7	4.8	4.8	5.0	5.0
Cassava	6.7	6.5	6.1	5.1	5.2	5.4	4.9	4.5	4.7
Soybean	0.8	0.7	0.7	0.8	0.8	0.8	0.7	0.8	1.0
Sugarcane	3.2	3.3	3.3	3.3	3.3	3.0	3.6	3.7	4.0
Other upland crops	3.1	3.1	3.0	2.8	2.7	2.7	3.2	3.3	3.4
Total rice	81.5	81.4	81.7	82.6	83.3	83.2	82.7	82.7	82.0
Total upland crops	18.5	18.6	18.3	17.4	16.7	16.8	17.3	17.3	18.0

Among the crops, only 'lowland rainfed rice' is grown in every province except four provinces in Central Highlands of Vietnam. To have a basin-wide coverage of rainfed rice, in this study, we define 'main rainfed rice' as the 'lowland rainfed rice' of Laos, Thailand, Cambodia and the Mekong Delta of Vietnam and the 'upland rice' of Central Highlands. For main rainfed rice we have selected all 14 sites for simulation. Apart from the Central Highlands of Vietnam, upland rice is also grown in Laos and Cambodia alongside lowland rainfed rice. There is no data on yield of upland rice in Cambodia, and therefore it was not considered. Upland rice in Laos is also planted almost at the same time of that of the 'lowland rainfed rice' in the upland areas of the country. The impact of climate change and the adaptation strategies for minimizing the adverse impact would therefore is expected to be similar to that of the 'lowland rainfed rice'; hence was not considered separately for impact analysis.

Irrigated rice is grown in dry season when rainfall is very low and almost negligible. The variation of PET is much lower than rainfall within the zones of different country. Therefore, we have considered one site in each country (L1, T3 and V2) for simulation of irrigated rice. Yield data of irrigated rice was not available for Cambodia, hence, was not considered.

Many upland crops (crops other than rice are generally termed together as upland crops) are grown in the basin mostly in rainfed conditions in the wet season (Nesbitt, 2005). Mainuddin et al. (2008) analysed the productivity of the upland crops and found that among the upland crops maize (28% of the total harvested area of upland crops), cassava (26%) and sugarcane (22%) are predominant. Cassava is not a basin-wide crop and is grown mostly in northeast Thailand (93% of total basin harvested area in 2000 and 86% in 2003). Sugarcane is also predominant in northeast Thailand (80% of total area in 2003 and 73% of total area in 2000). Among the upland crops, maize is the widely spread across the basin and is considered for simulation. Cultivation of maize is not uniformly distributed among the provinces of the riparian countries. Analysing the zone-wise distribution of harvested area of maize based on the data available from the official statistical website of the respective riparian countries, we have considered two zones having highest harvested area from each country. These are L2 (33% of the total harvested area) and L3 (56%) in Laos, T3 (28%) and T4 (67%) in Thailand, C2 (81%) and C3 (11%) in Cambodia and V1 (81%) and V3 (16%) in Vietnam.

6.7. Model set up, calibration and validation

For hydrological modelling in the MRC-DSF, the whole basin is divided into sub-catchments (Figure 2.2). The AquaCrop model was set up for each location considering the climatic data of the sub-catchment and provincial average yield data. There are about 700 sub-catchments of varying size covering the LMB's 76 administrative provinces. Yield of crop are not available at the sub-catchment level. Hence, we assume that provincial average yield (within which the sub-catchment is located) represents the yield of the crop in the sub-catchment. Figure 6.1 shows the sub-catchments selected for simulation with the province and zone it is representing.

The yield of a particular crop depends on the planting date, fertilizer applications, pesticides and herbicides applications, and inter-cultural management of the crop field. These vary from field to field and year to year. To minimise the impact of this variation, the baseline condition for model simulation was considered for 5 years 1996-2000. As discussed in the earlier Chapters, baseline climatic parameters are available for 1985 to 2000 only, though more recent crop data are available. In the model, we used the crop calendar published by the MRC (Nesbitt, 2005) in defining the general crop growing period. It is well established that the use of fertilizer is below the optimum level in the basin particularly in Laos, Thailand and Cambodia (Hasegawa et al. 2008, Linquist and Sengxua 2001, Fukai 2001). Harvest index is highly variable as a function of water availability and rice variety (Homma et al. 2004; Hayashi et al. 2007). To calibrate and validate the model, we tried to match the model yield with the observed yield by changing the planting date, fertilizer stress and harvest index but keeping them same for every year. AquaCrop model considers the field management (such as pest and diseases control, weed control, etc.) of the crop at the optimum level which is mostly not the case in real situation. The impacts of these are embedded in the fertilizer stress in calibration and validation.

Table 6.3 shows the planting date used in the model for calibration and validation with model generated growing period. The planting date used and the growing period are well within the range of the crops defined by FAO (Allen *et al.* 1998) and used by other researchers in the basin (Phaloeun *et al.* 2004, Chea *et al.* 2001, Sihathep *et al.* 2001, Makara *et al.* 2001, Boualaphanh et al. 2001, Linquist and Sengxua 2001, Hasegawa et al. 2008, Kono et al., 2001, Shimizu et al., 2006). The harvest index used in calibration varied from 0.25 to 0.41 which is within the range reported by Hayashi et al. (2007). Hayashi et al. (2007) evaluated 14 rice genotypes in northeast Thailand and found that the harvest index varied from 0.21 to 0.46 for transplanted rice. Hasegawa et al. (2008) used a constant value of 0.3 (30%) based on the previous observations for two of the primary rice cultivars (KDML105 and RD15) grown in northeast Thailand (Ohnishi et al. 1999; Naklang et al. 2006). We have found harvest index as 0.27, 0.30, 0.30 and 0.31 for the four sites in northeast Thailand at calibration and validation.

Comparison of observed yield (provincial average yield available from the statistical websites as mentioned earlier) with the model yield for main rainfed rice, irrigated rice and maize for each location is shown in Figures C.1 to C.14, C.15 to C.17, and C.18 to C.25, respectively in Appendix C. Comparison of average (1996-2000) yield with the model average yield for main rainfed rice is shown in Figures 6.2 and 6.3. Figures 6.4 and 6.5 compare the average yield of irrigated rice and maize. It is well evident from the figures that the model well represents the average condition of the selected sites.

For climate change scenarios of A2 and B2, we ran the model with generated climatic parameters such as rainfall, PET, maximum and minimum temperature for the period of 2010 to 2050 keeping all the soil, crop, and irrigation and management parameters same as used in the baseline condition. CO_2 emission has also been considered varied from year to year for the simulation period according to SRES scenarios.

Table 6.3 Planting date used in the model for different crops with growing period

Site No	Main rainfed rice		Irrigated rice		Maize	
	Planting date	Growing period, day	Planting date	Growing period, day	Planting date	Growing period, day
L1	20 May	130	1 Nov	132		
L2	1 June	137			1 May	132
L3	15 June	144			1 May	132
T1	1 July	137				
T2	20 June	137				
T3	20 June	134	1 Nov	130	1 May	132
T4	10 July	130			1 May	132
C1	20 June	129				
C2	15 May	131			1 May	132
C3	20 June	132			1 May	132
C4	20 June	132				
V1	20 April	130			1 May	132
V2	1 July	120				
V3	1 July	120	1 Nov	120	1 May	132

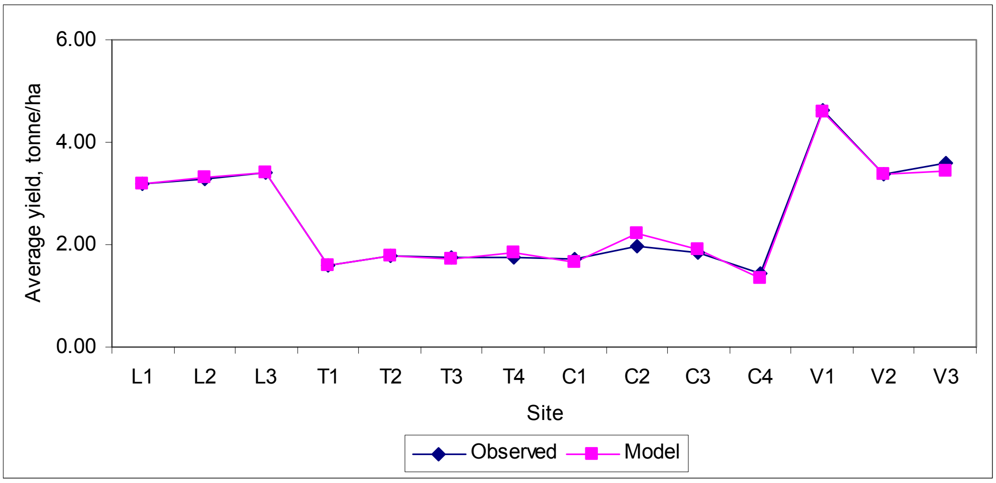


Figure 6.2 Average yield of main rainfed rice, observed and modelled

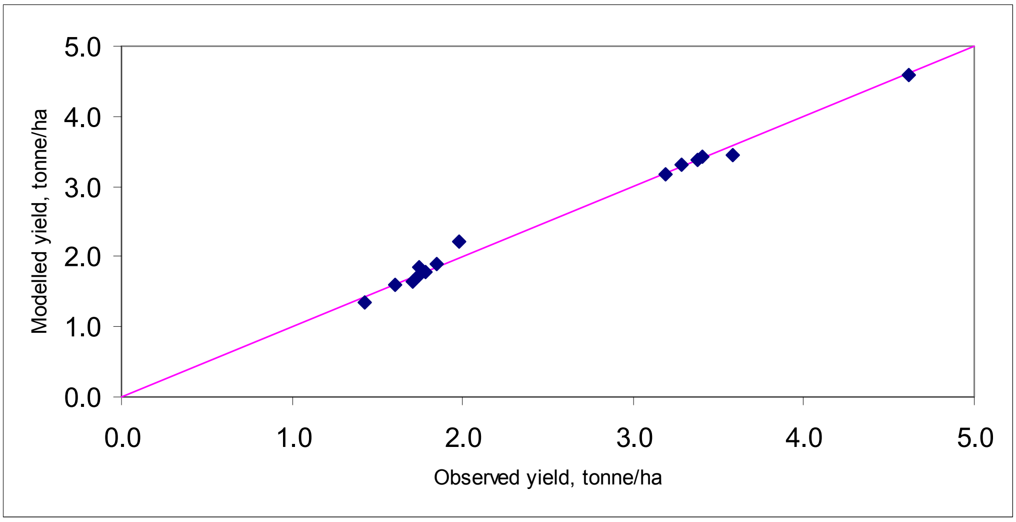


Figure 6.3 Comparison of average observed and modelled yield of main rainfed rice (1:1 plot)

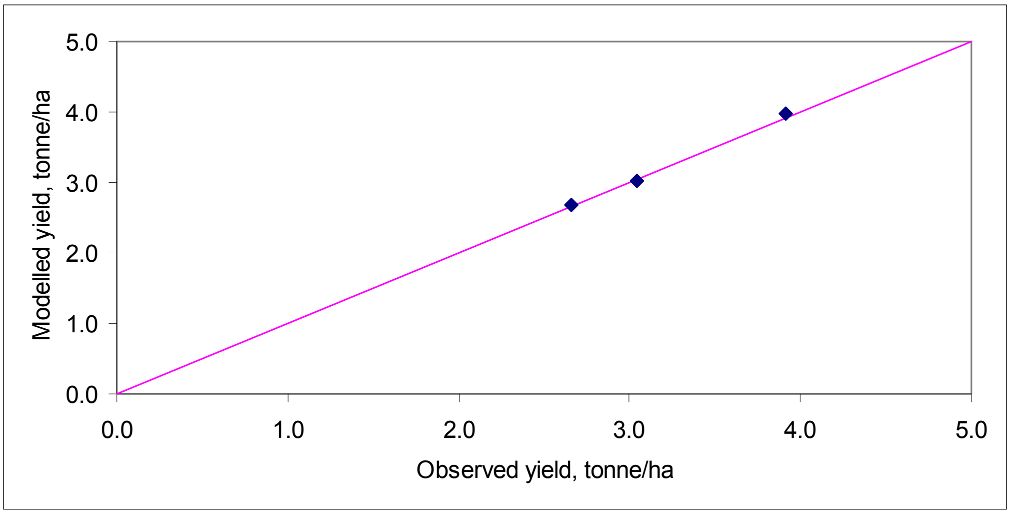


Figure 6.4 Comparison of average observed and modelled yield (1:1 plot) of irrigated rice

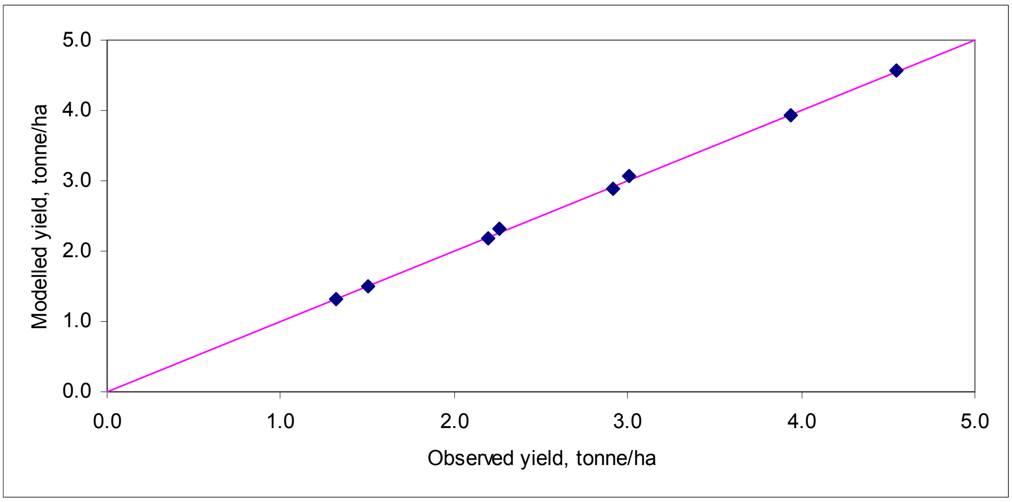


Figure 6.5 Comparison of average observed and modelled yield (1:1 plot) of maize

6.8. Impact of climate change on the yield of major crops

6.8.1. Main rainfed rice

The average yield of rice for the baseline, A2, and B2 scenarios for all locations is shown in Figure 6.6. Figure 6.7 shows percentage change of yield from baseline for A2 and B2 climate scenarios. Results suggest that yield of rice will increase for all the sites in Laos and Thailand for both scenarios except for B2 scenario in site L1. In general, projected yield is higher in A2 scenario in Laos and for B2 scenario in Thailand (except site T2). For the sites in Cambodia and Vietnam, projected yield is slightly higher compared to the baseline yield for two sites in Cambodia (C2 and C3, 2.7 and 6.3%, respectively) and two sites in Vietnam (V1 and V2, 6.4 and 11.9%, respectively) for A2 scenario only. Yield decreases in all sites for B2 scenarios in these two countries. The reduction of yield is highest (14.2%) in the site C1 followed by C4 (5.1%) for A2 scenario. For B2 scenario, the reduction is highest in site V3 (11.0%) followed by V1 (10.1%) and C3 (8.4%).

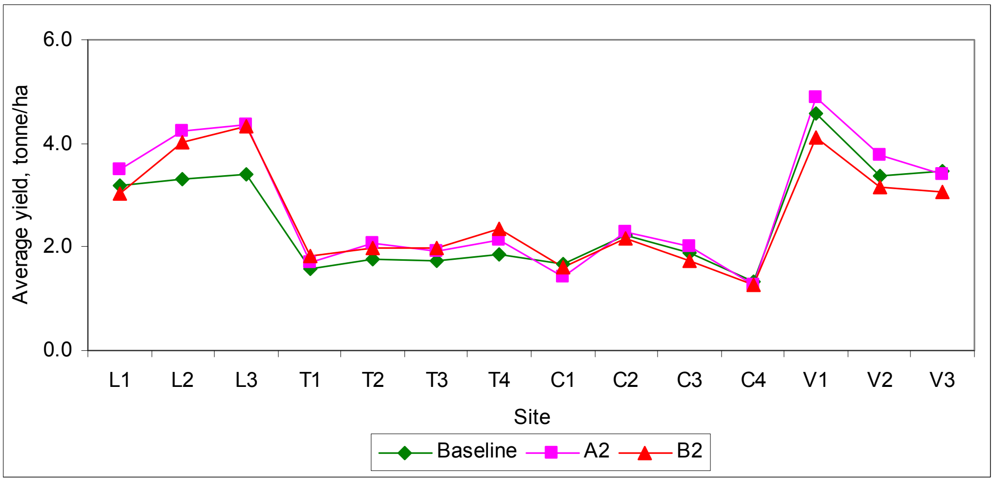


Figure 6.6 Comparison of baseline average yield of main rainfed rice with projected average yield for A2 and B2 scenario

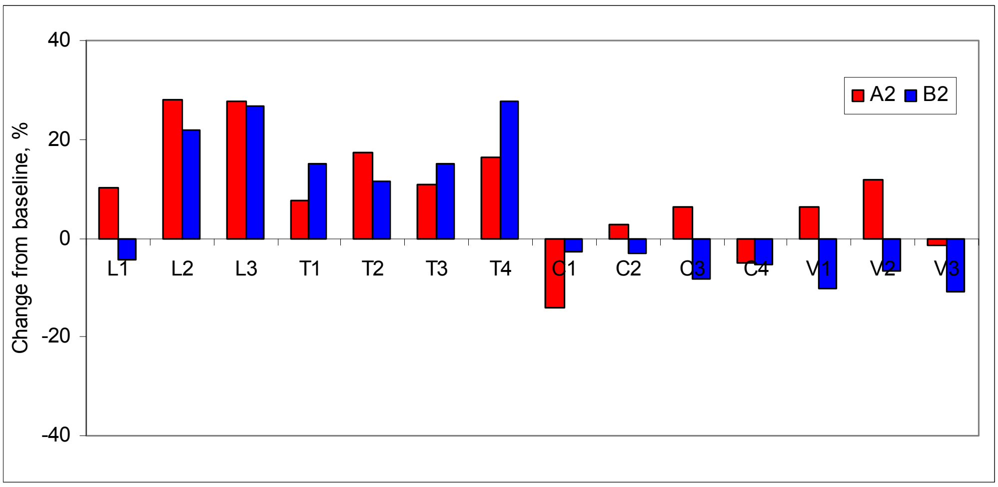


Figure 6.7 Change in average yield of main rainfed rice for A2 and B2 scenario with respect to the baseline average yield

Figures 6.8 and 6.9 show the basin-wide impact on the yield of main rainfed rice. These map have been created by up-scaling or extrapolating the results of individual sites (shown in Figure 6.7) to the respective zones. Results suggest that yield of rice will increase for much of the basin except for a small part of Cambodia and Vietnam in A2 scenario, and about half of the basin in B2 scenario (all sites in Cambodia and Vietnam and one site in Laos).

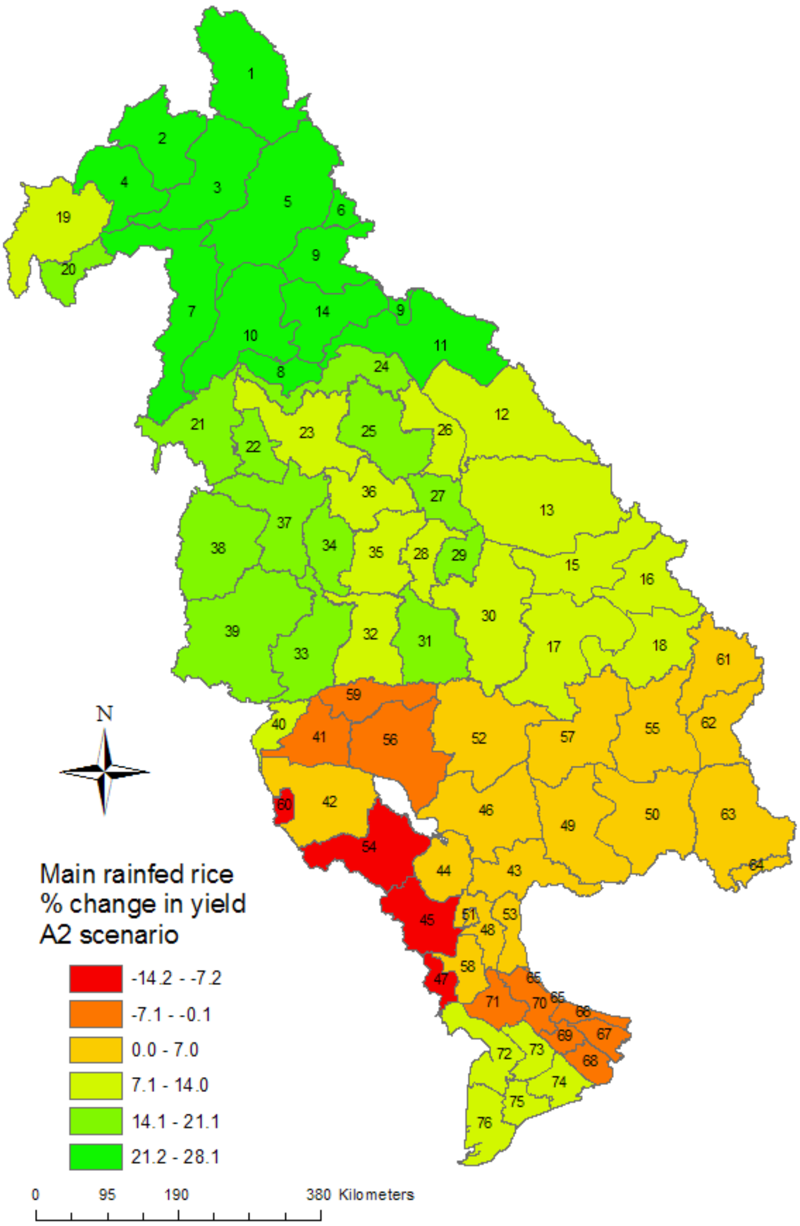


Figure 6.8 Basin-wide changes in average yield of main rainfed rice for A2 scenario

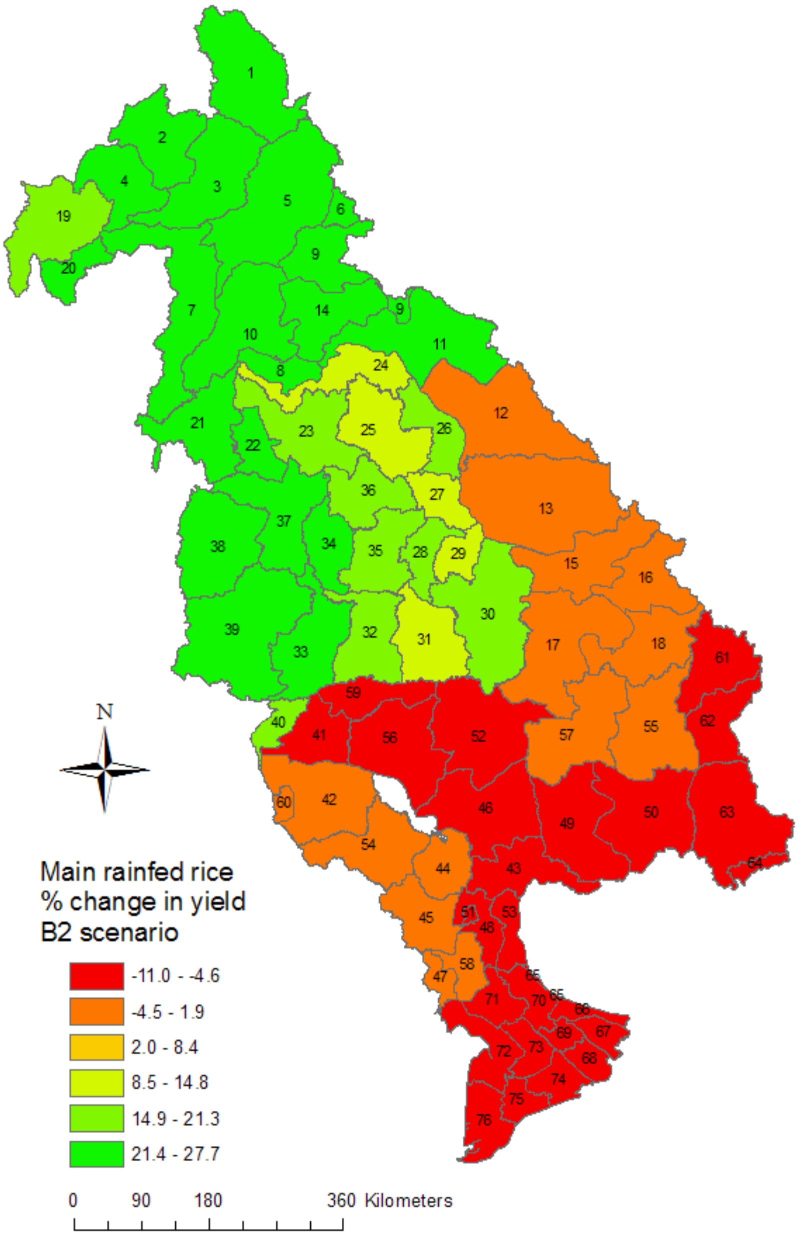


Figure 6.9 Basin-wide changes in average yield of main rainfed rice for B2 scenario

There is high variation in projected yield due to climate change from year to year. Figure 6.10 shows the year to year variation in yield for one site (L1) as an example. As shown in the Figure, yield varies from 0 to about 5.00 tonne/ha. Figures 6.11 and 6.12 show the exceedence probability curve of yield under climate change scenarios for all 14 sites. It is evident from the Figures (6.10 through 6.12) that minimum yield in some sites is zero which indicates that there was no harvest at all in some years during the simulation period (2010-2050). Table 6.4 shows the coefficient of variation (CV) of yield and number of years of no harvest during the simulation period. Site C1 has the highest number of failure (6 years) for both A2 and B2 scenarios. In general, total crop failure occurs in the lower half of the basin in the areas of Cambodia and Vietnam. As the baseline condition is limited to only 5 years, we have compared the CV of the projected yield with that of the observed yield for the period of 1993 to 2004 in Table 6.4. The CV of projected yield is comparatively much higher than the CV of observed yield. Though the CV of observed yield was estimated based on 11 years of data compared to the 41 years in case of the projected yield, however, it can be stated that the variation in yield would be higher due to climate change in future. This indicates higher variability in the climate in the future (Figure 3.4).

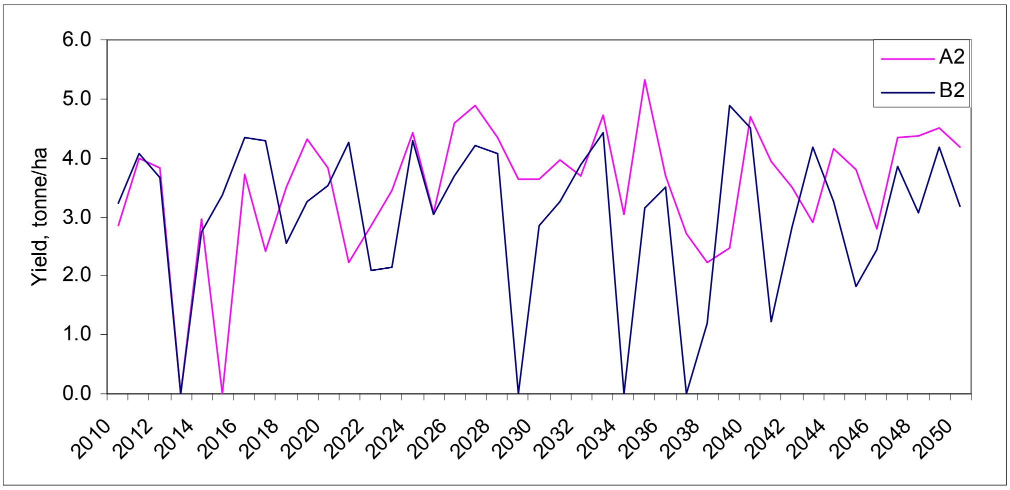


Figure 6.10 Yield variation in projected yield of main rainfed rice during the simulation period for site L1

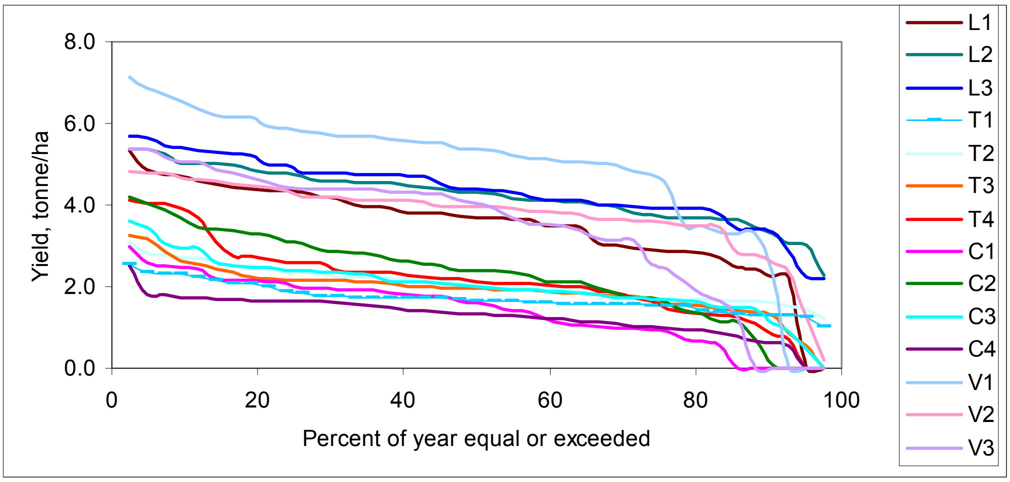


Figure 6.11 Exceedance probability showing the projected yield of main rainfed rice for A2 scenario

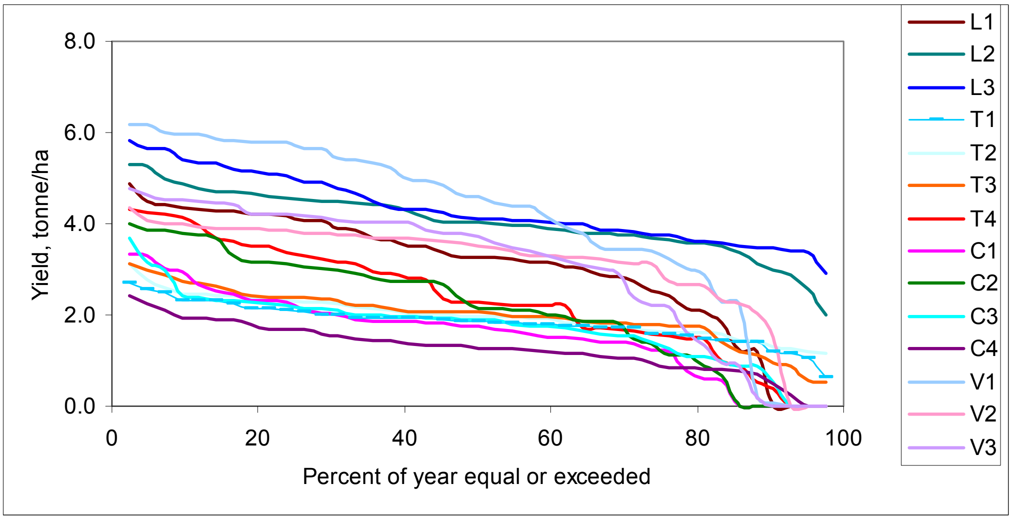


Figure 6.12 Exceedance probability showing the projected yield of main rainfed rice for B2 scenario

Table 6.4 Coefficient of variation (CV) of observed and projected yield of main rainfed rice and number of years in the simulation period with no harvest

Site	CV of observed yield for the period of 1993-2004	Scenario A2			Scenario B2		
		CV of projected yield	No of year with no harvest	% of year with no harvest	CV of projected yield	No of year with no harvest	% of year with no harvest
L1	0.08	0.32	2	4.9	0.44	4	9.8
L2	0.11	0.16	0	0.0	0.17	0	0.0
L3	0.08	0.19	0	0.0	0.17	0	0.0
T1	0.04	0.20	0	0.0	0.23	0	0.0
T2	0.06	0.20	0	0.0	0.22	0	0.0
T3	0.11	0.32	1	2.4	0.30	0	0.0
T4	0.06	0.45	2	4.9	0.52	3	7.3
C1	0.19	0.58	6	14.6	0.57	6	14.6
C2	0.14	0.49	3	7.3	0.57	6	14.6
C3	0.25	0.34	1	2.4	0.45	3	7.3
C4	0.16	0.38	2	4.9	0.44	2	4.9
V1	0.07	0.36	3	7.3	0.46	2	4.9
V2	0.10	0.24	0	0.0	0.34	3	7.3
V3	0.09	0.48	5	12.2	0.49	4	9.8

Natural ecosystems and agricultural production systems are significantly affected by climate, such as air temperature, radiation, rainfall, wind direction and speed, to name a few. Among these, the influence of rainfall is very large in both natural and ago-ecosystems (Nawata et al., 2005). Regional variation is also large, thus the influence of rainfall characteristics on vegetation is rather complicated in tropical monsoon area. Agricultural production is naturally unsteady under such unstable and erratic rainfall conditions (Nawata et al., 2005). Thus one of the main factors of the variation in yield is the variation in rainfall during the growing season of main rainfed rice.

Figures 6.13 and 6.14 present the average rainfall, and potential evapotranspiration (PET) during the growing period (date of planting to harvest) of main rainfed rice for baseline, A2, and B2 scenario. Table 6.5 shows the change in average growing season rainfall, PET, actual evapotranspiration (AET) and average yield due to climate change from the baseline average condition. The baseline period considered for crop simulation is 1996-2000. Due to high variability of rainfall from year to year, Table 6.5 also includes change in rainfall considering the baseline period of 1985 to 2000 as considered in the previous Chapters. Growing season rainfall increases generally in sites in Laos and Thailand and decreases in Cambodia and Vietnam. The change in PET and AET is predominantly positive except few sites. The increase and decrease of the climatic parameters, particularly rainfall, is highly dependent on the date of transplanting. Early or late transplanting may results in less or more rainfall during the growing season because of the highly seasonal nature of the rainfall. There is no clear correlation between the changes in rainfall, PET and AET with the yield.

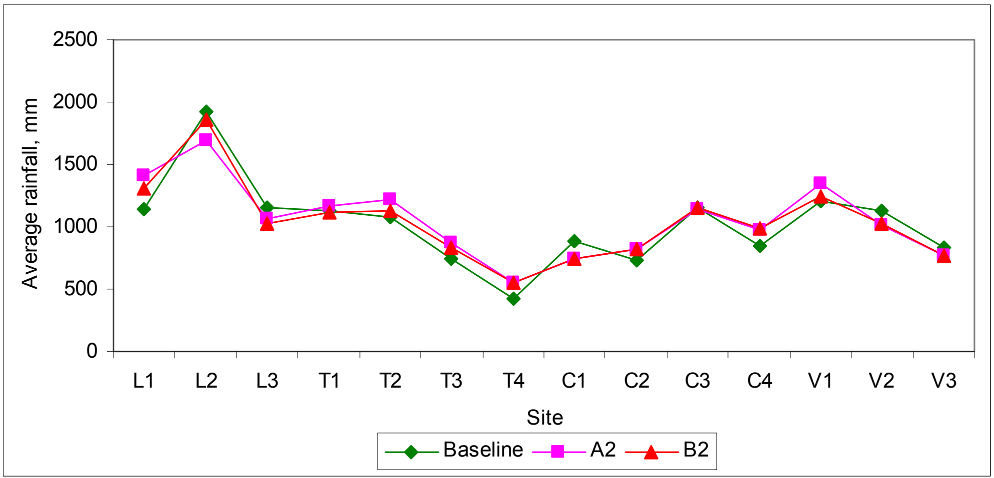


Figure 6.13 Comparison of average rainfall during the growing season of main rainfed rice for baseline, A2, and B2 scenario

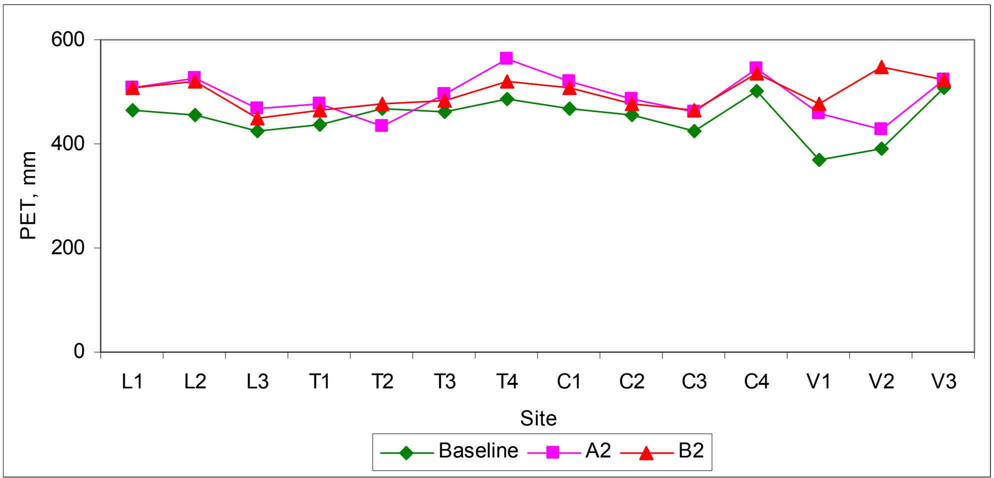


Figure 6.14 Comparison of potential evapotranspiration (PET) during the growing period of main rainfed rice for baseline, A2, and B2 scenario

Table 6.5 Change of average rainfall, potential evapotranspiration (PET) and actual evapotranspiration (AET) during the growing season, and average yield due to climate change from the baseline average (negative numbers are highlighted)

Site	% change from the baseline, A2					% change from the baseline, B2				
	Rainfall (1985-2000)	Rainfall (1996-2000)	PET	AET	Yield	Rainfall (1985-2000)	Rainfall (1996-2000)	PET	AET	Yield
L1	+14.1	+23.4	+9.0	+7.4	+10.3	+4.8	+14.1	+9.0	+6.0	-4.3
L2	-8.5	-12.2	+15.9	+8.8	+28.1	+0.4	-3.3	+14.5	+6.9	+21.9
L3	+5.3	-7.9	+9.6	+8.7	+27.6	+2.6	-10.6	+5.7	+6.0	+26.6
T1	+5.5	+2.9	+9.3	+2.5	+7.7	+1.8	-0.8	+6.3	+1.0	+15.1
T2	+13.9	+13.2	-7.3	-14.4	+17.2	+5.9	+5.1	+1.8	-4.5	+11.4
T3	+12.5	+17.2	+7.7	+0.7	+10.8	+6.5	+11.2	+4.9	-0.3	+15.1
T4	+16.0	+31.5	+15.8	+3.3	+16.5	+15.2	+30.8	+6.9	+2.2	+27.7
C1	-0.4	-16.4	+10.7	+3.8	-14.2	+0.3	-15.6	+8.3	+2.5	-2.9
C2	-0.5	+12.7	+6.7	+5.0	+2.7	-0.9	+12.2	+4.5	+1.1	-3.0
C3	-2.2	-1.3	+9.0	+4.8	+6.3	-1.6	-0.6	+9.4	+3.2	-8.4
C4	-0.8	+15.4	+8.4	+6.2	-5.1	+0.9	+17.0	+6.8	+1.9	-5.2
V1	+8.8	+11.3	+24.4	+15.7	+6.4	+0.3	+2.8	+29.8	+12.1	-10.1
V2	-2.1	-10.9	+9.5	+1.4	+11.9	-0.9	-9.7	+40.6	+25.7	-6.8
V3	+3.9	-8.8	+2.9	-4.7	-1.6	+5.1	-7.6	+3.1	-5.4	-11.0

As shown in Table 6.5, in some sites, yield increases or decreases with the increase or decrease of total growing period rainfall, respectively. In some sites (for example L2, L3), the total rainfall during the growing period decreases though yield increases and vice versa (L1, C2, C4, and V1 for B2 scenario). For the sites L2 and L3 in Laos, though the total amount of rainfall during the growing period decreases and PET increases, yield increases. Apart from the distribution of rainfall, rainfall in these areas is also much higher than the water requirements (PET) of rainfed rice (compare Figures 6.13 and 6.14). Therefore, though the rainfall has decreased the reduced amount is still much higher than the requirement of the crop and therefore yield is not affected. For the site V1 in B2 scenario, rainfall increases slightly (2.8%) but PET increases by about 30% resulting in yield loss of about 10%.

Nawata et al. (2005) showed that the number of rainy days in the rainy season has large regional variation in Northeast Thailand, but it was not correlated to annual rainfall. For agricultural production, the number of rainy days is more important than mean rainfall amount per rainy day or annual rainfall. Well-distributed rain may reduce the occurrence of drought (Nawata et al., 2005). Dry spells, which are one of the biggest factors reducing agricultural productivity and stability in Northeast Thailand and Laos (Fukui and Hawkes, 1993), may occur with lower frequency in areas with abundant rainy days in the rainy season (Nawata et al., 2005). The duration of rainy season has also relative large regional variation and is not strongly correlated to annual rainfall (Nawata et al., 2005).

Figures 6.15 and 6.16 present projected daily rainfall and PET of A2 scenario for 2013, 2015 and 2023 for site L1. The projected total rainfall during the growing period in 2013 and 2015 is 1025 and 952 mm, respectively compared to 603 mm in 2023. Yet there was no harvest in 2013 and 2015 but the yield was 3.44 tonne/ha for 2023. As we can see in the Figure 6.15, there was almost no rainfall during the period of day 11 to day 41 for the year 2013 and 2015 but PET was very high (up to about 8.0 mm/day, Figure 6.16). Therefore, the crop may have died because of this prolonged drought or could not recover even though there was lot of rainfall afterwards. In 2023, there was rainfall almost every day during that period, though very low, (about 2.0 to 4.0 mm/day) and the requirement was also low (PET is up to 4.0 mm/day). The crop therefore may not have experienced any water stress to the extent that it affects yield. The analysis suggests that while total amount of rainfall during the growing season is important the distribution of rainfall and PET is also very important for successful crop cultivation. Drought is a major production constraint for rainfed lowland rice, being particularly severe in Northeast Thailand. It also affects large areas of rice cultivation in Laos and Cambodia (Fukai 2001).

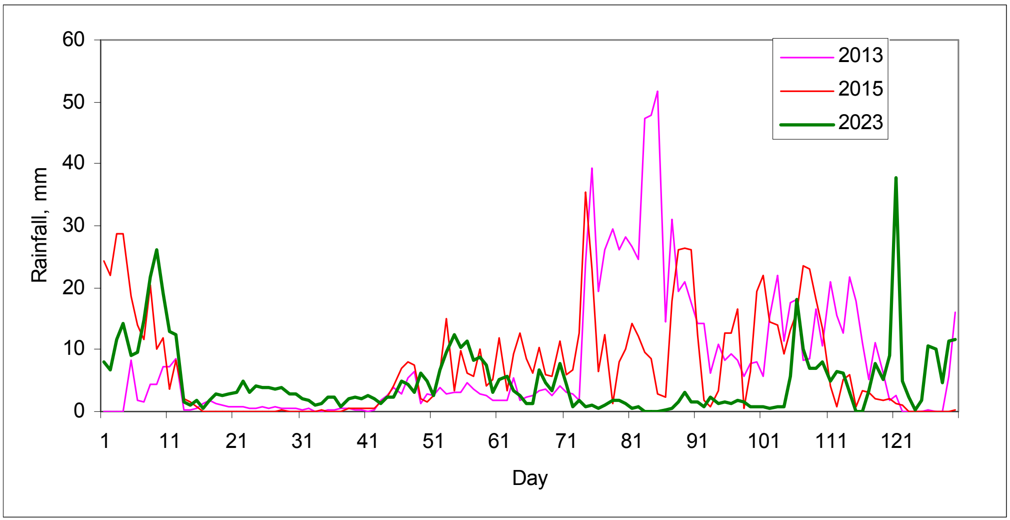


Figure 6.15 Daily rainfall during the growing period of main rainfed rice in site L1 on 2013, 2015 and 2023 for A2 scenario

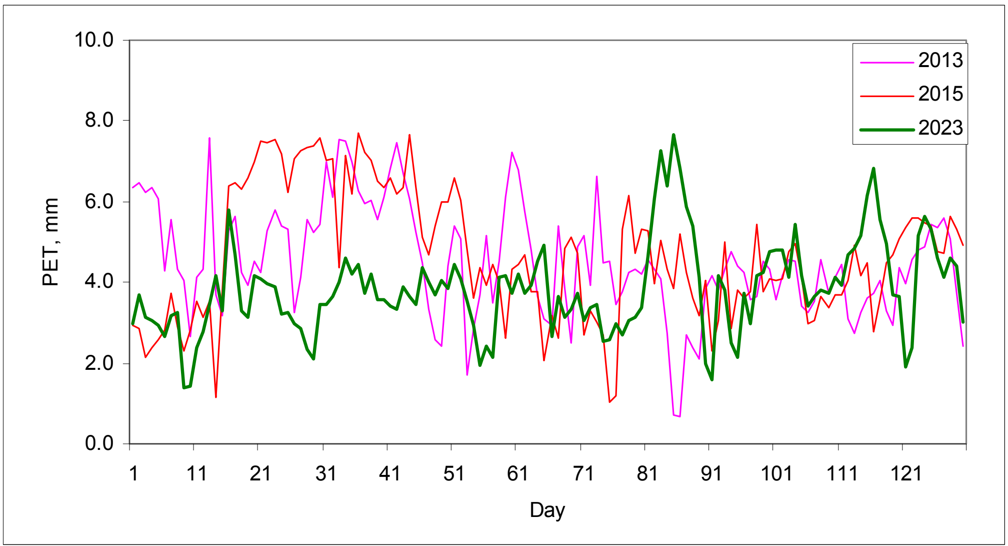


Figure 6.16 Daily PET during the growing period of main rainfed rice in site L1 on 2013, 2015 and 2023 for A2 scenario

Adequate water during the total growing period is needed for vigorous growth and high yield of rice. Because plants have to recover from transplanting and for formation of the roots, adequate water supply just following transplanting is important. For high yields, it is required to maintain a certain level of water depth in the paddy field at different growth stages (Doorenbos and Kassam, 1979). The most sensitive periods to water deficit are flowering and the second half of the vegetative period. When moisture content of the soil decreases to 70 to 80% of the saturation value, rice yields begin to decline. At a soil water content of 50% of saturation, yield decrease is 50 to 70 percent. At a soil water content of 30%, no yield can be expected and plants die when soil water content is below 20% (Doorenbos and Kassam, 1979). Daily rainfall and potential evapotranspiration, and date of transplanting determine the level of soil water content in the field. If soil water content is below the critical level for a prolonged period, no yield can be expected even with higher total growing period rainfall.

Rice yield is highly sensitive to the transplanting date, with earlier transplanting dates resulting in a substantially higher yield than later planting dates in northeast Thailand (Hasegawa et al., 2008). Hasegawa et al. (2008) showed that simulated grain yield for the crop transplanted in June was more than two times the yield for crops transplanted in August in northeast Thailand. Adequate rainfall during the land preparation and nursery period is thus very important for early transplantation of rice. Areas with a large amount of rainfall, transplanting occurred early, resulting in a long growth duration that ensured high yields; in contrast, areas with limited rainfall had later transplanting and shorter growth duration (Hasegawa et al., 2008).

Temperature exerts a major influence on rice growth and yield (Baker et al., 1992). Biomass accumulation increases with increasing water temperature from 18 to 33°C (Matsushima et al., 1964). Tillering is similarly stimulated with increasing temperature across a temperature range from about 15 to 33°C (Nishiyama, 1976). Increased temperature may also affect the growth and yield of rice in several other ways. The response of rice to temperature differs with variety (Doorenbos and Kassam, 1979). However, in general, temperatures between 22 and 30° are required for good growth at all stages but during flowering and yield formation small differences between day and night temperatures are required for good yield. Optimum daytime air and water temperatures for the growth of rice are in the range of 28 to 35°C (Doorenbos and Kassam, 1979). The temperature at the time of flowering affects the spikelet fertility and hence the yield (Krishnan and Surya Rao, 2005). Even a small difference of just 1°C could result in a large yield decrease due to lower number of grains being formed (Sheehy et al., 2006).

Table 6.6 shows the average maximum and minimum temperature during the total growing period, during initial and development stage, and during the flowering stage of main rainfed rice for all 14 sites. Both projected average maximum and minimum temperatures increases about 1°C compared to the baseline for both A2 and B2 scenarios at all growth stages. However, average maximum temperature (which is usually daytime temperature) is well below 35°C and within the optimum range of 28 to 35°C as specified by Doorenbos and Kassam (1979). Average minimum temperature is also within the range of good growth. Average maximum and minimum temperatures do not indicate whether the plant was subject to cold and heat stress. Cold and heat stress might affect pollination (Raes et al., 2009a). In AquaCrop, the upper threshold for the minimum air temperature is considered at 8°C below (cold stress) and the lower threshold of the maximum air temperature at which pollination starts to fail is considered at 35°C (heat stress). Minimum temperature is never below 8°C during the growing period of rainfed rice for all scenarios. So there is no impact from cold stress. Table 6.7 shows the projected number of days per year the maximum temperature is above 35°C for baseline, A2 and B2 scenarios at flowering stage of the crop. Maximum temperature is above 35°C for about 3 to 10 days of the total growing period (40-50 days) for all the sites in Laos, Thailand and Cambodia. There is almost no change in Vietnam. Number of day/year with maximum temperature decreases sharply with increase in temperature. Temperature of higher than 38°C is about a day per year except few sites (L2, L3 and C3). This may have had some impact on yield.

Apart from the variation in rainfall, temperature and PET, the increasing concentrations of greenhouse gases such as CO_2 may have significant effect on rice growth and development (Aggarwal, 2003; Johnson and Lincoln, 1990). The net assimilation rate and canopy net photosynthesis increases with increasing CO_2 concentration (Krishnan et al., 2007). When photosynthesis is enhanced by increased CO_2, the carbon/nitrogen (C/N) ratio also increases in the plants, which can reduce the nutritional quality of leaves and increase feeding by the herbivorous insects (Johnson and Lincoln, 1990). The elevated CO_2 concentration was also found to accelerate the development but shorten the total growth duration of rice (Krishnan et al., 2007). There can be considerable changes in the nutrient-cycling processes in soils also (Strain, 1985). Rice crop management may also become easier under high CO_2 regime since the enhanced competitiveness may result in decrease weed pressure (Bazzaz et al., 1989). In the absence of temperature increase, many studies have shown that the net effect of doubling of CO_2 was increase in the yield of rice (Bachelet et al, 1992; Kim et al., 2003).

AquaCrop considers 369.47 ppm by volume as the reference atmospheric CO_2 concentration. It is the average atmospheric CO_2 concentration for the year 2000 measured at the Mauna Loa Observatory in Hawaii (Raes et al., 2009). In the simulation of A2 and B2 scenarios, we have considered CO_2 concentration varies linearly from 401 to 536 ppm for A2 scenario and 389 to 478 ppm for B2 scenario, respectively, for the period of 2010 to 2050. To see the impact of increased CO_2 concentration in the atmosphere, we have carried out simulation in two sites (highest increase of yield, L3 and highest decrease in yield, (C1) keeping CO_2 concentration at 369.47 ppm (reference atmospheric CO_2 concentration at 2000). Figure 6.17 shows the change in yield from baseline for A2 and B2 scenarios with varied and constant CO_2 concentration. In site C1, yield decreases from baseline average of 1.65 tonne/ha to 1.14 tonne/ha (-31.0%) at constant CO_2, while with varied CO_2 concentration yield decreases to only 1.42 tonne/ha (- 14.2%) for A2 scenario. That means average yield increases about 25% with higher CO_2 concentration in the atmosphere compared to the CO_2 concentration at the reference level. For B2 scenario, the increase is about 16%. In site L3, projected average yield is 27.6 and 2.2% higher for A2 scenario and 26.6 and 9.0% higher for B2 scenario compared to the baseline average yield, respectively with varied and constant CO_2 concentration. The increased CO_2 concentration in the atmosphere increases the yield again by about 25% and 16% respectively, for A2 and B2 scenario in site L3.

Table 6.6 Comparison of average maximum and minimum temperature during the total growing period, initial and development stage and the flowering stage of main rainfed rice for both scenarios

Site	Total growing period						Initial and development stage						Flowering stage					
	Max temp, °C			Min temp, °C			Max temp, °C			Min temp, °C			Max temp, °C			Min temp, °C		
	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2
L1	31.4	+0.8	+1.0	24.2	+0.9	+1.2	32.1	+0.8	+1.1	24.6	+0.9	+1.2	30.8	+0.6	+0.9	24.1	+0.8	+1.1
L2	31.5	+0.9	+1.1	24.3	+1.5	+1.6	32.4	+0.6	+0.8	25.0	+1.5	+1.7	30.8	+0.8	+0.8	24.1	+1.1	+1.0
L3	31.6	+0.5	+0.6	22.9	+1.2	+1.3	31.9	+0.0	+0.0	24.0	+0.8	+0.7	31.5	+1.1	+1.0	23.2	+1.3	+1.2
T1	32.0	+1.4	+1.5	23.2	+0.6	+0.8	32.6	+1.4	+1.6	23.8	+0.8	+1.0	31.8	+1.4	+1.4	23.7	+0.5	+0.5
T2	31.4	+1.0	+1.0	23.2	+1.0	+1.1	31.7	+0.7	+0.7	24.1	+0.9	+0.8	31.1	+1.1	+1.1	23.4	+1.0	+1.1
T3	31.6	+1.0	+1.1	23.9	+0.9	+1.1	31.9	+1.1	+1.1	24.4	+1.1	+1.1	31.1	+0.9	+1.1	24.0	+1.0	+1.1
T4	31.0	+1.0	+1.2	23.2	+0.9	+1.2	31.5	+1.0	+1.1	23.7	+1.1	+1.2	30.7	+1.2	+1.3	23.5	+1.1	+1.2
C1	31.2	+1.0	+1.1	24.3	+0.4	+1.0	32.0	+1.0	+0.9	24.3	+0.4	+0.7	30.7	+1.1	+1.5	24.2	+0.5	+1.5
C2	31.3	+1.1	+1.3	23.9	+0.9	+1.1	32.0	+1.0	+1.2	24.3	+0.7	+0.9	31.2	+1.1	+1.5	23.7	+1.1	+1.6
C3	32.0	+0.9	+1.2	23.8	+1.0	+1.2	32.7	+1.0	+1.4	23.8	+1.1	+1.5	31.5	+1.0	+1.2	23.7	+1.0	+1.2
C4	31.0	+1.0	+1.1	23.5	+0.8	+1.0	31.6	+0.9	+1.0	24.0	+0.7	+0.8	30.9	+1.0	+1.3	23.5	+1.1	+1.4
V1	23.8	+1.3	+1.8	22.1	+0.9	+1.4	24.5	+1.8	+2.4	22.7	+1.5	+2.1	23.2	+1.2	+1.5	21.5	+0.8	+1.1
V2	27.9	+0.9	+1.0	26.7	+0.7	+1.4	28.0	+0.8	+1.0	26.9	+0.6	+1.4	28.0	+0.8	+0.7	26.8	+0.7	+1.3
V3	28.6	+0.8	+0.8	26.7	+0.5	+0.6	28.6	+0.7	+0.9	26.5	+0.3	+0.5	28.5	+0.6	+0.6	27.0	+0.5	+0.5

Table 6.7 Comparison of average number of day/year maximum temperature is above 35°C for baseline, A2 and B2 scenarios at the flowering stage of main rainfed rice

Site	No of days/year temperature is above the specified temperature at flowering stage																	
	Temp > than 35°C			Temp > than 36°C			Temp > than 37°C			Temp > than 38°C			Temp > than 39°C			Temp > than 40°C		
	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2
L1	0.0	3.1	3.3	0.0	1.9	2.2	0.0	1.2	1.4	0.0	0.8	1.0	0.0	0.4	0.6	0.0	0.2	0.4
L2	0.2	7.8	8.4	0.0	5.6	6.1	0.0	3.6	3.9	0.0	2.2	2.5	0.0	1.1	1.7	0.0	0.8	1.0
L3	0.0	10.3	9.4	0.0	6.3	5.6	0.0	4.0	3.5	0.0	2.1	1.9	0.0	1.0	0.9	0.0	0.5	0.4
T1	0.4	8.6	8.0	0.2	4.2	4.1	0.2	1.7	1.1	0.0	0.6	0.4	0.0	0.1	0.1	0.0	0.0	0.0
T2	0.0	6.4	7.0	0.0	3.4	3.2	0.0	1.4	1.1	0.0	0.6	0.6	0.0	0.3	0.2	0.0	0.1	0.1
T3	0.0	5.5	5.4	0.0	2.7	3.0	0.0	1.4	1.5	0.0	0.6	0.6	0.0	0.2	0.4	0.0	0.0	0.1
T4	0.0	6.4	7.0	0.0	3.3	3.6	0.0	1.5	1.5	0.0	0.2	0.7	0.0	0.0	0.2	0.0	0.0	0.0
C1	1.6	6.3	6.5	0.8	3.2	3.3	0.0	1.4	1.6	0.0	0.5	0.8	0.0	0.1	0.4	0.0	0.0	0.1
C2	2.0	8.7	10.2	0.2	5.2	6.0	0.0	2.3	3.2	0.0	0.7	1.5	0.0	0.1	0.4	0.0	0.0	0.1
C3	0.0	6.5	6.1	0.0	4.0	4.3	0.0	2.1	2.5	0.0	1.1	1.5	0.0	0.4	1.0	0.0	0.2	0.6
C4	1.4	6.0	7.0	0.4	3.0	3.7	0.0	1.0	1.8	0.0	0.4	0.8	0.0	0.2	0.4	0.0	0.1	0.2
V1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
V3	0.0	0.6	0.6	0.0	0.3	0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

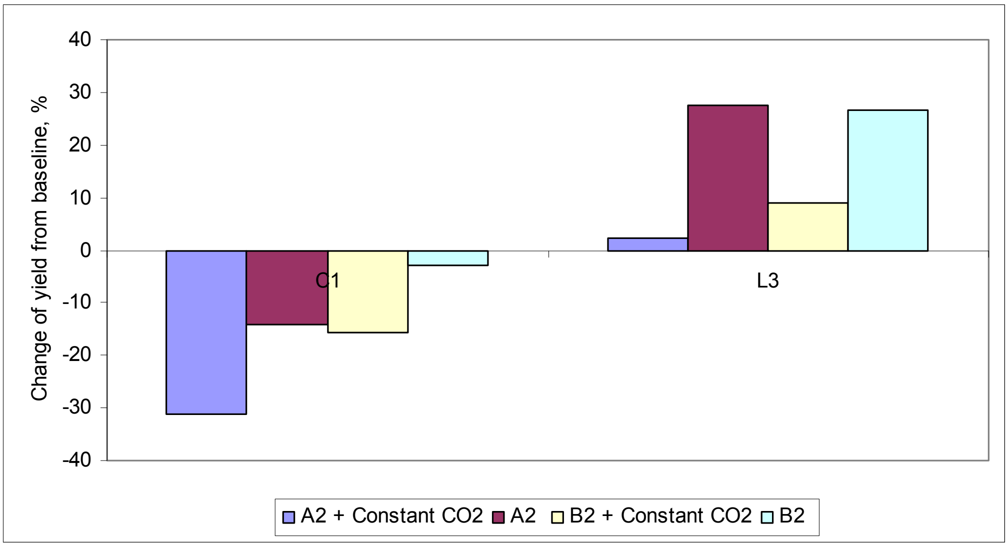


Figure 6.17 Change in projected yield of main rainfed rice for varying and constant CO_2 concentrations in the atmosphere

Krishnan et al. (2007) studied the impact of elevated CO_2 and temperature on rice yield in 10 different sites across eastern India using ORYZA1 and INFOCROP models. They found that for every 1°C increase in temperature, ORYZA1 and INFOCROP rice model predicted average yield changes of -7.2 and -6.7%, respectively, at the CO_2 level of 380 ppm. But increases in the CO_2 concentration up to 700 ppm led to the average yield increases of about 30.7% by ORYZA1 and 56.4% by INFOCROP rice. Matthews et al. (1997) simulated the impact of climate change on rice production in Asia using ORYZA1 and SIMRIW models. They found that at 340 ppm CO_2 level, ORYZA1 predicted an average -7.4% changes in yields for every 1°C increase in temperature, while SIMRIW predicted -5.3%°C^{-1}. A doubling of CO_2 concentration resulted in a 36% increase in yield according to ORYZA1, but only 24% according to SIMRIW. The results of this study support the findings of both Matthews et al. (1997) and Krishnan et al. (2007).

6.8.2. Irrigated rice

Irrigated rice is grown during the period of November to March, the lowest rainfall period of the year. The average (1981-2005) provincial rainfall during this period ranges (spatially among the provinces) from 2.7 to 18.0% (37 mm to 308 mm) of total rainfall in Laos, 2.3 to 6.1% (33 mm to 82 mm) in Thailand, 3.2 to 12.4% (51 mm to 239 mm) in Cambodia, and 12.5 to 19.2% (206 mm to 397 mm) in Vietnam. The rainfall also varies highly from year to year. Total rainfall during this period for the baseline condition (1985-2000) varies from 0 to 811 mm in site L1 in Laos, 3 to 120 mm in site T3 in Thailand and 68 to 395 mm in site V3 in the Mekong Delta of Vietnam. Table 6.8 presents the change in projected rainfall and PET during the growing period of irrigated rice. Projected rainfall decreases in all sites compared to the baseline average of 1985-2000 except for scenario B2 for site T3 where there is almost no change. But compared to the baseline period of 1996-2000, projected rainfall will be higher in L1 and lower in sites T3 and V2 for both scenarios. In site L1, rainfall during the growing period from 1985 to 1988 was comparatively very high (700-800 mm). The average baseline rainfall excluding these years is 47 mm compared to which projected rainfall would also increase. Projected PET is expected to increase (Table 6.8); the highest increase will be in site V3.

Table 6.8 Change in average rainfall and PET during the growing period of irrigated rice for baseline, A2 and B2 scenario

Site	Baseline rainfall, mm		Change in rainfall with respect to 1985-2000 average, mm		Change in rainfall with respect to 1996-2000 average, mm		Baseline average (1996 – 2000) PET, mm	Change, mm	
	Average of 1985-2000	Average of 1996-2000	A2	B2	A2	B2		A2	B2
L1	248	36	-120	-128	+91	+83	714	+7	+24
T3	48	67	-3	+2	-21	-16	536	+11	+9
V2	210	304	-51	-6	-144	-100	495	+148	+124

Due to the increase in PET and decrease in rainfall, the irrigation requirements increase. If the increased irrigation requirements are met, then there will be no impact on yield of rice due to change in rainfall and PET. In practice, irrigation requirements vary from year to year due to variability in rainfall and PET, and farmers supply water to the field based on demand. Therefore, farmers will gradually adapt to the increased requirements due to climate change and the impact of this will be the increased water diversion from the river. Table 6.9 shows the irrigation requirements estimated using the models at MRC-DSF for baseline, A2 and B2 scenarios. Projected irrigation diversion will increase about 11% compared to the baseline requirements for both A2 and B2 scenarios. The highest increase will be in the Mekong Delta of Vietnam ranging from 15 to 18% (Table 6.9). Eastham et al. (2008) estimated the increase in irrigation requirements for the basin as 3 to 8%.

Table 6.9 Total irrigation requirements of different scenarios for dry season irrigated rice

Area	Irrigation requirements, MCM			Increase in requirements with respect to baseline (%)	
	Baseline	A2	B2	A2	B2
Great Lake	4269	4535	4533	6.2	6.2
Areas upstream of Kratie	14076	15089	14713	7.2	4.5
Vietnam Delta	17173	19779	20211	15.2	17.7
Total	35519	39403	39457	10.9	11.1

Diversion of more irrigation water due to increased requirements may have several impacts as follows:

The existing irrigation system delivery capacity may not be enough to deliver the increased requirements; hence, there may be a need to increase the capacity.

Increased diversion for irrigation will reduce the dry season flow in the river which may significantly affect the river ecology and overall environment. There could be more salt water intrusion in the Mekong Delta of Vietnam.

The cost of production would increase due to the cost of additional irrigation.

In simulating the yield of dry season irrigated rice, we have considered adequate irrigation supply to the field and that crop does not suffer from water stress. The irrigated yield effects are, therefore, from the temperature changes and atmospheric CO_2 concentration only. To distinguish the impact of temperature and atmospheric CO_2, we ran the model with varying CO_2 concentration and keeping CO_2 concentration constant at the reference level for future projection of both scenarios. The results are presented in Figure 6.18. With varying CO_2 concentration, projected yield increases 28.0 and 9.6% for site L1, 22.0 and 14.3% for site T3, 20.3 and 14.9% for site V2, respectively for A2 and B2 scenario.

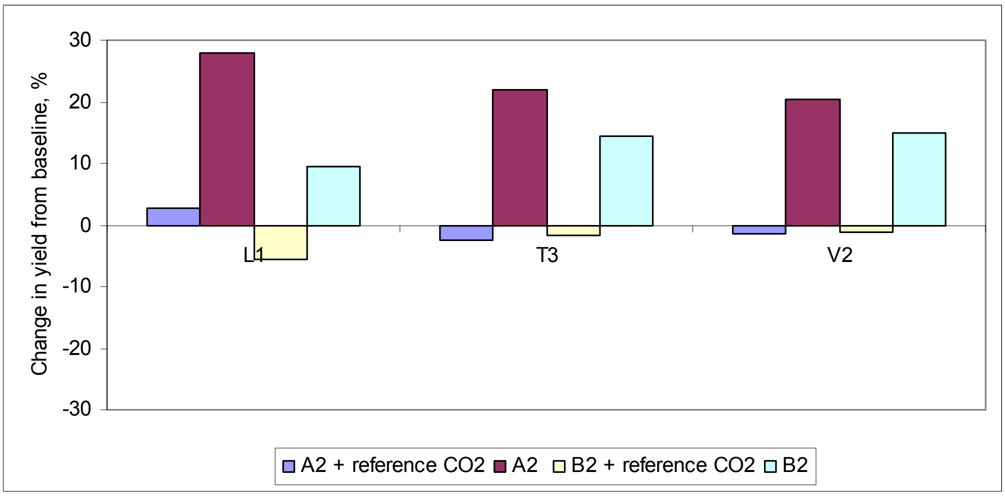


Figure 6.18 Change in average projected yield of irrigated rice for varying and constant CO_2 concentrations in the atmosphere

Due to changes in temperature only (Table 6.10), projected yield decreases from 1.2 to 2.5% in sites T3 and V2 for both scenarios. But in site L1, projected yield increases (2.7%) in scenario A2 and decreases (5.5%) in scenario B2. The reason for this could be the increase or no change in temperature in A2 compared to the decrease in temperature in B2 during the growing period and at the initial and development stage (Table 6.10). Low temperature can cause stress that affects crop development and growth (at initial and development stage) which ultimately affects yield (Raes et al., 2009a; Baker et al., 1992). The average number of days per year temperature is less than 8°C is also higher in B2 than that in A2 (Table 6.11). While increase in average minimum temperature in A2 helped increase yield, the decrease in minimum temperature may have affected the yield negatively in B2.

Table 6.10 Comparison of average maximum and minimum temperature during the total growing period, initial and development stage and the flowering stage of dry season irrigated rice for baseline, A2 and B2 scenarios

Site	Total growing period						Initial and development stage						Flowering stage					
	Max temp, °C			Min temp, °C			Max temp, °C			Min temp, °C			Max temp, °C			Min temp, °C		
	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2	Baseline temp	Change A2	Change B2
L1	29.7	0.0	-0.3	16.6	0.0	-0.3	28.3	0.2	-0.3	16.2	0.2	-0.3	29.8	-0.4	-0.6	15.6	-0.3	-0.5
T3	30.7	+0.2	0.0	18.0	+0.2	-0.1	29.8	0.5	0.1	18.0	0.4	0.0	30.4	-0.2	-0.4	16.7	-0.3	-0.5
V2	26.9	+0.7	+0.6	25.9	+0.4	+0.5	27.1	1.2	0.7	26.0	0.7	0.7	26.4	+0.3	+0.4	25.5	+0.2	+0.3

Table 6.11 Comparison of average number of day/year maximum temperature is above 35 and 40°C for baseline, A2 and B2 scenarios at the flowering stage of dry season irrigated rice

Site	Total growing period						Initial and development stage						Flowering stage					
	Maximum temp > 35°C			Minimum temp < 8°C			Maximum temp > 35°C			Minimum temp < 8°C			Maximum temp > 35°C			Minimum temp < 8°C		
	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2	Baseline	A2	B2
L1	0.0	14.6	14.9	0.0	7.6	7.8	0.0	1.8	2.1	0.0	2.9	3.6	0.0	4.0	4.0	0.0	4.0	3.6
T3	0.0	13.2	14.0	0.0	2.1	1.3	0.0	3.1	3.8	0.0	0.8	0.5	0.0	1.7	2.1	0.0	1.1	0.7
V2	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

During the flowering stage of the crop, both projected maximum and minimum temperature decreased compared to the baseline temperature and equal number of days (4 days/year) maximum temperature was above 35°C. Therefore, the impact on yield could be for the change and duration of the minimum temperature during the initial and development stage only. Comparing these with the results of the main rainfed rice of the site L1 (Table 6.7), we can find that number of days per year maximum temperature was greater than 35°C, was less in rainfed rice than that in irrigated rice. This indicates that there may be no or negligible impact of temperature on the yield of main rainfed rice. The impact was predominantly due to change in rainfall and increase CO_2 concentration in the atmosphere only. Nelson et al. (2009) showed that yields of important crops in Southeast Asia fall substantially in both scenarios unless CO_2 fertilization is effective in farmers' fields.

6.8.3. Maize

Maize is the most important crop in the lower Mekong Basin among the upland crops in terms of harvested area (Table 6.2). Maize cultivation has doubled in Laos and Cambodia during the period of 1993-2003 and increased fourfold in Vietnam during the period of 1995-2004 (Mainuddin et al., 2008; Mainuddin and Kirby, 2009). In Thailand, the cultivated area decreased slightly over the same period. Table 6.12 shows the baseline rainfall, PET and yield with projected change due to climate variation for A2 and B2 scenarios. Compared to the average baseline rainfall of the period 1985-2000, the projected rainfall is expected to increase in all sites except site C3 (for both scenario) and L2 (only for A2 scenario). Projected PET is also increases due to increase in maximum and minimum temperatures (Table 6.12 and 6.13). The increase of PET is highest in site V1 (21.1 and 25.4%), and the lowest in sites C2 (3.5% for both A2 and B2) and T4 (4.0 and 3.1%). However, increased PET is much lower than the projected rainfall. There is no negative impact of these changes on the yield of maize. Yield increases in all sites (Table 6.12) for both scenarios. The increase is higher in A2 scenario (24.7-27.1%) compared to B2 scenario (16.0-18.6%). The increase in yield is almost uniform with very small variation from site to site.

Figures 6.19 and 6.20 show the exceedence probability curve of yield under climate change scenarios for all 8 locations. It is evident from the Figures that, there is no crop failure (no harvest) during the simulation period (2010-2050) and year to year variation in yield is very low. The coefficient of variation in yield is around 0.08 for A2 scenario and 0.06 for B2 scenarios for all sites.

Maize is very sensitive to frost, particularly in the seedling stage (in the month of May for these sites) but it tolerates hot and dry atmospheric conditions so long as sufficient water is available to the plant and temperatures are below 45°C (Doorenbos and Kassam, 1979). For all sites minimum temperature is highest during the seedling stage of maize and within the growing season the temperature is well above the temperature to crease frost. So there is no impact on yield due to frost. Number of days per year maximum temperature is above 45°C is also negligible (Table 6.13). So it is also highly unlikely to have any impact on the yield.

Table 6.12 Comparison of rainfall, temperature, PET for the growing period, and yield of maize

Site	Baseline (1985-2000) rainfall, mm	Change in rainfall, mm		Baseline average PET, mm	Change in PET, mm		Baseline average yield, tonne/ha	Change in yield, tonne/ha	
		A2	B2		A2	B2		A2	B2
L2	1872	-118	+59	446	+63	+68	2.88	+0.71	+0.46
L3	1078	+45	+27	379	+40	+36	2.33	+0.57	+0.37
T3	857	+327	+323	330	+26	+19	3.93	+1.02	+0.68
T4	461	+106	+110	442	+18	+14	3.06	+0.77	+0.50
C2	577	+9	+34	464	+16	+16	1.31	+0.33	+0.22
C3	1131	-46	-10	430	+38	+46	1.49	+0.39	+0.25
V1	1367	+142	+59	355	+75	+90	2.18	+0.59	+0.41
V3	636	+12	+31	502	+34	+36	4.57	+1.17	+0.73

Table 6.13 Comparison of maximum and minimum temperature for the growing period of maize

Site	Baseline average maximum temperature, °C	Change in maximum temperature, °C		Baseline average minimum temperature, °C	Change in minimum temperature, °C		Number of days/year maximum temperature > 45°C		
		A2	B2		A2	B2	Baseline	A2	B2
L2	32.1	+0.5	+0.6	24.8	+1.1	+1.2	0.0	0.9	1.7
L3	32.3	+0.4	+0.4	23.5	+1.1	+1.0	0.0	0.3	0.4
T3	32.5	+1.0	+1.1	24.5	+1.0	+1.1	0.0	0.4	0.4
T4	32.4	+1.0	+1.1	24.0	+0.9	+1.0	0.0	0.0	0.0
C2	32.6	+0.9	+1.1	24.3	+0.8	+1.0	0.0	0.0	0.0
C3	32.3	+1.1	+1.3	23.8	+1.1	+1.3	0.0	0.1	0.1
V1	23.7	+1.2	+1.6	22.0	+0.9	+1.2	0.0	0.0	0.0
V3	28.7	+1.3	+1.4	26.8	+0.8	+1.0	0.0	0.0	0.0

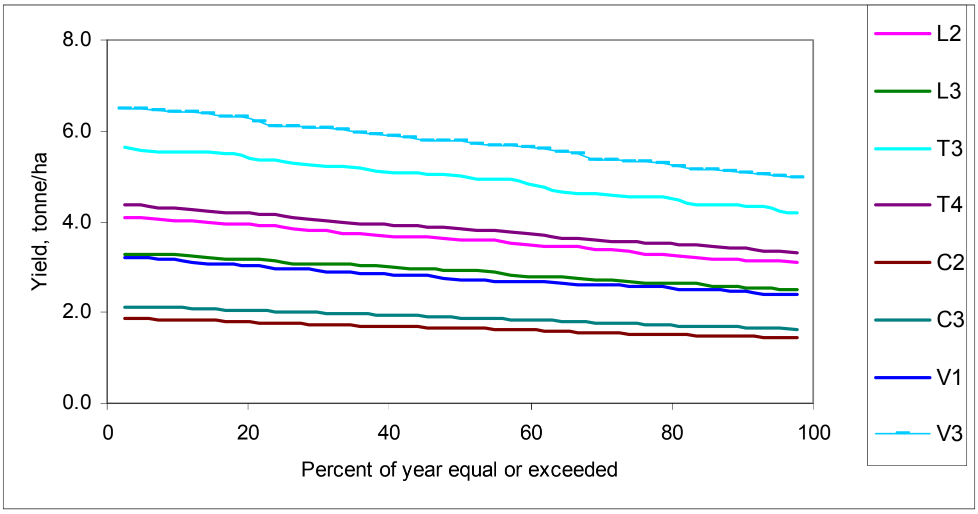


Figure 6.19 Exceedance probability showing the projected yield of maize for A2 scenario

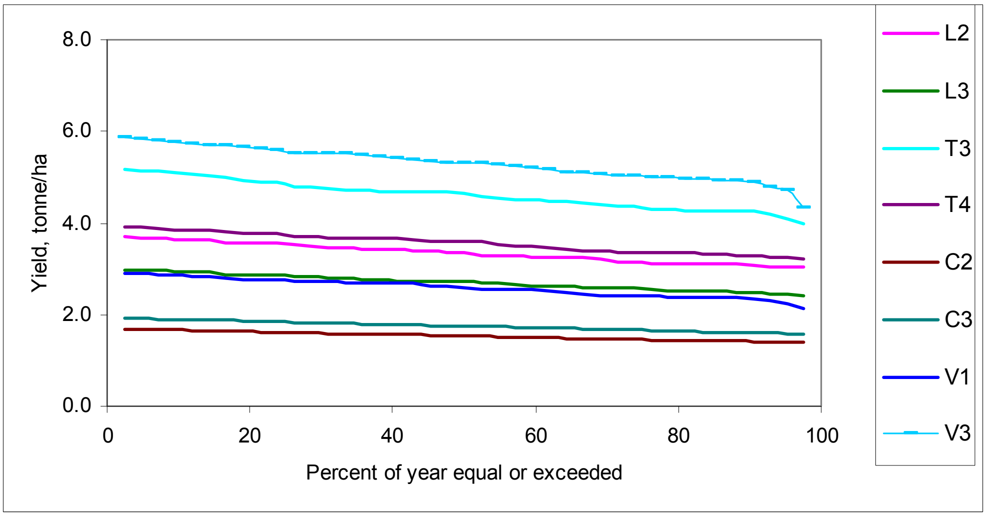


Figure 6.20 Exceedance probability showing the projected yield of maize for B2 scenario

Chinavanno (2004), based on analysis done using the data of Khon Kaen province of Northeast Thailand, showed that different scenarios of CO_2 conditions affected the flowering and maturity days of maize and that yield would increase. To see the impact of atmospheric CO_2 concentration on the yield, we ran the model considering CO_2 at the reference level for both scenarios. Figure 6.21 compares the change in yield from the baseline condition for both varying and constant CO_2 concentration in the atmosphere. It is clearly evident from the Figure (6.21) that there is almost no impact on the yield of maize due to climatic variations (rainfall, temperatures, PET). The increase in yield is due to the increase in CO_2 concentration in the atmosphere. Eastham et al. (2008) also concluded that there is no impact on the yield of maize in the basin due to change in rainfall, PET and temperatures.

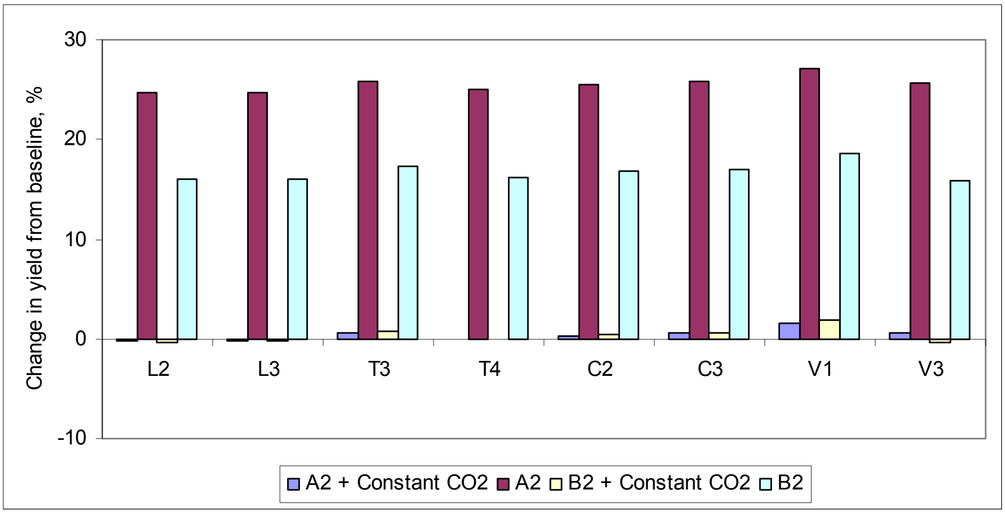


Figure 6.21 Change in projected yield of maize for varying (A2 and B2) and constant CO_2 concentrations in the atmosphere

6.9. Discussion

Estimates of impact of climate change on crop production could be biased depending upon the uncertainties in climate change scenarios, region of study, crop models used for impact assessment and the level of management (Aggarwal and Mall, 2002). In this study, we have used PRECIS regional climate model based on ECHAM4 Global Circulation Model, one of the 24 GCMs used in the 4th Assessment Report of the IPCC. There are significant differences between GCMs with regard to climate changes simulated at the regional scale, particularly for precipitation (Chiew et al., 2008; Eastham et al., 2008). Therefore, GCMs can at best be used to suggest the likely direction and rate of change of future climates (Krishnan et al., 2007). There are several crop models as well for the same crop that can be employed for impact assessment of climate change and the results vary from model to model (Krishnan et al., 2007; Aggarwal and Mall, 2002). PRECIS regional climate model based on ECHAM4 GCM has been used by TKK and SEA START RC (2009) to see the water and climate change in the lower Mekong Basin but not used in to see the impact on agricultural productivity. Chinnavanno (2004), Chinvanno and Snidvongs (2005), and SEA START RC (2006) used Conformal Cubic Atmospheric Model (CCAM) to generate data for impact studies using crop models such as MRB Rice Shell (developed by Multiple Cropping Center, Chiang Mai University, Thailand) and DSSAT (Jones et al., 2003). None used the model AquaCrop in this region. However, the trend of the results (impact of climate change on crop productivity) of this study is grossly similar to that of the other studies as discussed in the following paragraphs.

Probably the earliest study on the impact of climate change on rice production in the Southeast Asian regions was reported by Matthews et al. (1995, 1997). Matthews et al. (1997) simulated potential rice yield in South and Southeast Asian countries including Thailand using two crop simulation models, ORYZA1 (Kropff et al., 1994) and SIMRIW (Horie, 1987). The crop models were calibrated for the *indica* variety IR64 for all sites. They have generated climate data using three separate GCMs; General Fluid Dynamics Laboratory (GFDL) model, Goddard Institute of Space Studies (GISS) model and United Kingdom Meteorological Office (UKMO) model. The change in temperature considered as +4.0, +4.2 and + 5.2°C respectively for the three models. For Thailand ORYZA model predicted changes in regional rice production of + 9.3, -4.7 and -0.9 for the GFDL, GISS and UKMO scenarios, respectively. The corresponding changes predicted by SIMRIW were +4.2, -10.4 and -12.8%. The main reason of this change is the impact of increased temperature on the spikelet fertility of that particular variety of rice. When a more tolerant (to temperature) genotype was used as varietal adaptation, ORYZA1 model predicted that rice production in Thailand would change by +40.7, +38.4, and +40.0% under the GFDL, GISS and the UKMO scenarios respectively, while SIMRIW predicted corresponding changes of +18.7, 24.9 and 25.3%. The change in temperature considered as +4.0, +4.2 and + 5.2 respectively for the three models. In this study, change in temperature for the growing period of main rained rice in Thailand (Table 6.6) varies from +1.0 of +1.5°C, much lower than considered by Matthews et al. (1997). The impact of this was found very low or negligible in this study. Therefore, the result of this study (increase in yield up to about 28%) is comparable and in agreement, in general, to the result of varietal adaptation scenario of Matthews et al. (1997).

The Ministry of Environment of Cambodia (Ministry of Environment, 2002 cited in ICEM, 2009) attempted to assess the country's future climate using two GCMs; the CCSR (Center for Climate System Research, University of Tokyo) and CSIRO (Commonwealth Scientific and Industrial Research Organization, Australia) models. The global warming scenarios used in the analysis were the SRES A2 and SRES B1. They reported that the potential impacts of climate change include changes to rice productivity, with increases in wet season crops in some areas and decreases in others. Under elevated CO_2, yields of wet season rice might increase. However, there is a chance that under changing climate, rice yield in some provinces would be more variable than under current conditions. The results is very similar to that reported here; yield increases in sites C2 and C3 and decreases in C1 and C4 for A2 scenarios and decreases in all sites for B2 scenario. The CV of projected yield, which indicates the variability in yield, is much higher than the CV of current observed yield as shown in Table 6.4.

Chinvanno (2004) simulated the yield of rice, maize, sugarcane and cassava by MRB-rice shell and DSSAT model using simulated weather data from the CCAM (Conformal Cubic Atmospheric Model) climate model, which cover three periods (year 1980-89, 2040-49 and 2066-75) in fields in Laos and northeast Thailand. Whilst the results show that climate change is likely to have a positive impact on rice, maize and sugarcane yield in the future, yield of cassava is projected to decrease. The results of this study are broadly similar to that of Chinvanno (2004).

Chinvanno and Snidvongs (2005) studied the potential impact of climate change using the field experiment data set-up in Chiang Rai (in the zone of T3), Sakhon Nakhon (in the zone of T1) and Sa Keaw (in the zone of T3) (province 19, 25 and 40, respectively in Figure 6.1) provinces of Thailand. The study used the MRB-Rice Shell, which links the CERES-Rice model with the spatial databases, found that there is no significant difference between the observed and simulated yield of rice at dry, medium and wet years climate change scenarios. The results of this study indicate that yield would increase about 8-15% in the site representing these provinces. SEA START RC (2006) using DSSAT model shows that yield of rice in the study sites (in the zone of T1, Ubon Ratchathani province, No. 30 in Figure 6.1) in Thailand will increase by 3-6%; however, yields may reduce by almost 10% in the study site in Laos (site L1, Savannakhet province, No. 13 in Figure 6.1). In this study, we have found that yield would also increase about 8 to 15% in the site in Thailand and would increase 10% in A2 scenario and decrease over 4% in B2 scenario in the site in Laos.

According to SEA START RC (2006), rice production in the Mekong River delta in Vietnam tends to be severely impacted by climate change, especially summer-autumn (main rainfed rice) crop production, of which the yield may reduce by over 40%. This study indicates that yield would decrease by about 11% in this area. However, results of the study by Hoanh et al. (2003) using SWAP model in a location in the Mekong River Delta show that, for A2 scenario, rice production will increase substantially in the future, about 10% in 2010- 2039 to 40% in 2070-99. The main reasons of yield increase are changes in CO_2 concentration and temperature. The B2 shows only a small increase, about 10% in 2070-99.

Eastham et al. (2008) assessed all 24 GCMs and selected 11 out of them based on their capacity to represent seasonal temperature and precipitation in the basin (including ECHAM4) to generate climate data for 2030. The generated data (median condition) were then used to assess the impact of climate change on crop yield at sub-basin level (Kirby et al., 2010) using FAO (Doorenbos and Kassam, 1979) yield response function (which does not take into account the impact of temperature and CO_2 directly on plant growth). They suggested that yield of rainfed rice would slightly decrease in the upper part of Laos (up to 1.5%) and increase (up to 3.3%) in the sub-basins comprising the areas of northeast Thailand. There is no change in yield in the lower part of the basin, areas within Cambodia and Vietnam. In this study, we have found that yield would also increase in northeast Thailand and in general would decrease in the lower part of the basin for the period of 2010-2050.

For irrigated rice, Eastham et al. (2008) estimated that for the median climate condition of 2030, the yield of irrigated rice in the lower Mekong Basin would decrease by 2% for the basin if irrigation requirements are not met compared to the 1.2 to 2.5% decrease due to temperature change in this study. Projected irrigation diversion would increase by about 11% compared to the 3 to 8% in the study by Eastham et al. (2008). For maize, similar to the results of this study, Eastham et al. (2008) also concluded that there is no impact on the yield of maize in the basin due to change in rainfall, PET and temperatures.

As discussed above, there was considerable difference in the impact of climate change on rainfed rice yields calculated by different crop models using climatic data generated by different GCMs. The impact also varies from location to location even within a country. Krishnan et al. (2007) showed that average yield increases of about 30.73% by one model (ORYZA1) and 56.37% by another model (INFOCROP) for the same locations in India. Aggarwal and Mall (2002) showed that magnitude of this impact can be biased up to 32% depending on the uncertainty in climate change scenario, level of management and crop model used. Though the trend of the results of this study in general are similar to that of the other studies in the region, these uncertainties need to be kept in view while interpreting the possible impacts of the projected climate change scenarios on agriculture.

The study does not take into account the impact of extreme events such as floods, extreme drought, sea level rise, cyclones, storm, etc. which may become more frequent with higher intensity due to climate change. The current GCMs are not able to predict the frequency of these catastrophic events such as hurricanes, floods or even the intensity of monsoons, all of which can be important in determining crop yields (Krishnan et al., 2007). Flooding, salinity intrusion and sea level rise (as shown in Table 4.15 to 4.17 and Figure 4.8) may have a severe impact on the agriculture of the Mekong Delta. With a sea level rise (SLR) of 1.0 metre, which is predicted to occur by 2100, 31% of the Mekong River Delta may be inundated affecting 27% of the population of the Delta (Carew-Reid, 2007). Wassmann et al. (2004) showed that rice production will be affected through excessive flooding in the tidally inundated areas and longer flooding periods in the central part of the Vietnamese Mekong Delta as a result of the sea level rise due to climate change. These adverse impacts could affect all three cropping seasons, main rainfed crop, winter-spring crop and summer-autumn crop unless preventative measures are taken. SEA START RC (2006) based on farmer interview in Thailand and Lao PDR stated that extreme climate events may cause loss of rice productivity by average 30-50% from flood in moderate flood year.

6.10. Conclusions

The following key conclusions can be drawn from the results of the modelling described in this Chapter.

1. For A2 scenario, with the current planting date, yield of main rainfed rice may increase by about 10-28% in Laos and 8-17% in Thailand by 2050. In part of Cambodia, yield may increase by about 6% and in other part yield may decrease by about 14%. In the Central Highlands of Vietnam, yield of rainfed upland rice may increase by 6%. Yield of rainfed rice may decrease by 2% in the upper half of the Mekong Delta while may increase by 11% in the lower half of the Delta.
2. For B2 scenario, yield of main rainfed rice may increase by about 15 to 28% on Laos and Thailand (except some area of Laos where yield may decrease slightly with the current planting date). However, yield may decrease all over Cambodia (up to 9%) and Vietnam (up to 11%).
3. Yield increase is higher in A2 scenario while the decrease is higher in B2 scenario.
4. The impact on the yield of rainfed rice is mainly due to the variability of rainfall during the growing period of rainfed rice and increased CO_2 concentration in the atmosphere. The impact of increased temperature is negligible on rainfed rice.
5. Increased CO_2 concentration in the atmosphere help increase yield of rice by 25% in A2 scenario and 16% in B2 scenario. This offsets the negative impact of other climatic variables such as temperature and heat, and contributes to net positive increase in yield.
6. There is high variation in yield from year to year indicating higher uncertainty of the climatic variables.
7. For irrigated rice, projected irrigation diversion is about 11% higher compared to the baseline requirements for both A2 and B2 scenarios. The highest increase will be in the Mekong Delta of Vietnam ranging from 15 to 18%.
8. Temperature has adverse impact on the yield of irrigated rice (yield decreases up to 6%). However, increased CO_2 concentration in the atmosphere offsets the negative impact and may increase yield up to 28% in Laos, 22% in Thailand and 15% in Vietnam if full irrigation is provided.
9. Yield of maize may increase all over the lower basin by about 27% in A2 scenario and 19% for B2 scenario. The increase is predominantly because of increased CO_2 concentration in the atmosphere.
10. The trend of the results is grossly similar to that of the other studies in the region.
11. The study does not take into account the impact of extreme events such as floods, extreme drought, sea level rise, cyclones, storm, etc., the impact of which on the productivity of the crop could be significant.

The conclusions are based on modelling rice yields with current management (planting dates, fertiliser, etc.). In the next chapter, we consider the impact of management adaptations.

7. ADAPTATION STRATEGIES, AND IMPLICATION ON BASIN'S FOOD SECURITY

7.1. Introduction

Various definitions of adaptation are available in literature. Smithers and Smit (1997) defined adaptation as "changes in a system in response to some force or perturbation, which in this case is related to climate". IPCC (2001) refers adaptation to "adjustments in ecological, social or economic systems in response to actual or expected stimuli and their effects or impacts". It involves adjustments to reduce the vulnerability of communities, regions, or activities to climatic change and variability (IPCC, 2001).

FAO (2007b) classifies adaptation to two main types: autonomous and planned adaptation. Autonomous adaptation is the reaction of, for example, a farmer to changing precipitation patterns, in that s/he changes crops or uses different harvest and planting/sowing dates. This is also called short-term adaptation (FAO, 2007b). Planned adaptation measures are conscious policy options or response strategies, often multi-sectoral and long-term in nature, aimed at altering the adaptive capacity of the agricultural system or facilitating specific adaptations. For example, deliberate crops selection and distribution strategies across different agriclimatic zones, substitution of new crops for old ones and resource substitution induced by scarcity (Easterling, 1996).

ADB (2009b) has listed some widely used adaptation strategies for agriculture sector based on the general trends in the change in temperature and shift in rainfall pattern. These are:

a) Changing in the planting dates

b) Developing of drought resistant varieties

c) Adapting of flood tolerant crops and crop varieties

d) Following conservation management practices

e) Changing tillage practices

f) Increasing water use efficiencies

g) Enhancing seed bank

h) Introducing high intensity cropping system

i) Utilizing crop residue and biomass

j) Intercropping and crop rotation

k) Diversifying into non-farm activities

Many of these adaptation strategies are not relevant to this study. Of these, the easiest adaptation is to adjust the sowing dates (Krishnan et al., 2007). Previous studies had suggested that adjusting sowing dates might be a simple and powerful tool for mitigating the effects of a potential global warming (Baker and Allen, 1993). Adjustment of management practices may also help to offset any detrimental effects of climate change on rice production (Krishnan et al., 2007). Farm level analyses have shown that large reductions in adverse impacts from climate change are possible when adaptation is fully implemented (Mendelsohn and Dinar 1999).

Among the crops considered in the study (described in Chapter 6), only the productivity of main rainfed rice is adversely affected in some parts of the basin. The adaptation strategies considered here are, therefore, for main rainfed rice.

7.2. Adaptation strategies for rainfed rice

7.2.1. Shifting planting date

We have tested following adaptation strategies related to shifting planting date.

Adaptation strategy 1: Shifting the planting date backward by two weeks from the planting date used in baseline condition for all sites for both A2 and B2 scenarios (designated as A2+2WBP and B2+2WBP)

Adaptation strategy 2: Shifting the planting date forward by two weeks from the planting date used in baseline condition for all sites for both A2 and B2 scenarios (designated as A2+2WFP and B2+2WFP)

Figure 7.1 shows the comparison of baseline yield with the average yield of main rainfed rice for A2 scenario with baseline, two weeks backward and two weeks forward planting date. Percentage change in yield with respect to the baseline is shown in Figure 7.2. As shown in the figure, shifting the planting date can further increase yield (in some sites where yield increases with baseline planting date) or minimize the negative impact in the areas where yield is adversely affected (all sites in Thailand except T4, all sites in Cambodia and Vietnam). Baseline planting produces higher yield in all sites in Laos and site T4 in Thailand. Backward planting increases yield in the remaining sites (T1, T2, and T3) in Thailand. Shifting the planting date forward greatly increases yield in sites in Cambodia and Vietnam. The changes in some sites are quite significant. In site T2, yield increases 34% from baseline yield for two week backward planting while decrease about 15% for two weeks forward planting. In site V1, yield decreases 17% for two weeks backward planting and increases 24% for two weeks forward planting.

For scenario B2, two weeks forward planting increase yield or offset negative yield in all sites except L2, L3 and T2 (Figures 7.3 and 7.4). With baseline planting date for B2, yield decreased (up to 11%) in all sites in Cambodia and Vietnam and one site (L1) in Laos. Shifting the planting date two weeks forward greatly reduces this negative impact (maximum reduction is 6% in V3) in 4 sites (C3, C4, V2 and V3) and increases (from the baseline average yield) yield after offsetting the negative yield (up to 7.3%) in the remaining sites (L1, C1, C2 and V1).

As discussed in Section 6.8.2, there may be no impact of temperature (both positive and negative) on the yield of main rainfed rice. Therefore, change in yield due to shifting the planting date is mainly due to the change in rainfall (both total amount and distribution over the growing period). Figures 7.5 and 7.6 show the change in rainfall from the baseline condition for different planting dates for A2 and B2 scenario, respectively. In general, except few sites, higher increase in yield is correlated to the increase in total amount of rainfall for both scenarios (compare the figure 7.2 and 7.5; 7.3 and 7.6). For example, in Thailand for backward planting total amount of growing season rainfall is higher so is the yield.

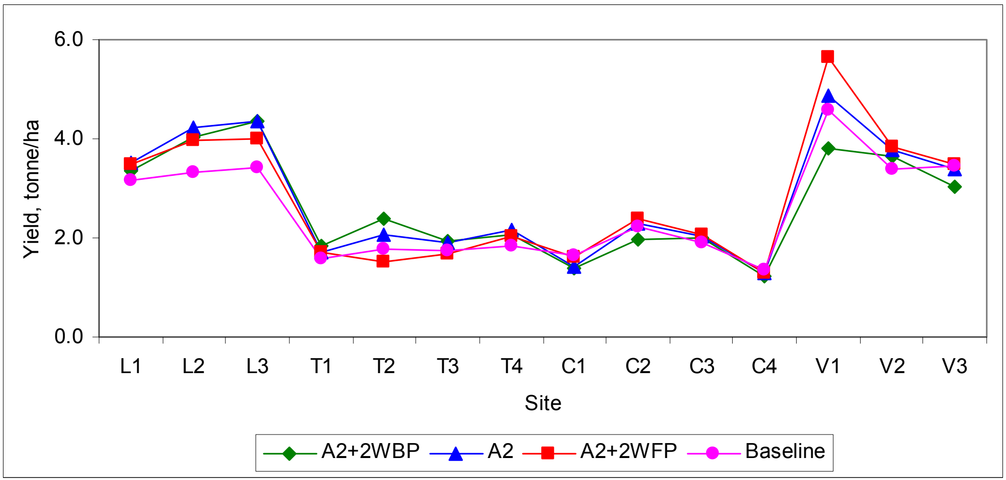


Figure 7.1 Comparison of average yield of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for A2 scenario

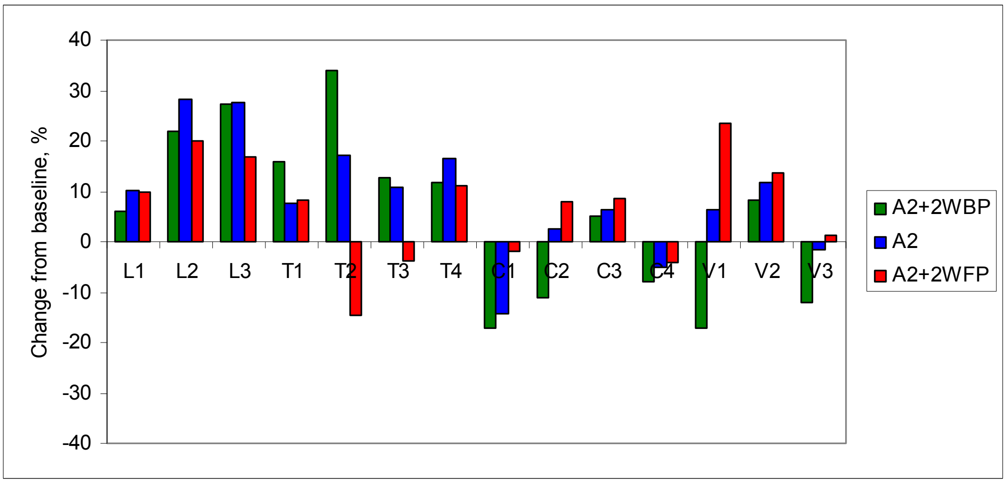


Figure 7.2 Change in average yield of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for A2 scenario

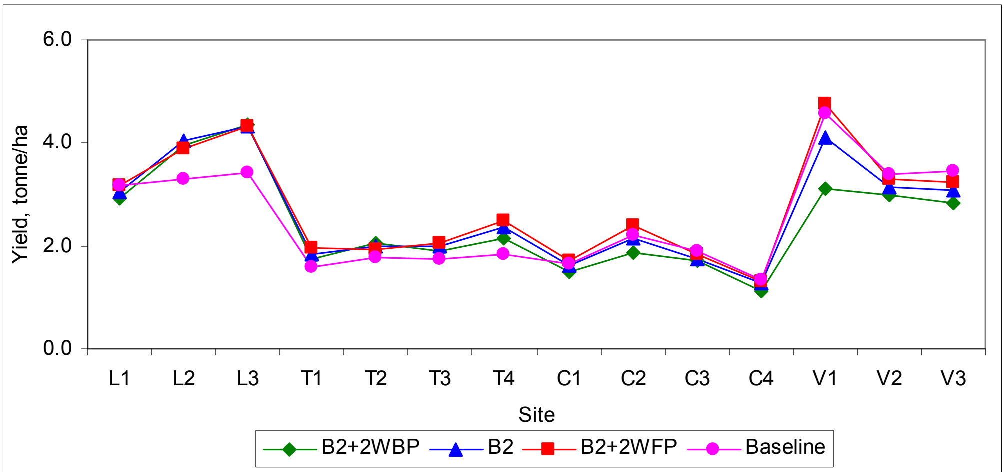


Figure 7.3 Comparison of average yield of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for B2 scenario

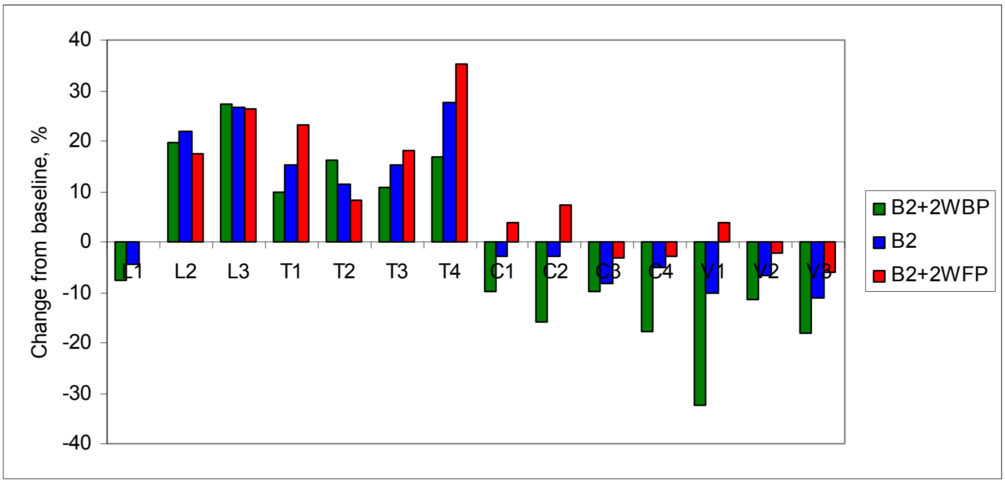


Figure 7.4 Change in average yield of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for B2 scenario

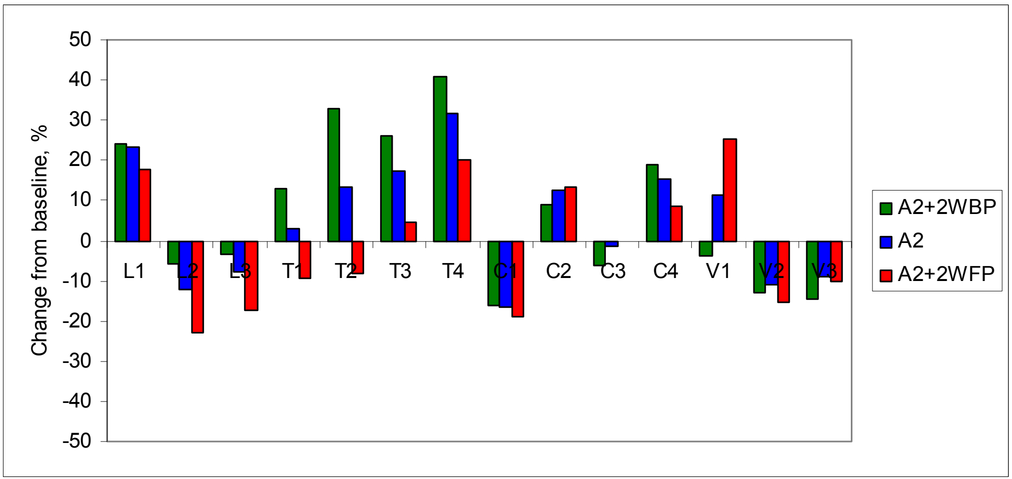


Figure 7.5 Change in total growing period rainfall of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for A2 scenario

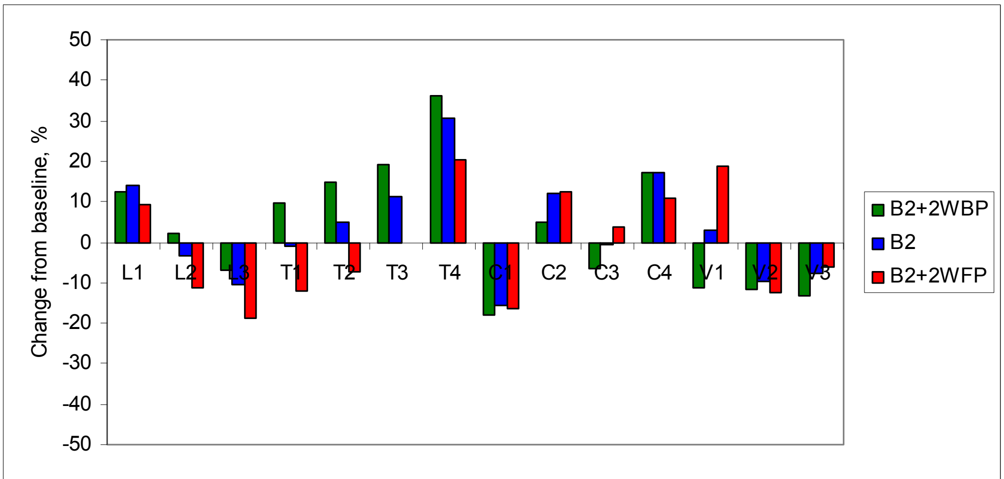


Figure 7.6 Change in total growing period rainfall of main rainfed rice with baseline, 2 weeks backward and 2 weeks forward planting for B2 scenario

In addition to the amount of rainfall, due to shift in planting date, crops may have experienced water stress or relief during the critical stages of crop growth, which may have also affected yield. For example, for site L1, with baseline planting date, there is no harvest in 2013 and 2015. Shifting the planting date backward increases the year with no harvest to three (2013, 2015 and 2021), while shifting the planting date forward decreases the number of years with no harvest to zero. Table 7.1 and 7.2 show the number of years of no harvest during the simulation period for the best planting date (having highest increase or lowest decrease among the baseline, backward and forward planting date) for A2 and B2 scenario, respectively. Number of years with no harvest decreases in shifting the planting to the adaptive date (either backward or forward) compared to the baseline planting date for all sites. One of the reasons of higher average yield in shifting the planting to the adaptive date is the less numbers year with no harvest. With adaptive planting date, year to year variation (represented by CV) in yield during the simulation period also decreases compared to that of baseline planting (Table 7.1 and 7.2).

Considering the best planting date of each site, basin-wide impact on the yield of main rainfed rice is shown in Figures 7.7 and 7.8). These map have been created by up-scaling or extrapolating the results of individual sites to the respective zones. Results suggest that only a small portion of the basin in Cambodia will have modest negative yield (up to 4.3%) for A2 scenario. For B2 scenario, in addition to some area in Cambodia yield will also decrease in the Mekong Delta up to 5.9%. Though it was not tested, it is very unlikely that shifting the planting date further backward or forward will reduce the negative impact on yield.

Though shifting the planting date reduces the negative impact of climate change on rainfed rice for sites C1 and C4 in scenario A2 and C3, C4, V2 and V3 for scenario B2, it does not completely offset the negative impact. Therefore, some other adaptation strategies may be needed for these sites.

Table 7.1 Adaptive planting date, change in average yield (compared to baseline average yield) and comparison of CV and number of years with no harvest for baseline planting date and adaptive planting date for A2 scenario

Site	Adaptive planting date for higher yield	No of year with no harvest with baseline planting date	No of year with no harvest with adaptive planting date	CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date (%)
L1	Baseline	2	2	0.32	0.32	10.3
L2	Baseline	0	0	0.16	0.16	28.1
L3	Baseline	0	0	0.19	0.19	27.6
T1	Backward	0	0	0.20	0.22	16.0
T2	Backward	0	0	0.20	0.18	33.9
T3	Backward	1	2	0.32	0.35	12.8
T4	Baseline	2	2	0.45	0.45	16.5
C1	Forward	6	5	0.58	0.51	-2.0
C2	Forward	3	0	0.49	0.38	7.9
C3	Forward	1	1	0.34	0.34	8.6
C4	Forward	2	1	0.38	0.32	-4.3
V1	Forward	3	0	0.36	0.19	23.6
V2	Forward	0	0	0.24	0.18	13.6
V3	Forward	5	2	0.48	0.43	1.3

Table 7.2 Adaptive planting date, change in average yield (compared to baseline average yield) and comparison of CV and number of years with no harvest for baseline planting date and adaptive planting date for B2 scenario

Site	Adaptive planting date for higher yield	No of year with no harvest with baseline planting date	No of year with no harvest with adaptive planting date	CV of projected yield with baseline planting date	CV of projected yield with adaptive planting date	Change in yield with adaptive planting date (%)
L1	Forward	4	0	0.44	0.28	0.1
L2	Baseline	0	0	0.17	0.17	21.9
L3	Backward	0	0	0.17	0.19	27.4
T1	Forward	0	0	0.23	0.22	23.3
T2	Backward	0	0	0.22	0.26	16.2
T3	Forward	0	0	0.30	0.29	18.1
T4	Forward	3	1	0.52	0.44	35.3
C1	Forward	6	5	0.57	0.49	3.8
C2	Forward	6	2	0.57	0.42	7.3
C3	Forward	3	1	0.45	0.39	-3.2
C4	Forward	2	2	0.44	0.40	-2.8
V1	Forward	2	4	0.46	0.38	3.8
V2	Forward	3	0	0.34	0.22	-2.2
V3	Forward	4	4	0.49	0.43	-5.9

7.2.2. Adjustment of management practices

Fertilizer use in the basin is currently at sub-optimal level (i.e. there is fertility stress) particularly in the areas in Laos, Thailand and Cambodia (Hasegawa et al. 2008, Linquist and Sengxua 2001, Fukai 2001). In setting up the model, we have considered fertility stress as one of the model setup parameters and found fertilizer use in some sites is as low as 40% (60% fertility stress). The year to year variation in yield (as shown in Figure 6.10), as discussed above, is mainly due to the variation in the availability of rainfall during the growing period. Due to low rainfall or poor distribution of rainfall, crops periodically suffer from water stress which reduces yield depending on the intensity of water stress, causing yield variation from year to year. In some years, due to prolonged dry spell, the crop is completely destroyed with no harvest at all, as shown in Table 7.1 and 7.2. The impact of a dry spell can be effectively minimized using supplementary irrigation and better management of soil water conditions. To see the impact of reduced fertility stress (or increased application of fertilizer) and supplementary irrigation, we have considered the following adaptation strategies.

Adaptation strategy 3: Use full supplementary irrigation when required with baseline planting date (designated as A2+SI, and B2+SI)

Adaptation strategy 4: Reduce fertility stress (RFS) by 10% from the stress considered in setting up the model with baseline planting date (designated as A2+RFS, B2+RFS)

Adaptation strategy 5: Combining 2 weeks forward planting with 10% reduction in fertility stress (A2+2WFP+RFS, B2+2WFP+RFS)

Adaptation strategies 1 and 2 offset the negative impacts on yield of climate change. In most areas, one or other of the strategies results in a positive increase in yield – that is, any negative climate change impact is more than offset, and an increase in yield results. However, in a few areas, neither of the strategies resulted in an increase in yield (Tables 7.1 and 7.2). For these few remaining areas, the strategies 3, 4 and 5 were tried. We applied these strategies only at representative sites in Cambodia and Vietnam: at site C1 (fertility stress is reduced from 50% to 40%) and V3 (fertility stress is reduced from 25% to 15%). Figure 7.9 compares the average yield of rainfed rice for different adaptation strategies including the strategies 1 and 2 with that of baseline, A2 and B2 scenarios. The percentage change in projected yield with respect to the baseline yield is presented in Figures 7.10 and 7.11 respectively for A2 and B2 scenario. For site C1, supplementary irrigation completely offset the negative yield with baseline planting date and increases the projected yield from 1.42 tonne/ha (A2) to 1.87 tonne/ha with an increase of 31.6%. The net increase in projected yield compared to the baseline average yield is 13.2%. However, reduction of fertility stress increases the yield much higher to 2.96 tonne/ha, an increase of 78.7% from the baseline average yield. The highest increase (3.27 tonne/ha, 97.5% increase from the baseline average) can be achieved by 2 weeks forward planting (from the baseline) with 10% reduction in fertility stress. The result is also similar for scenario B2.

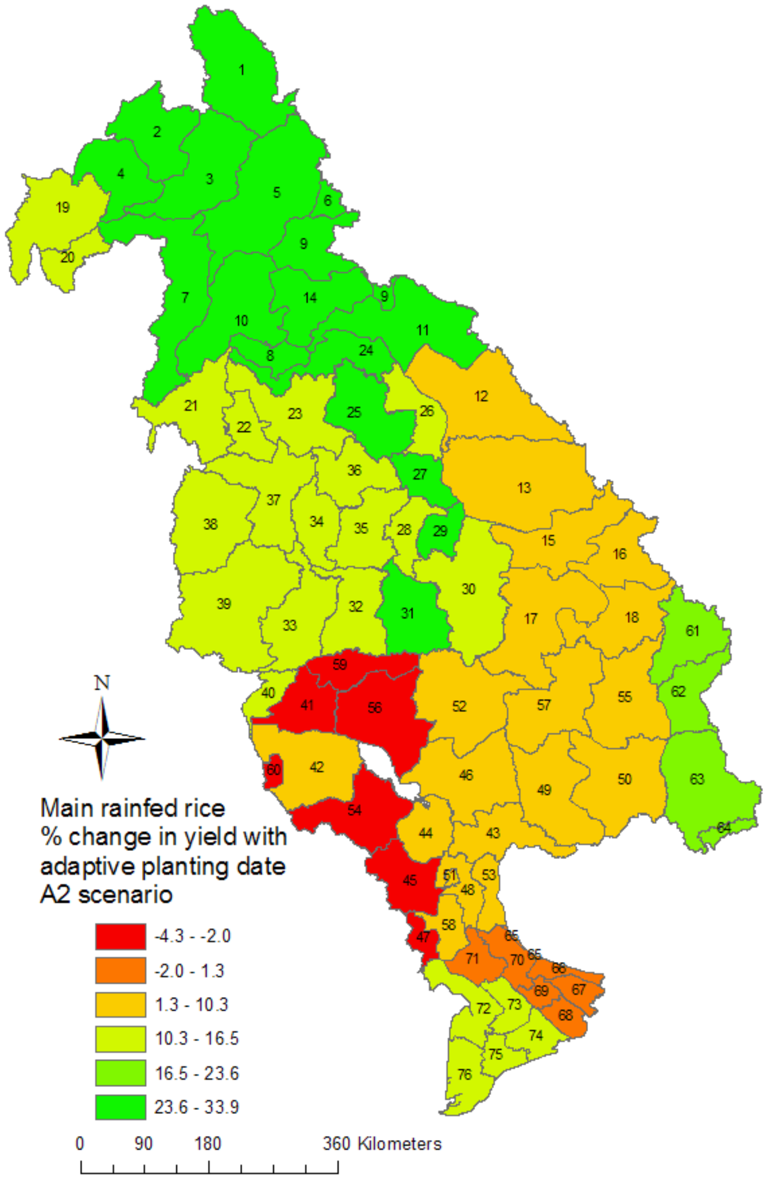


Figure 7.7 Basin-wide changes in average yield of main rainfed rice for A2 scenario with adaptive planting date

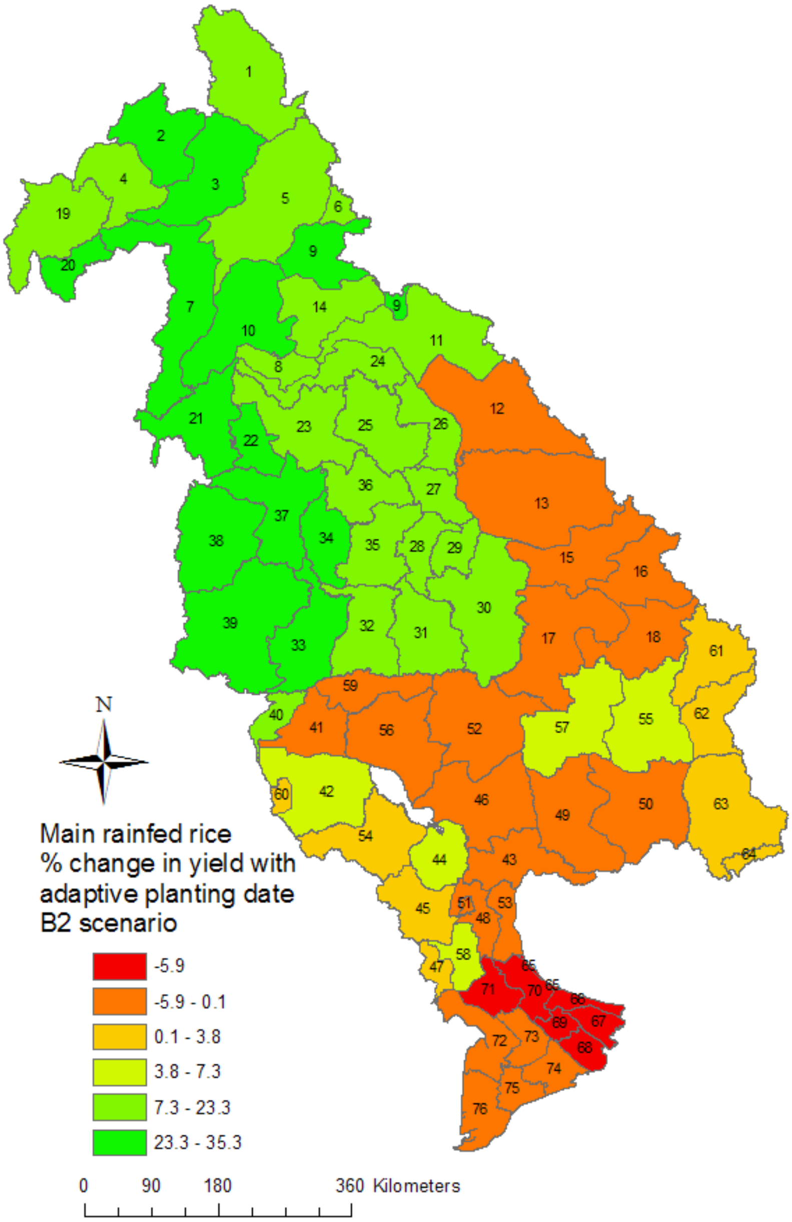


Figure 7.8 Basin-wide changes in average yield of main rainfed rice for B2 scenario with adaptive planting date

For site V3 in scenario B2 (highest decrease, 11%), 10% reduction of fertility stress offsets the negative impact on yield and increases yield from the projected average yield of 3.07 tonne/ha to 3.51 tonne/ha; an increase of 14.3%. The increase in yield compared to the baseline average yield is very small, 1.6%. This can further be increased to 6.3% by shifting the planting date two weeks forward. However, supplementary irrigation provide highest increase in yield from baseline average of 3.45 tonne/ha to 4.28 tonne/ha, a net increase of 24.2% after offsetting 11% decrease in yield without supplementary irrigation. Comparing the results of sites C1 and V3, we can see that reduction of fertility stress is more effective in site C1 or in areas with poor fertilizer application, while supplementary irrigation is more effective in site V3 or in areas with higher fertilizer application. It can be expected that these adaptation strategies will also be applicable to the other sites and similar increases in yield can be achieved.

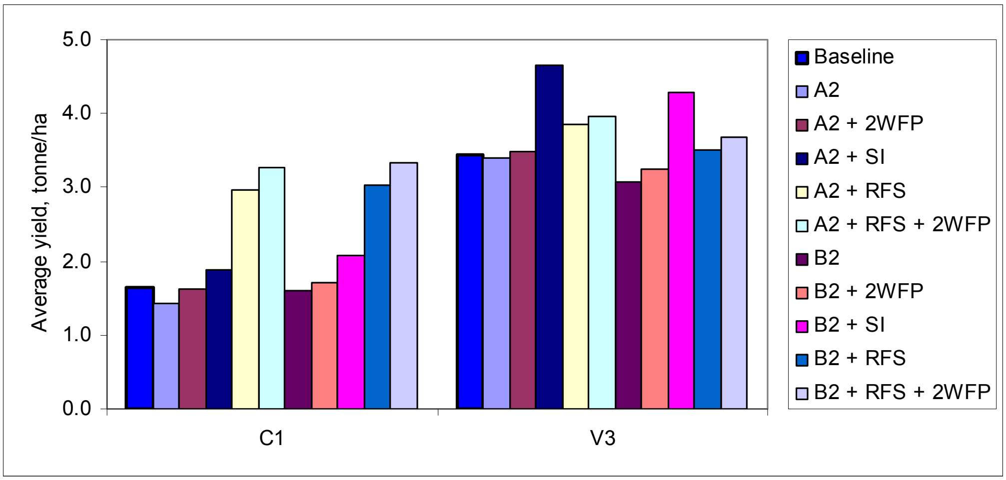


Figure 7.9 Average yield of main rainfed rice for different adaptation strategies at sites C1 and V3

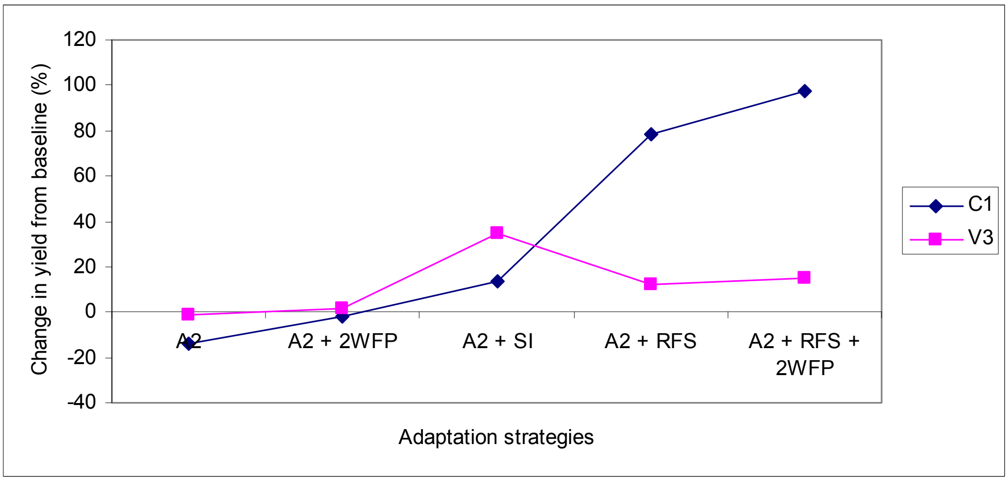


Figure 7.10 Change in average yield of rainfed rice for different adaptation strategies at sites C1 and V3 for A2 scenario

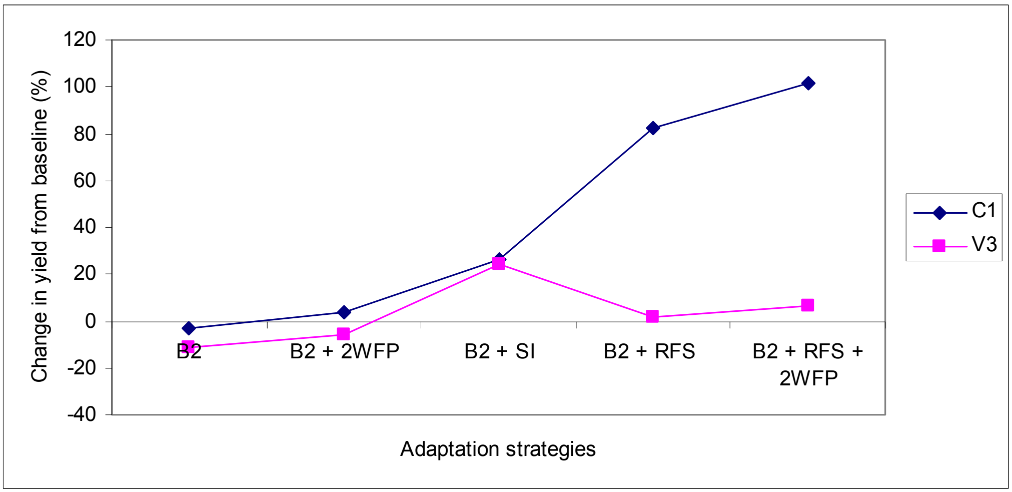


Figure 7.11 Change in average yield of rainfed rice for different adaptation strategies at sites C1 and V3 for B2 scenario

7.3. Discussion on adaptation strategies

The adaptation strategies applied here are the most common strategies already practiced by farmers. The availability of water is the key factor that determines the transplanting of rainfed rice as 150 mm-250 mm of water is necessary to prepare the field for seedling transplanting or sowing (Smith, 1992). Thus, in areas with more rain, transplanting may begin earlier than in areas with limited or delayed rainfall. The crop calendar under rain-fed lowland conditions spans a potentially wide transplanting or sowing window (Kono et al., 2001). Variability in the water conditions due to variability in rainfall and toposequential differences between the paddy fields appear to explain the wide windows for sowing and transplanting (Sawano et al., 2008). Sawano et al. (2008) showed that the crop calendar of northeast Thailand can be expressed as a function of cumulative precipitation from June onward. Therefore, shifting the planting date is unlikely to have any impact on the overall cropping pattern of the region as this variation is already accommodated in the crop calendar.

Reduction of fertility stress or application of more fertilizer was used in the sites of Cambodia and Vietnam. Among the riparian countries fertilizer use is lowest in Cambodia and highest in Vietnam. Therefore, the results (Figures 7.10 and 7.11) show that yield is more sensitive to fertilizer application in Cambodia than that of Vietnam. Low fertilizer application, low use of high yielding varieties, periodic drought and inadequate management practices are the major cause of low productivity of rice in Cambodia (Rickman et al, 2001; Fukai and Kam, 2004; Makara et al, 2004). Soil fertility is also a major problem in Laos and Thailand due to the permeable nature of the sandy soils in the region (Fukai et al., 1998). Reduction of fertility stress is expected to have significant positive impact on the yield of rice in these countries.

Drought is a major production constraint for rainfed lowland rice grown in Laos, Thailand and Cambodia, but the frequency of drought problem is the highest in Northeast Thailand (Fukai et al., 1998). As discussed in Chapter 6, increased rainfall due to climate change, which minimise the occurrence of drought, is the predominant factor of getting higher yield of rainfed rice in these countries. The variation in yield (Figure 6.10) can be further minimised by applying supplementary irrigation when required. Supplementary irrigation is practiced where there is irrigation infrastructure, in the areas near the confluence of major rivers, and along the tributaries. Field survey by Shimizu et al. (2006) in the provinces of Kratie (province no, 49 in Figure 6.1), Kampong Cham (no. 43), Kandal (no. 48) and Takeo (no. 58) of Cambodia revealed that some rainfed paddy fields do not depend solely on rainfall, and that they have supplementary sources of water such as small ponds close to paddy fields or water in lowlands along the farm road. Groundwater from shallow tubewells are also used as supplementary irrigation in some provinces in Cambodia such as Svay Rieng, Prey Veng and Takeo (IDE, 2009; Vang et al.,2009) However, supplementary irrigation is rather limited in Laos, Thailand and in some parts of Cambodia mainly due to lack of irrigation infrastructure.

Supplementary irrigation requirement for rainfed rice is lowest in Vietnam among the riparian countries of the lower Mekong (Mainuddin and Kirby, 2009a). The majority of the irrigated area of the Basin is in the Mekong Delta which is fed by the network of irrigation canals. There are 120 irrigation schemes in the Mekong Delta. Low requirements and opportunities for supplementary irrigation have enabled farmers in the Delta to grow high yielding varieties, using high input such as fertilizer and pesticides without fear of losing harvest, resulting in much higher productivity of rice than the other riparian countries (Mainuddin and Kirby, 2009a). Thus supplementary irrigation is not new in the Delta and is being used as one of the adaptation strategies to get higher yields of rice.

The capacity to select and apply appropriate methods and tools to prepare for adaptation is dependent upon understanding the effects of climate change, and associated enhanced climate variability at the local and national levels. In this study, attention has focused only upon the capacity for adaptation at the farm level. Strengthening adaptive capacity at this level is not likely to be sufficient without changes in national policy and the international political economy of the agricultural sector (Burton and Lim, 2005). Agriculture has a strong record of adaptability (Burton and Lim, 2005) and the prospects are good for the lower Mekong that this can be maintained in face of the threat from global climate change.

7.4. Implication on basin's food security

The population of the Lower Mekong is likely to rise from the present 67 million in 2010 to perhaps more than 88 million in 2050 (UN Population Division, 2006). Table 7.3 shows the estimated 2050 population for each of the riparian countries (within the Mekong Basin) using country average growth rates, current rough rice consumption per capita, and the per capita rough rice production in 2000. In all countries, per capita rice production is much higher than the per capita consumption. At the basin level, production per capita is almost 3 times higher than the consumption per capita. Thailand and Vietnam are in the top five rice exporting countries in the world according to the FAOSTAT (http://faostat.fao.org) database. Cambodia has also become a net exporter of rice in recent years. Laos still imports rice but this was only 13,690 tonnes in 2000 and 14,650 tonnes in 2006 (http://beta.irri.org/solutions/index.php?option=com_content&task=view&id=250). However, the basin as a whole produces more rice than is required to feed the population. The extra rice produced in the basin is therefore either exported or used to feed the population in non-rice growing areas.

Considering the projected production with adaptive planting date for main rainfed rice, and increased population in 2050, rice production per capita will still be higher than per capita consumption for Thailand (216%), Vietnam (175%), Laos (13%), and lower for Cambodia (−10%) for the A2 scenario (Table 7.3). For the B2 scenario, changes in production per capita will be 233% for Thailand, 149% for Vietnam, 4% for Laos and -12% for Cambodia. At the basin level, rice production per capita will be 123% and 114% higher than the consumption per capita respectively for A2 and B2 scenario. This will vary from year to year due to the variation in the average yield of main rainfed rice (Figure 7.12). However, with economic growth, fish and meat consumption are likely to increase (Delgado et al., 1999; Delgado et al., 2007); as a result, rice consumption would decrease towards the standard rice consumption of 150 kg/capita (Minot and Goletti, 2000). All these factors strongly suggest that there would be no adverse impact of climate change in feeding the extra population of the basin in 2050. Mainuddin and Kirby (2009a, 2009b) and Kirby and Mainuddin (2009) analysed the temporal trend in rice production and showed that the increase in rice production is in pace with the increase in population in the basin, and concluded that food security of the basin is unlikely to be affected by the increased population. This does not take into account the potential positive impact of climate change on the yield of rainfed (Table 7.1 and 7.2) and irrigated (Figure 6.18) rice.

However, if we consider the changes in productivity due to climate change and adaptation strategies alone as modelled in this study (i.e. ignoring the increase in production that is happening anyway, as reported by Mainuddin and Kirby, 2009a, 2009b and Kirby and Mainuddin, 2009), as shown in Table 7.3 the production per capita in 2050 could be significantly lower than that in 2000 in all riparian countries except Thailand. This indicates that the export of rice outside the basin (both inside and outside the country) would decrease from the 2000 level. Export potential could be maintained, if production per capita for 2000 can be achieved in 2050 by increasing production. Table 7.3 shows the average yield of rice (total production divided by total harvested area in a year) necessary to achieve to maintaining the current per capita production. Yield of rice has to be increased to 5.44, 2.20, 4.24 and 6.36 tonne/ha, respectively for Laos, Thailand, Cambodia and Vietnam. Projected average yield with adaptive planting date is also presented in the Table. Obviously, the projected average yield is lower than the required yield except Thailand. At the basin level, the required average yield is 4.15 tonne/ha against the projected yield of 3.2 and 3.1 tonne/ha respectively for A2 and B2 scenario.

Shifting the planting date does not offset the negative yield in some sites in Cambodia and Vietnam (Tables 7.1 and 7.2 and Figures 7.7 and 7.8), therefore, we have considered reduction of fertility stress and application of supplementary irrigation as further adaptation measures. If we consider the increase in yield due to these additional adaptation measures (Figures 7.10 and 7.11) only for the sites (highlighted in Tables 7.1 and 7.2) with negative impact, the average yield at the basin level increases to 3.3 and 3.6 tonne/ha respectively for A2 and B2 scenario. Reduction of fertility stress and application of supplementary irrigation will have similar impact (as shown in Figures 7.10 and 7.11) on the other sites in the basin particularly in Laos, Thailand and Cambodia. Linquist and Sengxua (2001) showed that applying fertilizer alone increased yield by 134% and 107% in the Champassak (province no. 17 in Figure 6.1) and Saravane (province no. 15) provinces of Laos. Considering similar impact of increase fertilizer application in Laos, Thailand and Cambodia, and supplementary irrigation in Vietnam, projected average yield should be closer (if not higher) to the required yield to keep the current export potential.

The attainable yield of irrigated and rainfed lowland rice in Thailand (whole country) may be 6–8 and 4.5– 6.0 t/ha, respectively (Kupkanchanakul, 2000). Boonjung (2000) showed that the attainable yield of rainfed rice in Northeast Thailand as 3.2 t/ha even with the current local varieties. The attainable farm yield of irrigated rice in Vietnam (whole country) is reported as 8.5 t/ha (FAO, 2004) and average attainable yield considering all rice is 6.1 t/ha (Duwayri et al., 2000). Attainable yield of both rainfed rice and dry-season irrigated rice in Cambodia is 4–6 t/ha (Shimizu et al., 2006). The rice ecology in the lowlands of Laos is quite similar to that of Cambodia and Thailand; therefore similar productivity potential can be expected. However, these do not consider the significant positive impact of increased CO_2 concentration in the atmosphere as shown in Figures 6.17 and 6.18. The required yield to maintain export potential is lower or very close (only for Vietnam) to the attainable yield without CO_2 fertilization. Therefore, it would be possible to maintain per capita current production by increasing the productivity of the current areas cultivated. This does not even consider current growth in irrigated area in the dry season.

In addition to the increase in productivity of the current areas under cultivation, it is also possible to increase total production by bringing new areas under cultivation or increasing dry season irrigated area. Cropping intensity of rice (ratio of total cultivated area of rice to the total physical area of rice available in a year) is less than 100% for Thailand, Laos and Cambodia (Mainuddin et al., 2008). Only in Vietnam, rice cropping intensity was about 140% in 2000. This indicates that there is potential to increase rice cropping intensity both by bringing new land under cultivation (except Vietnam) and by increasing dry season irrigated area, particularly in Laos, Thailand and Cambodia. But the environmental consequences of increasing dry season irrigation are unknown. Due to climate change, dry season flow is expected to increase (Table 4.8 and Figure 4.5), which will offset some of the increased diversion of water from the river (Table 6.9) to meet the demand of existing irrigated area. New irrigation development will further reduce the flow of the river in the dry season and may affect the Mekong Delta which is vulnerable to reduced mainstream flow in the dry season accompanied by enhanced salinity as a consequence of intrusion from the sea (Kristensen 2001). Podger et al. (2004) estimated that the impact of a high agricultural development scenario on flows in the Mekong would be modest (without the impact of climate change), but the impact on the environment and ecology of the basin, particularly on the fisheries could be significant.

In conclusion, the current rate of increase in both production and productivity of rice is considerably greater than is required to feed the expected extra population by 2050. In addition, there is considerable potential to increase production by applying simple adaptation measures and to some extent by sustainable increase in irrigated area. The increase in CO_2 concentration in the atmosphere is also expected to offset any negative impact of climate change and increase yield significantly. All these clearly suggest that food security at the basin level may not pose any challenge and current export potential of the basin can be maintained. Haddeland et al. (2006) state that rice production in the basin is enough to provide food security for 300 million people. However, food security for all individuals also requires that the production is distributed equitably. This remains a major challenge. As stated earlier, the study does not consider the impact of extreme events such as floods, sea level rise, cyclones, storm, etc. which may become more frequent with higher intensity due to climate change and may have severe impact on food security.

Table 7.3 Rough rice consumption and production per capita, and country-wise current and projected average yield

Country	Projected population of 2050[1] (million)	Rough rice consumption per capita (2000)[2] (kg/capita)	Rough rice production per capita (2000) (kg/capita)	Rough rice production per capita considering 2050 production and population (with adaptive planting date) (kg/capita)		Average yield of rice considering total production and total harvested area in 2000 (tonne/ha)	Projected average yield with adaptive planting date in 2050 (tonne/ha)		Average yield necessary to maintain current per capita production with no additional area (tonne/ha)
				A2	B2		A2	B2	
Laos	9.3	254	422	286	265	3.06	3.7	3.4	5.44
Thailand	25.4	153	455	482	508	1.99	2.3	2.5	2.20
Cambodia	21.9	201	336	181	176	2.16	2.3	2.2	4.24
Vietnam	31.2	218	840	600	543	4.19	4.5	4.1	6.36
Lower Basin	87.8	192	562	428	412	2.85	3.2	3.1	4.15

Note: [1]Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision, http://esa.un.org/unup
[2]This is the average for the whole countries, while all other figures are for the areas of the country within the Mekong Basin.
[2]Source: International Rice Research Institute (IRRI) http://www.irri.org/science/ricestat/data/may2008/WRS2008-Table17-USDA.pdf

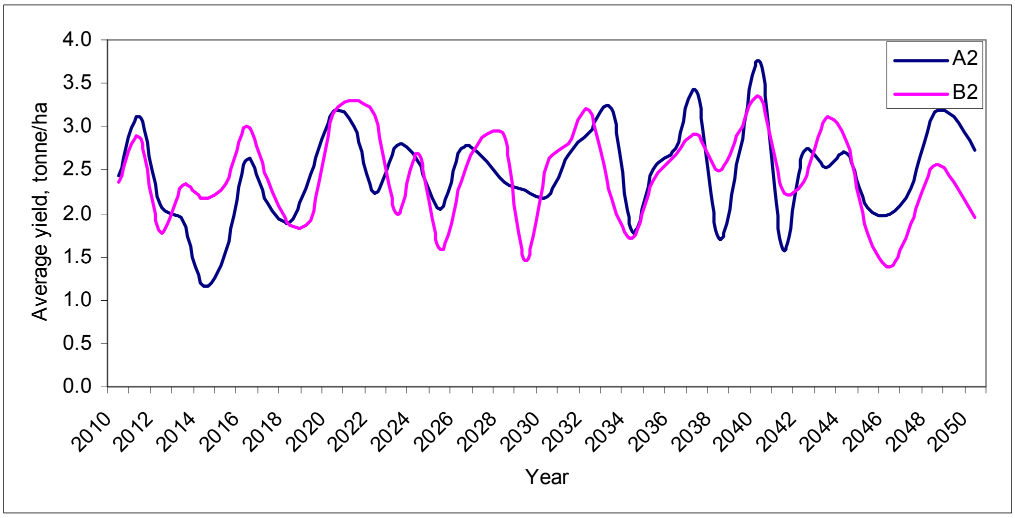


Figure 7.12 Basin average yield of main rainfed rice for A2 and B2 scenario

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. General conclusions

In general, after the adjustments made by comparing the scenario data with the observed data in the past and applying this to the future, the PRECIS climate data shows a trend of a slight increase in precipitation throughout the Mekong Basin, except in Cambodia and Vietnam. The projection shows wetter rainy seasons from now to 2050 with a precipitation increase of 1.2 - 1.5 mm/year. The increase in Scenario B2 is less than that in Scenario A2. Wetter dry seasons in the UMB, with an increase of 0.9 mm/year, are also projected, but the change in precipitation in the LMB is insignificant. Temperatures are projected to increase by about 0.023°C/year. These projections are similar to the assessments from other studies.

In the high-flow season, the impacts of climate change and effects of development are in opposite directions. Under the same climate conditions as in 1985 - 2000, development brings about a decrease of 8 - 17% in river flow (Scenario S3 - S2), but under the future climate change in 2010 - 2050, the effects are less at about 7 - 14% (Scenario S5 - S4) in comparison with the assumption of the future continuation of the Baseline. Climate change would bring about an increase of about 2 – 11% in river flows when compared to that in the past (Scenario S4 - S2). The combined effects of development and climate change may cause a decrease in discharge of up to 13% at one station, but an increase of 3% at another, depending on the climate change scenarios and the location of stations (Scenario S5 - S2). Such variation is a good reflection of the fact that the current development plan has not been prepared to adapt to climate change.

In the low-flow season, although impacts of climate change and effects of development are changes in the same direction of increasing river flows, the combined effects are complex. Under the same climate conditions as in 1985 - 2000, development brings about an increase of 30 - 60% in river discharge (Scenario S3 - S2), but climate change results in a smaller increase of about 18 - 40% (Scenario S5 - S4) in comparison to the assumption that the Baseline continues in the future. Climate change increases river flow by about 18 - 30% (Scenario S4 - S2). The effect of both climate change and development may cause an increase in discharge of up to 40 - 76% (Scenario S5 - S2), depending on the climate change scenarios and the location of stations.

The effects of development will be to cause a decrease in the overall annual discharge of about 3 - 8% under both the past climatic conditions and the future climate change (Scenarios S3 - S2, and S5 - S4). Conversely, climate change would increase the river discharge by 4 - 14% under both the Baseline and the Development Scenarios (Scenarios S4 - S2, and S5 - S3). The effect of both climate change and development may cause an increase in discharge of about 2 - 12% (Scenario S5 - S2), depending on the climate change scenario and the location of the stations. These changes show that a seasonal analysis is needed for dealing with development and climate change issues.

Climate change will bring about a slight increase of about 5.5 – 8% in the contribution of snowmelt to the annual water yield at the Chinese-Lao border. Although the contribution of snowmelt in the dry season (such as in March) is more significant, its percentage contribution to the river discharge does not change by a great deal, and becomes even smaller at stations further downstream.

Assuming that the Baseline will continue to hold good in the future, climate change will bring about an increase in the number of days with discharges above the mean of the high-flow season. Development can help to significantly reduce this number of days at upstream stations, but the effect is somewhat less at downstream stations. Development can also help in reducing the areas of flooding but climate change will increase these areas in worse years. Climate change could also increase the extent of the areas with saline intrusion but the increase in these areas is smaller than that of the areas of flooding. In contrast, development can help in reducing these affected areas. However, the uncertainties in any projection of future precipitation should be borne in mind when reaching these conclusions.

We studied the impact of climate change on floods and fisheries considering six climate change and basin development scenarios (described in Table 5.1, these scenarios are coded differently from the scenarios considered in studying the impact on flow regime). The results indicate that without further basin development over the next 20 years, both minimum and maximum water levels, and the flood indices described here are predicted to increase over the next 40 years as a consequence of climate change, but not significantly at the 5 % level. These increases will be greater under the A2 compared to the B2 emissions scenario. A similar response to climate change is predicted under the basin development scenarios (Scenarios 4-6), but again, climate change effects are not detectable at the 5 % significance level.

Without climate change, basin development is predicted to lower maximum (wet-season) water levels and the flood indices, but not significantly. With climate change, maximum water levels and flood indices are predicted to rise only marginally (but not significantly) above the baseline (i.e. no further development or climate change). The mean values of maximum water levels and flood indices are however lower than those predicted for the two climate change-only scenarios (Scenarios 2 & 3) implying that planned basin development activities will counteract the effects on fish biomass of increasing flood indices predicted under both climate change scenarios. The homogeneity of variance test results suggest that there the flood indices and therefore fish biomass will not be more variable under the future climate change and basin development scenarios compared to the baseline.

We have assessed the impact of climate change on the productivity of major crops grown in the basin using a crop simulation model – AquaCrop. In general, the results suggest that productivity of main rainfed rice, predominant crop in the basin, may increase significantly in the areas in Laos (10-28%) and Thailand (8-28%) and may decrease in the lower part of the basin in Cambodia (up to 9-14%) and Vietnam (2%-11%). The net change in productivity is mainly due to change in rainfall and increased CO_2 concentration in the atmosphere. Adverse impact on the yield of main rainfed rice in Cambodia and Vietnam can be offset and net increase in yield can be achieved by applying simple adaptation measures such as shifting the planting date, providing supplementary irrigation, and reducing fertility stress.

Increase temperature slightly affects the yield of irrigated rice but increased CO_2 concentration offsets this impact and result in a significant net increase (up to 18%) if increased irrigation requirements (11% for the basin) due to increase in evapotranspiration is provided. Therefore, for irrigated rice, the impact of climate change is partly direct, and may also be indirect through the effect of climate change on the flow of the river. Increased diversion for irrigation may reduce the dry season flow in the river which may significantly affect the river ecology and overall environment including salt water intrusion in the Delta. Productivity of maize is not affected at all adversely by any change in climatic parameters. Yield may increase significantly (up to 28%) all over the basin due to increased CO_2 concentration in the atmosphere.

Food security of the basin is unlikely to be threatened by the increased population, and the impact of climate change. There is even potential for the basin to maintain current levels of rice exports in the future if current trend of productivity continues. This will be further augmented by the increase of CO_2 concentration in the atmosphere.

The models assess the direct impact of rainfall, temperature and evapotranspiration on the productivity the major crops grown in the Basin for climate change conditions. Indirect impact of rainfall such as floods, drought, dry spells, sea level rise, etc. and the impact of natural disaster such as cyclones, storm is not considered in the analysis. All these extreme weather events may have significant and widespread adverse impact on yield. Despite these limitations and the assumptions made in both the GCM and the crop simulation models, the current study provides significant progress in our understanding of how future climates are likely to affect agricultural production and food security in the lower Mekong Basin.

8.2. Recommendations for further studies

Although this report analyses several impacts of climate change on the flow regime of the Mekong River, fisheries, and agricultural productivity, the results should be considered as a preliminary assessment. We present some suggestions for further efforts to improve the assessment which include:

1. We have used a single climate model, ECHAM4, with two climate change scenarios A2 and B2). The study by Eastham et al. (2008) showed a greater range of results amongst 11 models with one scenario (A1B) than we show here between the two scenarios. The results of this study are in the range indicated by other studies. Nevertheless, taking account of a wider range of climate models would lead to a greater understanding of the uncertainty in projections.
2. Daily data are required for the DSF model analyses of changes in flow regime. However, since the daily simulated data vary considerably in comparison with the observed data, adjustment methods are needed. Further study and testing of these methods are needed to ensure that proper projection trends will be maintained. Any analysis of extreme events, such as floods and droughts in the wet season, requires the daily distribution of precipitation, but the projection of daily variation would have to be further improved by future RCMs.
3. More observed climate data (involving more stations and covering a longer period) and other data used in modelling, such as land and water use, reservoir regulations and rules, and so on should be collected in order to improve climate change analysis. Most of the data currently available are for single or specific years, and these are interpolated or assumed to be the same for the whole of the study period. However, since climate change is a long process, records covering longer periods are required in analysing any variations. The Baseline and Development Scenarios used in this study were the BDP Scenarios defined by the end of 2008, and more information and data have been provided to the MRC by the national agencies to update the Scenarios. This updated information and data should be used in the next assessment of climate change.
4. The DSF models (SWAT, IQQM and ISIS) used in this study are those versions which were available at the end of 2008. Although these are specialist models of a high standard, there are several difficulties in their application to climate change study in a large and complex basin such as that of the Mekong. For the long period of 40 years, the input and output datasets are quite large (about 20 GB for SWAT and IQQM models, and 400 GB for the ISIS model). Supporting tools are needed to handle such large datasets for analysis. Although some tools have been developed, with this amount of data, the time taken for re-runs and analysis is too long. The direction of the modelling is to try to include as many details as possible (such as more sub-basins, reservoirs and irrigation systems) and this may not work for a basin-wide assessment. Therefore simplification of the Mekong model and development of sub-models for groups of sub-basins are needed, because even when more sub-basins are included, the models cannot be calibrated and validated for all sub-basins. The DSF models are also being refined to include more functions and for an improvement of the simulation accuracy, therefore new versions have been provided or under preparation. Updating to the new versions is a challenge for the modellers, particularly for model running with large datasets. For example, very often the ISIS model stops when running for a long period of 40 years without user-friendly debug functions.
5. The DSF was designed and set-up for the analysis of changes in flow regime in different scenarios to support Articles 5, 6 and 26 of the 1995 Mekong Agreement. Other parameters required for adaptation analysis such as food and energy production have not been generated, so Scenario S6 (Development + PRECIS data 2010 - 2050 + Adaptation strategies) has not yet been analysed. This can only be done after there are sufficient outputs from other models and analyses based on

outputs of the DSF, or with the new components of the DSF that are being improved at the MRC to provide an integrated modelling package that not only focus on flow changes but also on other changes.

6. For the baseline condition, due to unavailability of longer time series of climate data, the AquaCrop model has been set up for 1996-2000. Since then productivity of the crop has increased. It is therefore recommended to recalibrate and validate the model for recent years and then simulate the yield for future condition using the generated data of different GCM models as described in point 1 above.

8.3. Other recommendations

Some considerations follow from this research for policy or action in the Mekong. However, the general studies in this report will require more detailed study (as listed above) in association with the suggested actions.

1. The predicted more frequent and more extreme high flows may require consideration of flood mitigation.
2. The finding that flow impacts on fish may not be as great as the impact of barriers suggests that dams on migration routes will require careful impact assessments.
3. The adaptation strategies (changed planting dates, supplementary irrigation and increased use of fertilisers) will require development of education, extension and trials to the agricultural districts.

APPENDIX A. METHODS FOR ADJUSTMENT OF GCM BASED ON OBSERVED DATA

A.1 Adjustment of precipitation

Due to the deviation of the precipitation data generated by the PRECIS system from the observed precipitation, and to keep the outputs from baseline scenario SWAT models as close as possible to the observed flows at major monitoring points, the PRECIS sub-basin precipitation needs to be adjusted. For 1985 – 2000, the monthly precipitation time series for all SWAT sub-basins were adjusted against the sub-basin precipitation used for the SWAT model calibration (derived by the MQUAD program in the DSF using observed point - rainfall data as input). The approach adopted here is similar to the method 3 proposed by Hoanh et al. (2006) and can be explained as follows:

$$P_{adjCCM(sub\_i,month\_j)} = P_{CCM(sub\_i,month\_j)} - f \times \left(P_{CCM(sub\_i,month\_j)} - P_{calib(sub\_i,month\_j)}\right)$$

where:

$P_{adjCCM(sub\_i,month\_j)}$	=	Adjusted Climate Change Model monthly precipitation for sub-basin *i* in month *j* during 1985 – 2000
$P_{CCM(sub\_i,month\_j)}$	=	Simulated Climate Change Model monthly precipitation for sub-basin *i* in month *j* during 1985 – 2000
$P_{calib(sub\_i,month\_j)}$	=	Monthly precipitation used for SWAT model calibration (observed data) for sub-basin *i* in month *j* during 1985 – 2000
f	=	Adjustment factor (1.0 for complete adjustment)

After monthly precipitation variables had been adjusted and fitted to the sub-basin precipitation used for SWAT model calibration (observed data), the daily precipitation values were generated. To generate the daily precipitation values, the daily patterns from either observed data or Climate Change Model data were conditionally applied as follows:

$$P_{adjCCM(sub\_i,month\_j,day\_k)} = P_{adjCCM(sub\_i,month\_j)} \times P_{pat(sub\_i,month\_j,day\_k)}$$

When $\left(P_{CCM(sub\_i,month\_j)} - P_{calib(sub\_i,month\_j)}\right) < 0$

$$P_{pat(sub\_i,month\_j,day\_k)} = P_{calib(sub\_i,month\_j,day\_k)} / P_{calib(sub\_i,month\_j)}$$

when $\left(P_{CCM(sub\_i,month\_j)} - P_{calib(sub\_i,month\_j)}\right) \geq 0$

$$P_{pat(sub\_i,month\_j,day\_k)} = P_{CCM(sub\_i,month\_j,day\_k)} / P_{CCM(sub\_i,month\_j)}$$

where:

$P_{adjCCM(sub\_i,month\_j,day\_k)}$ = Adjusted daily Climate Change Model precipitation for sub-basin *i* in month *j* and day *k* during 1985 – 2000

$P_{adjCCM(sub\_i,month\_j)}$ = Adjusted monthly Climate Change Model precipitation for sub-basin *i* in month *j* during 1985 – 2000

$P_{pat(sub\_i,month\_j,day\_k)}$ = Daily pattern for sub-basin *i* in month *j* and day *k* during 1985 – 2000

$P_{CCM(sub\_i,month\_j)}$ = Monthly Climate Change Model precipitation for sub-basin *i* in month *j* during 1985 – 2000

$P_{calib(sub\_i,month\_j)}$ = Monthly precipitation used for SWAT model calibration (observed data) for sub-basin *i* in month *j* during 1985 – 2000

$P_{CCM(sub\_i,month\_j,day\_k)}$ = Daily Climate Change Model precipitation for sub-basin *i* in month *j* and day *k* during 1985 – 2000

$P_{calib(sub\_i,month\_j,day\_k)}$ = Daily precipitation used for SWAT model calibration (observed data) for sub-basin *i* in month *j* and day *k* during 1985 – 2000

For 1985 - 2000, first the daily PRECIS precipitation data were adjusted using both types of daily precipitation patterns based on the aforementioned conditions. However the outputs from the few Great Lake SWAT models have shown rather high deviations from their outputs using observed climate data. Hence finally only the patterns from daily observed precipitation were adopted. For all SWAT models, the adjustment factor of 1.0 was adopted except for the Lower Mekong SWAT Model 8 (Mun up to Rasi Salai), as the model output when compared to the output from observed climate data was significantly underestimated, therefore the factor of 0.9 was adopted.

For 2010 – 2050, the monthly PRECIS precipitation data for every 16 years were adjusted using the monthly adjustment values obtained from 1985 – 2000 and subsequently the daily PRECIS precipitation data were adjusted using daily precipitation patterns from future PRECIS data.

A.2 Adjustment of spikes in daily precipitation data

Option 1: Due to the original PRECIS Regional Climate Model data containing a number of days with extremely high daily precipitation values or spikes in several grid-cells (details mentioned in the full report), and the fact that these spikes still remain even after the calculation of sub-basin precipitation is performed, these spikes embedded into the precipitation data may cause the existence of an abrupt anomalous increase in the water yield hydrograph. This section explains an algorithm applied to adjust extremely high daily precipitation values or spikes by introducing so called "monthly threshold" and "day with rainfall". Monthly threshold is defined as the historical maximum daily precipitation in each month. Spikes will be reduced to the monthly threshold and the excess rainfall will be redistributed to the rainfall of the preceding and following days, assuming that these are "day with rainfall" to make sure that this excess rainfall will not be lost through evaporation or percolation if it is redistributed to a day without rainfall.

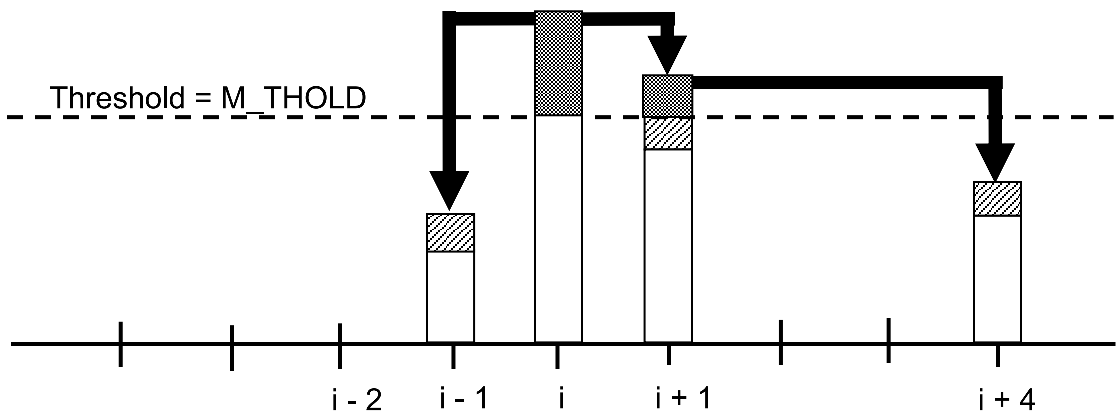


Figure A.1 Algorithm for adjustment of spikes in daily precipitation data.

Normally, the algorithm should be applied after monthly precipitation volumes have been adjusted using the method mentioned in the previous section. The following steps are applied for each calendar month to adjust spikes down to the monthly threshold.

Step 1) Calculate the excess rainfall to be distributed to the preceding and following days by using the rainfall weighted average approach. Suppose for the day *i* in a specific month in which the spike needs to be adjusted, first the excess rainfall will be calculated by

$$EXC\_PCP = P_i - M\_THOLD$$

$$EXC\_PCP1 = \frac{P_{i-1}}{P_{i-1} + P_{i+1}} EXC\_PCP$$

$$EXC\_PCP2 = \frac{P_{i+1}}{P_{i-1} + P_{i+1}} EXC\_PCP$$

where:

EXC_PCP	=	Total excess rainfall for the day *i* incorporating spike
M_THOLD	=	Threshold value for precipitation in the month
P_i, P_{i-1}, P_{i+1}	=	Daily precipitation for day *i* incorporating spike, preceding and following days respectively
EXC_PCP1	=	Excess rainfall to be distributed to preceding days
EXC_PCP2	=	Excess rainfall to be distributed to following days

Step 2) Distribute any excess rainfall or EXC_PCP1 to the preceding day with rainfall. If the excess rainfall occurs in the day after redistribution, the excess rainfall in that day will be distributed to the other preceding days with rainfall.

Step 3) Distribute EXC_PCP2 to the following day in the same way as used for the preceding days in step 2.

Step 4) In case the excess rainfall distributed to the preceding days reaches the first day of the month, or that distributed to the following days reaches the last day of the month, but the rainfall on that day is still over the monthly threshold, the distribution will be continued in reverse direction.

Usually, a spike will be absolutely dropped to corresponding monthly threshold after passing these steps, and the procedure will be repeated for the next spikes in the month. It should be noted that after adjusting the spikes in a particular month, the monthly rainfall volume is still unchanged.

Option 2: This simple approach is applied before adjustment of the monthly rainfall volume. The daily sub-basin rainfall from PRECIS RCM exceeding the corresponding monthly threshold will be dropped to the monthly threshold value. After comparing two options in this climate change study, finally this option 2 was selected to handle the spikes in the daily PRECIS rainfall data.

A.3 Adjustment of maximum and minimum temperatures

The Climate Change Model maximum and minimum temperatures during 1985 - 2000 also deviate from historical records, and in order to keep the outputs from baseline scenario SWAT models close to those using observed temperature data, the maximum and minimum temperatures obtained from the PRECIS Regional Climate Model need to be adjusted. To adjust maximum and minimum temperatures, monthly values are adjusted against the observed and subsequently the monthly adjustment value for a specific month is used to adjust the daily temperature values in that month. The following equations are applied to adjust maximum and minimum temperatures.

$$T_{diff\,(sub\_i,month\_j)} = \bar{T}_{CCM\,(sub\_i,month\_j)} - \bar{T}_{calib(sub\_i,month\_j)}$$

$$\bar{T}_{adjCCM\,(sub\_i,month\_j)} = \bar{T}_{CCM\,(sub\_i,month\_j)} - T_{diff\,(sub\_i,month\_j)}$$

$$T_{adjCCM\,(sub\_i,month\_j,day\_k)} = T_{CCM\,(sub\_i,month\_j,day\_k)} - T_{diff\,(sub\_i,month\_j)}$$

where:

$T_{diff\,(sub\_i,month\_j)}$	=	Monthly temperature adjustment value for a particular sub-basin *i* in month *j* during 1985 – 2000
$\bar{T}_{CCM\,(sub\_i,month\_j)}$	=	Monthly Climate Change Model temperature for a particular sub-basin *i* in month *j* during 1985 – 2000
$\bar{T}_{calib(sub\_i,month\_j)}$	=	Monthly observed temperature for a particular sub-basin *i* in month *j* during 1985 – 2000
$\bar{T}_{adjCCM\,(sub\_i,month\_j)}$	=	Adjusted monthly Climate Change Model temperature for a particular sub-basin *i* in month *j* during 1985 – 2000
$T_{adjCCM\,(sub\_i,month\_j,day\_k)}$	=	Adjusted daily Climate Change Model temperature for a particular sub-basin *i* in month *j* and day *k* during 1985 – 2000
$T_{CCM\,(sub\_i,month\_j,day\_k)}$	=	Daily Climate Change Model temperature for a particular sub-basin *i* in month *j* and day *k* during 1985 – 2000

There are some DSF temperature stations in particular those stations in Vietnam, for only observed daily mean temperature data are available. In the DSF, KB and the SWAT models have been set-up using daily mean temperature for both maximum and minimum temperatures. Therefore, both sub-basin PRECIS maximum and minimum temperatures were adjusted against the observed daily mean temperature. For adjustment for 2010 – 2050, the monthly adjustment values obtained from 1985 – 2000 were applied to adjust the future monthly temperature values and subsequently the daily values for every 16 years.

A.4 Adjustment of solar radiation and wind speed

To adjust the two climatic parameters of solar radiation and wind speed, firstly the monthly values were adjusted against the monthly observed data using the monthly ratios or factors between them, and subsequently these adjustment factors were applied to adjust the daily values in the month. The monthly ratios or factors have been selected as from testing, and the monthly deviation values may produce negative adjusted values for solar and wind speed. The adjusted monthly and subsequently daily values can be calculated from:

Solar radiation,

$$f_{r(sub\_i,month\_j)} = R_{calib(sub\_i,month\_j)} / R_{CCM(sub\_i,month\_j)}$$

$$R_{adjCCM(sub\_i,month\_j)} = f_{r(sub\_i,month\_j)} \times R_{CCM(sub\_i,month\_j)}$$

$$R_{adjCCM(sub\_i,month\_j,day\_k)} = f_{r(sub\_i,month\_j)} \times R_{CCM(sub\_i,month\_j,day\_k)}$$

where:

$f_{r(sub\_i,month\_j)}$	=	Monthly adjustment ratio or factor for solar radiation of sub-basin *i* in month *j*
$R_{CCM(sub\_i,month\_j)}$	=	Monthly Climate Change Model solar radiation for sub-basin *i* in month *j* during 1985 - 2000
$R_{calib(sub\_i,month\_j)}$	=	Monthly solar radiation used for SWAT model calibration (observed data) for sub-basin *i* in month *j* during 1985 – 2000
$R_{adjCCM(sub\_i,month\_j)}$	=	Adjusted monthly Climate Change Model solar radiation for sub-basin *i* in month *j* during 1985 – 2000
$R_{CCM(sub\_i,month\_j,day\_k)}$	=	Daily Climate Change Model solar radiation for sub-basin *i* in month *j* and day *k* during 1985 - 2000
$R_{adjCCM(sub\_i,month\_j,day\_k)}$	=	Adjusted daily Climate Change Model solar radiation for sub-basin *i* in month *j* and day *k* during 1985 – 2000

For wind speed:

$$f_{w(sub\_i,month\_j)} = W_{calib(sub\_i,month\_j)} / W_{CCM(sub\_i,month\_j)}$$

$$W_{adjCCM(sub\_i,month\_j)} = f_{w(sub\_i,month\_j)} \times W_{CCM(sub\_i,month\_j)}$$

$$W_{adjCCM(sub\_i,month\_j,day\_k)} = f_{w(sub\_i,month\_j)} \times W_{CCM(sub\_i,month\_j,day\_k)}$$

where:

$f_{w(sub\_i,month\_j)}$	=	Monthly adjustment ratio or factor for wind speed of sub-basin *i* in month *j*
$W_{CCM(sub\_i,month\_j)}$	=	Monthly Climate Change Model wind speed for sub-basin *i* in month *j* during 1985 - 2000

$W_{calib(sub\_i,month\_j)}$ = Monthly wind speed used for SWAT model calibration (observed data) for sub-basin *i* in month *j* during 1985 – 2000

$W_{adjCCM(sub\_i,month\_j)}$ = Adjusted monthly Climate Change Model wind speed for sub-basin *i* in month *j* during 1985 - 2000

$W_{CCM(sub\_i,month\_j,day\_k)}$ = Daily Climate Change Model wind speed for sub-basin *i* in month *j* and day *k* during 1985 - 2000

$W_{adjCCM(sub\_i,month\_j,day\_k)}$ = Adjusted daily Climate Change Model wind speed for sub-basin *i* in month *j* and day *k* during 1985 – 2000

To adjust the solar radiation and wind speed for 2010 – 2050, the same monthly adjustment ratios from 1985 – 2000 were employed to adjust the monthly and subsequently the daily values of the original PRECIS climate data for every 16 years.

APPENDIX B. TABLES RELATED TO IMPACT ON FISHERIES

Table B.1 Results of the Tukey post-hoc pairwise comparisions of mean maximum water level between the six scenarios.

Dependent Variable: WL max (m)
Tukey HSD

(I) Scenario	(J) Scenario	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-.5734	.36041	.606	-1.6113	.4646
	3	-.3382	.36041	.936	-1.3762	.6998
	4	.4584	.43467	.898	-.7934	1.7102
	5	-.2444	.36041	.984	-1.2823	.7936
	6	.0271	.36041	1.000	-1.0109	1.0650
2	1	.5734	.36041	.606	-.4646	1.6113
	3	.2352	.26618	.950	-.5314	1.0017
	4	1.0318	.36041	.052	-.0062	2.0697
	5	.3290	.26618	.819	-.4376	1.0956
	6	.6004	.26618	.218	-.1662	1.3670
3	1	.3382	.36041	.936	-.6998	1.3762
	2	-.2352	.26618	.950	-1.0017	.5314
	4	.7966	.36041	.238	-.2414	1.8346
	5	.0938	.26618	.999	-.6727	.8604
	6	.3653	.26618	.744	-.4013	1.1319
4	1	-.4584	.43467	.898	-1.7102	.7934
	2	-1.0318	.36041	.052	-2.0697	.0062
	3	-.7966	.36041	.238	-1.8346	.2414
	5	-.7028	.36041	.375	-1.7407	.3352
	6	-.4313	.36041	.838	-1.4693	.6066
5	1	.2444	.36041	.984	-.7936	1.2823
	2	-.3290	.26618	.819	-1.0956	.4376
	3	-.0938	.26618	.999	-.8604	.6727
	4	.7028	.36041	.375	-.3352	1.7407
	6	.2714	.26618	.911	-.4952	1.0380
6	1	-.0271	.36041	1.000	-1.0650	1.0109
	2	-.6004	.26618	.218	-1.3670	.1662
	3	-.3653	.26618	.744	-1.1319	.4013
	4	.4313	.36041	.838	-.6066	1.4693
	5	-.2714	.26618	.911	-1.0380	.4952

Based on observed means.

Table B.2 Back-transformed predicted mean fish biomass indicated by the daily catch rate of a *dai* (stationary trawl) unit (kg/day) for the six scenarios and two flood indices (FI1 and FI2).

	Predicted CPUE (kg/day) for FI 1						Predicted CPUE (kg/day) for FI 2					
Flood Year	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
1984												
1985	135			123			127			112		
1986	175			158			163			141		
1987	146			130			138			119		
1988	168			148			156			132		
1989	199			180			184			159		
1990	305			273			278			234		
1991	226			203			209			179		
1992	158			142			148			128		
1993	169			151			157			135		
1994	329			310			301			267		
1995	327			300			300			260		
1996	326			305			298			263		
1997	255			231			235			203		
1998	146			133			137			120		
1999	235			217			215			187		
2000												
2001												
2002												
2003												
2004												
2005												
2006												
2007												
2008												
2009												
2010		141	108		132	101		145	107		131	97
2011		274	145		259	136		287	143		258	129
2012		142	119		135	109		147	118		134	104
2013		123	117		112	107		127	115		112	103
2014		144	161		130	143		148	158		129	136
2015		151	372		143	347		158	363		142	319
2016		325	557		306	535		340	543		305	490
2017		131	203		117	186		135	199		117	174
2018		196	173		176	157		204	170		175	147
2019		305	337		300	329		320	329		299	303
2020		480	346		453	315		507	338		451	292
2021		182	324		167	310		189	317		167	287
2022		237	279		205	255		247	273		204	238
2023		126	96		117	91		130	95		117	89
2024		369	370		341	332		391	360		340	304
2025		258	219		242	208		271	214		241	194
2026		409	205		392	179		434	201		390	169
2027		222	410		204	388		234	399		203	353
2028		270	296		253	279		283	290		252	258
2029		125	108		116	99		129	107		116	96
2030		166	235		152	205		174	230		152	191
2031		249	502		228	494		261	490		227	452
2032		465	504		450	489		490	491		448	450
2033		181	221		167	210		188	217		167	197
2034		175	141		156	131		182	139		155	125
2035		508	264		503	252		537	258		501	233
2036		283	300		261	277		295	294		260	258
2037		259	209		240	186		270	205		240	175
2038		162	186		141	163		168	183		141	153
2039		171	395		153	376		178	384		153	345
2040		460	367		441	345		485	357		439	315
2041		231	157		215	145		242	155		214	138
2042		265	157		250	141		277	154		249	134
2043		138	363		130	341		143	354		130	314
2044		214	150		192	142		224	148		191	135
2045		101	120		93	112		103	118		93	107
2046		327	162		305	140		344	160		304	134
2047		378	436		366	411		398	425		364	376
2048		703	288		686	267		743	282		683	250
2049		243	157		229	140		253	154		228	133
2050												
Mean	210	230	229	190	214	212	194	241	224	168	213	199

APPENDIX C. COMPARISON OF OBSERVED YIELD WITH THE MODELLED YIELD

C1. Main rainfed rice

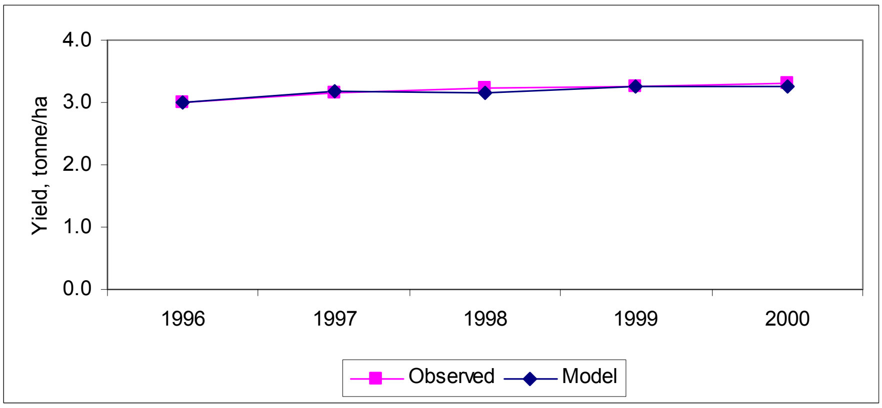


Figure C.1 Comparison of observed and model yield in site L1 (Savannakhet, Laos)

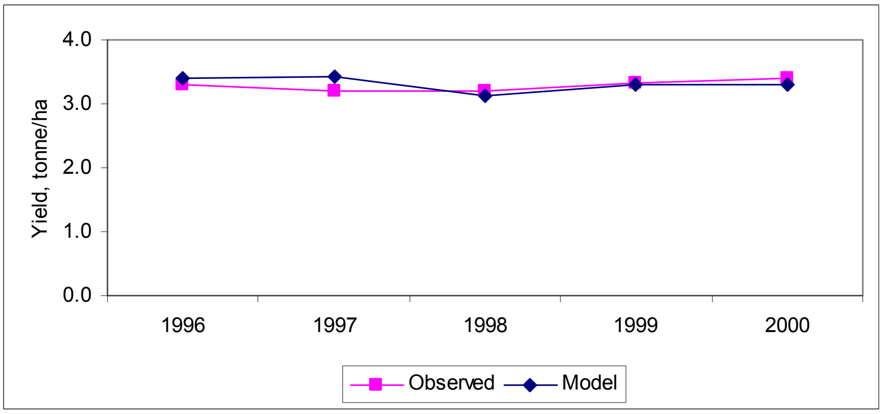


Figure C.2 Comparison of observed and model yield in site L2 (Vientiane Municipality, Laos)

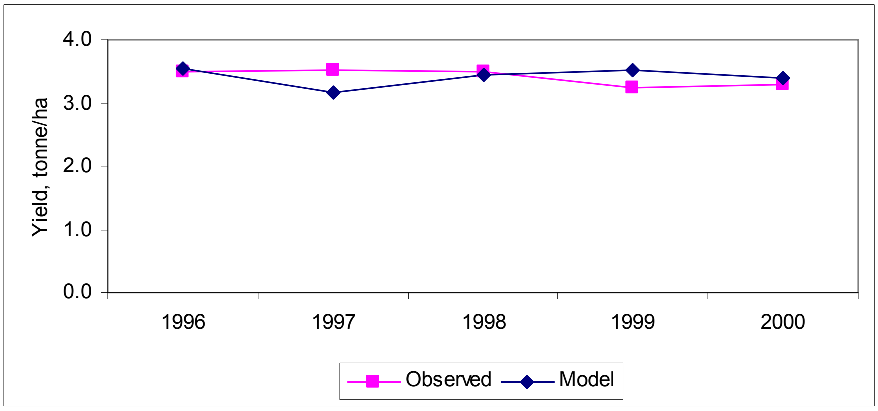


Figure C.3 Comparison of observed and model yield in site L2 (Oudomxay, Laos)

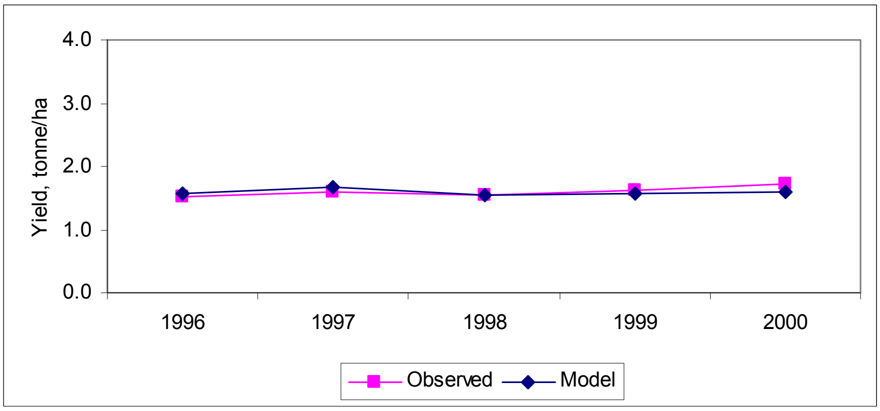


Figure C.4 Comparison of observed and model yield in site T1 (Ubon Ratchathani, Thailand)

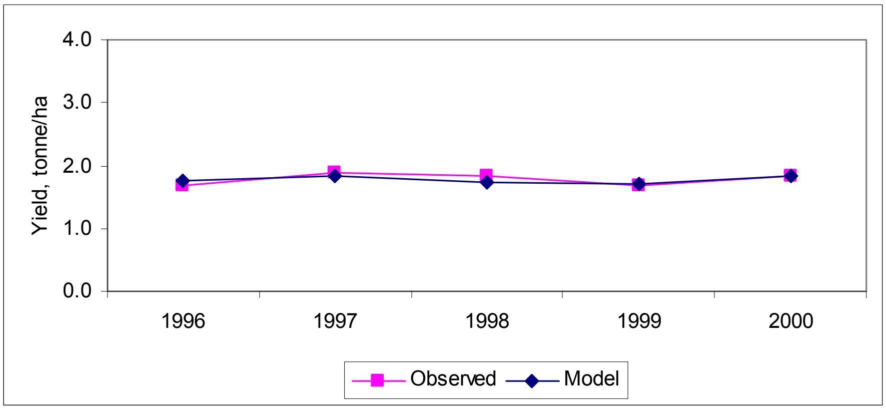


Figure C.5 Comparison of observed and model yield in site T2 (Sakhon Nakhon, Thailand)

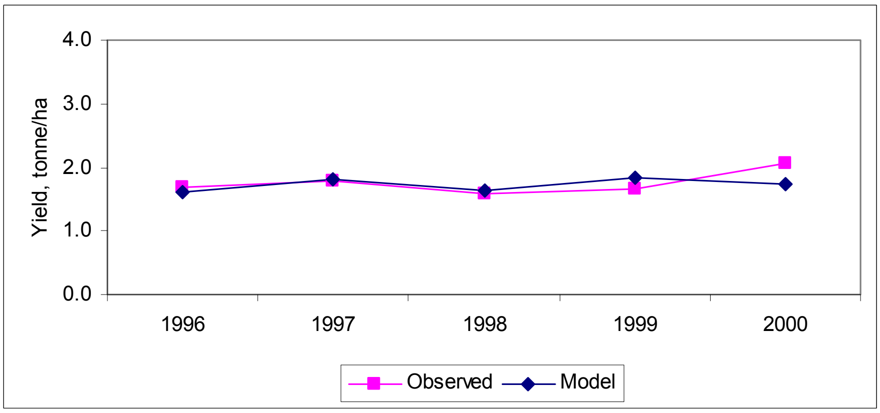


Figure C.6 Comparison of observed and model yield in site T3 (Roi Et, Thailand)

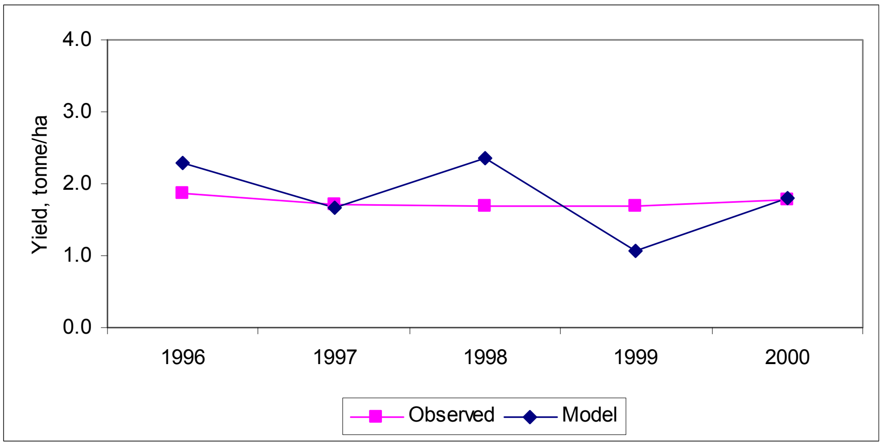


Figure C.7 Comparison of observed and model yield in site T3 (Nakhon Ratchasima, Thailand)

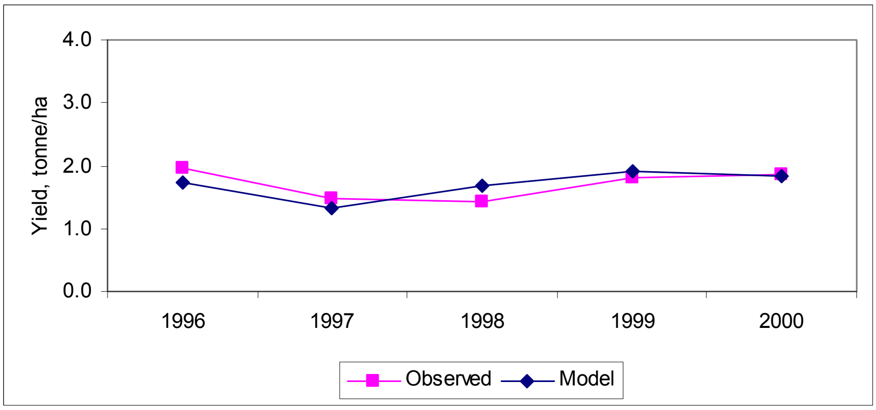


Figure C.8 Comparison of observed and model yield in site C1 (Kampong Speu, Cambodia)

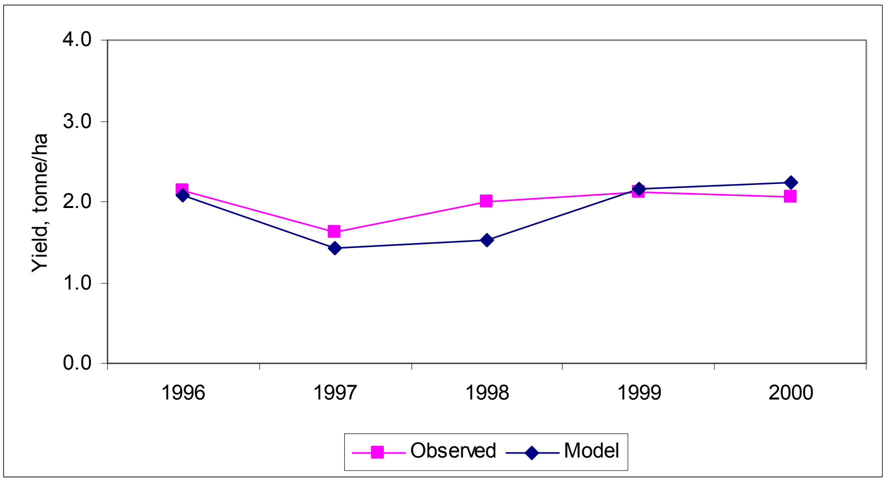


Figure C.9 Comparison of observed and model yield in site C2 (Battambang, Cambodia)

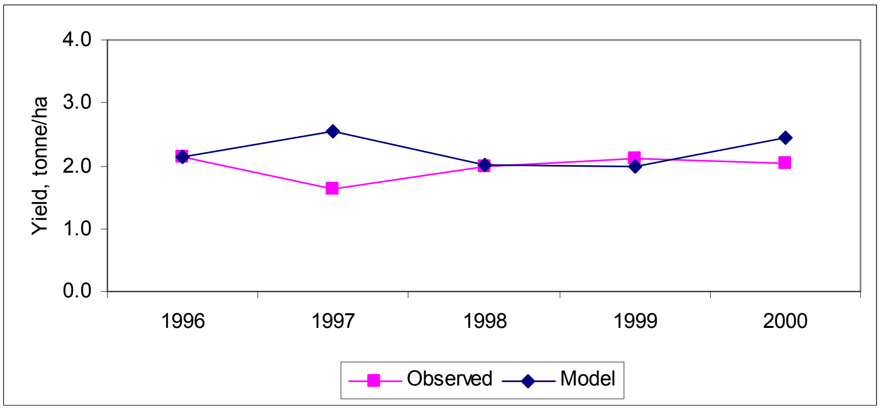


Figure C.10 Comparison of observed and model yield in site C3 (Kratie, Cambodia)

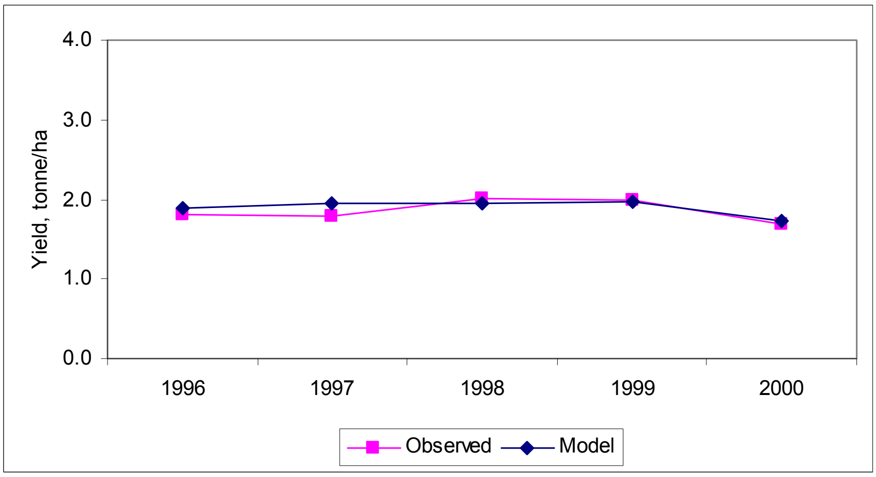


Figure C.11 Comparison of observed and model yield in site C4 (Siem Reap, Cambodia)

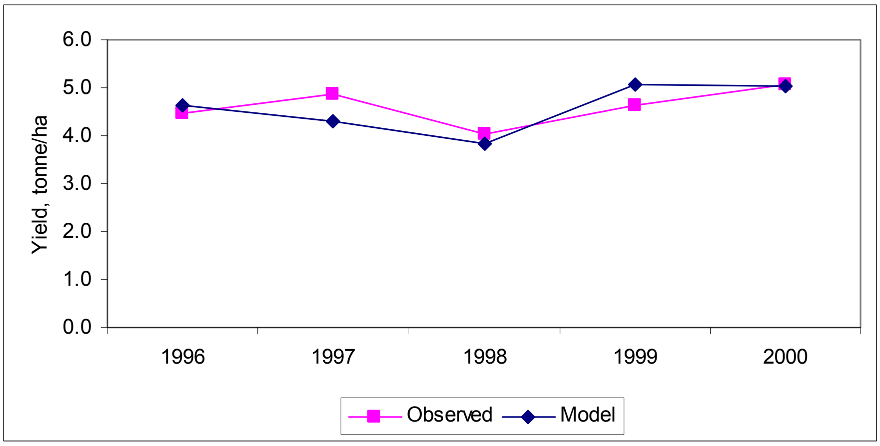


Figure C.12 Comparison of observed and model yield in site V1 (Gia Lai, Central Highlands, Vietnam)

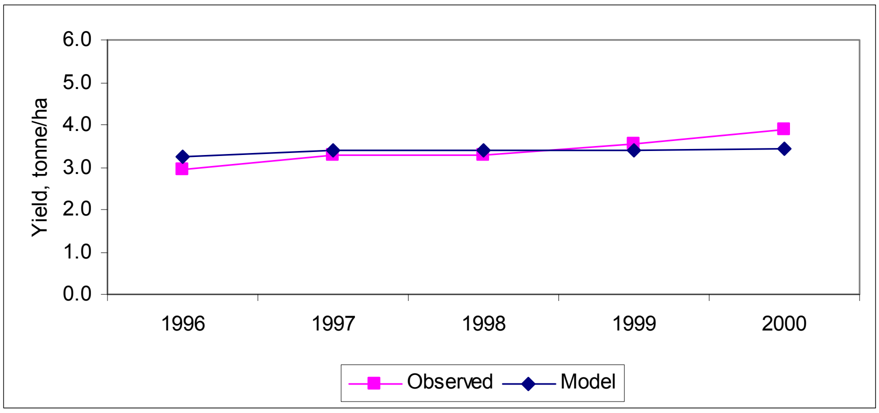


Figure C.13 Comparison of observed and model yield in site V2 (Kien Giang, Mekong Delta, Vietnam)

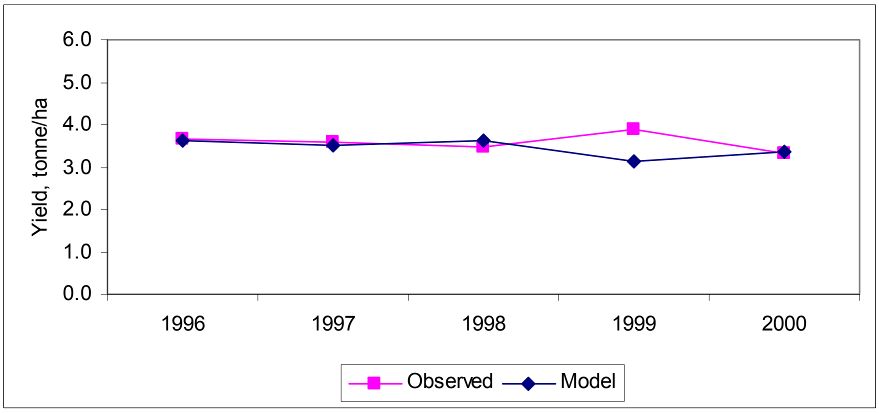


Figure C.14 Comparison of observed and model yield in site V3 (Dong Thap, Mekong Delta, Vietnam)

C2. Irrigated rice

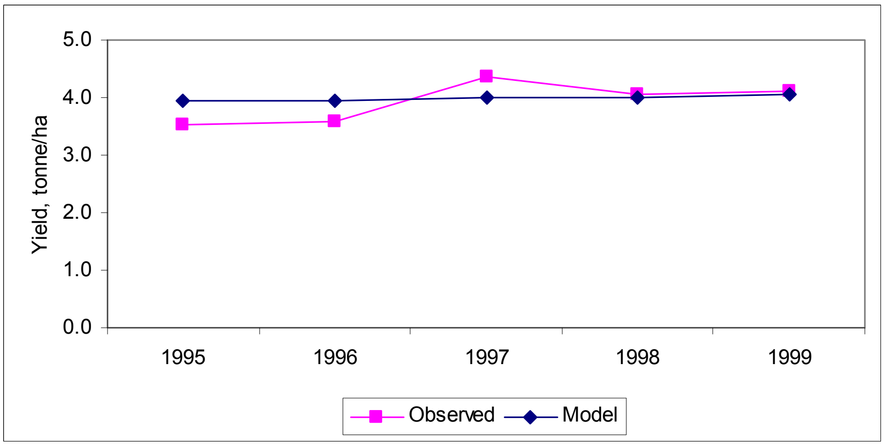


Figure C.15 Comparison of observed and model yield in site L1 (Savannakhet, Laos)

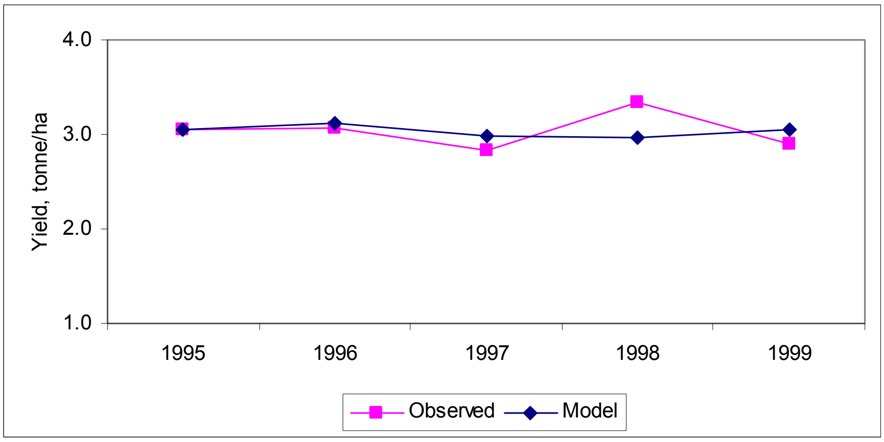


Figure C.16 Comparison of observed and model yield in site T3 (Roi Et, Thailand)

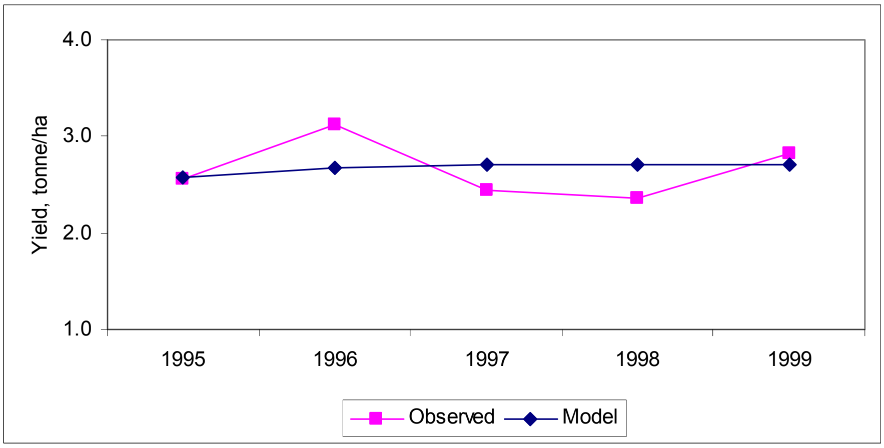


Figure C.17 Comparison of observed and model yield in site T3 (Kien Giang, Mekong Delta, Vietnam)

C3. Maize

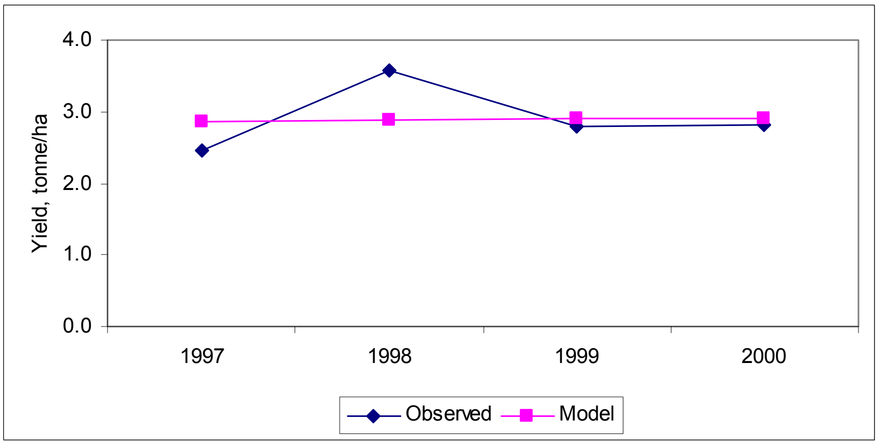


Figure C.18 Comparison of observed and model yield in site L2 (Vientiane Municipality, Laos)

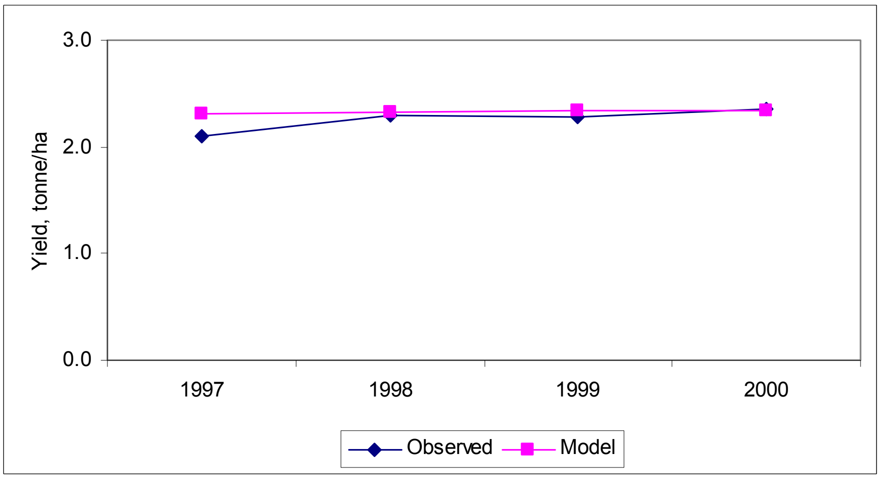


Figure C.19 Comparison of observed and model yield in site L3 (Oudomxay, Laos)

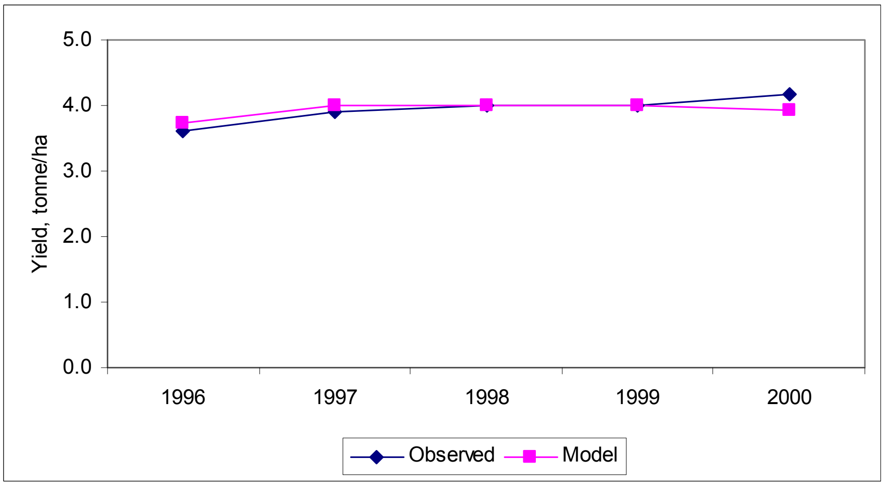


Figure C.20 Comparison of observed and model yield in site T3 (Roi Et, Thailand)

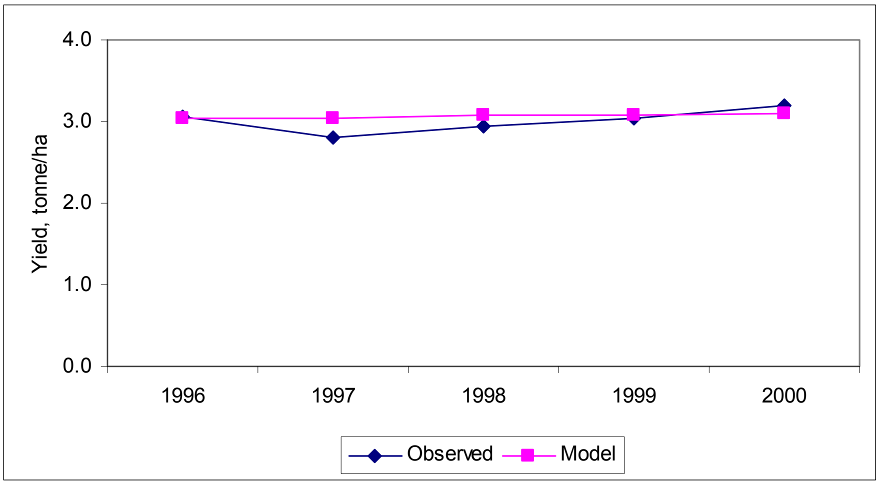


Figure C.21 Comparison of observed and model yield in site T4 (Nakhon Ratchasima, Thailand)

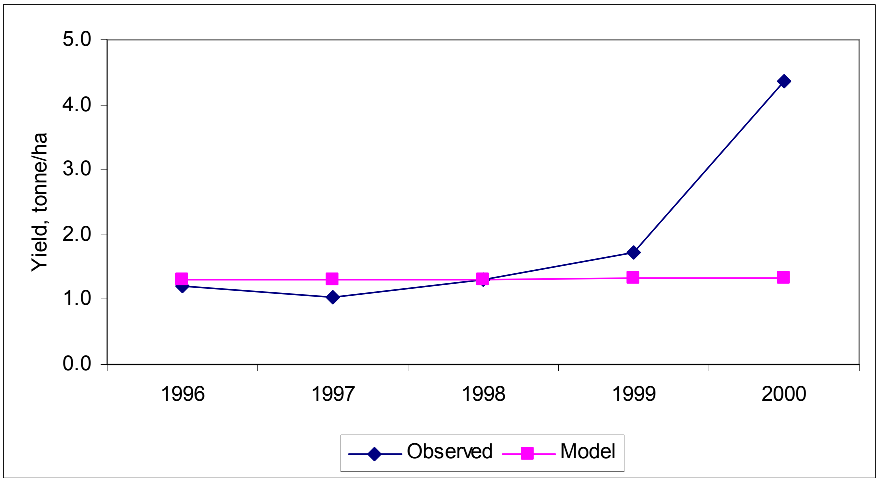


Figure C.22 Comparison of observed and model yield in site C2 (Battambang, Cambodia)

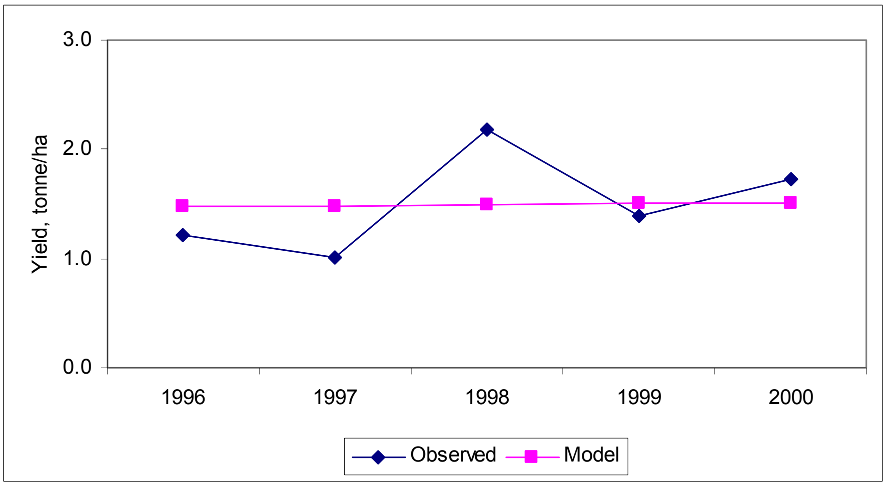


Figure C.23 Comparison of observed and model yield in site C3 (Kratie, Cambodia)

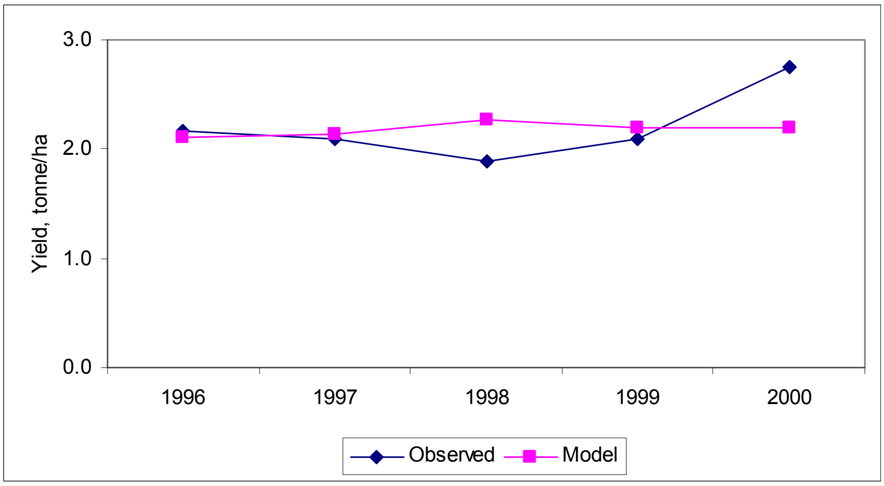


Figure C.24 Comparison of observed and model yield in site V1 (Gia Lai, Central Highlands, Vietnam)

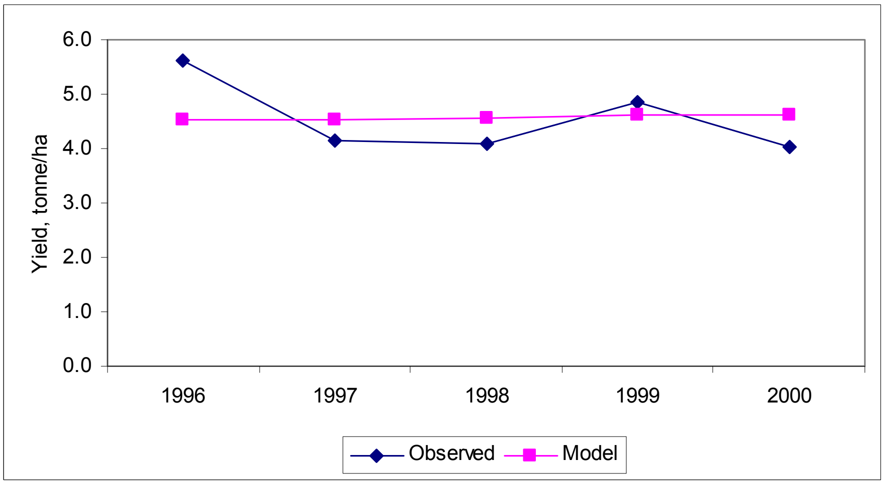


Figure C.25 Comparison of observed and model yield in site V3 (Dong Thap, Mekong Delta, Vietnam)

GLOSSARY

BDP	Basin Development Plan studied by the Mekong River Commission
CC	Climate change
CE	Coefficient of Efficiency
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DSF	Decision Support Framework – MRC's suite of computer-based numerical modelling and knowledge based tools
ECHAM4	A model based on the prevision model of the European Centre "European Centre for Medium Range Weather Forecast" (ECMWF) and modified by the German modelling centre and the Max Planck Institute to adapt it to the long term climatic simulations.
EP	Environment Program
GCM	Global Climate Model or General Circulation Model
IBFM	Integrated Basin Flow Management
IKMP	Information and Knowledge Management Programme
IPCC	Intergovernmental Panel on Climate Change
IQQM	Integrated Quantity Quality Model, a hydrologic modelling tool developed by the Department of Land and Water Conservation (DLWC), New South Wales, Australia for use in planning and evaluating water resource management policies.
ISIS	ISIS is a comprehensive software system developed by Halcrow and Wallingford Software, UK, for managing change in river basins.
IWMI	International Water Management Institute
KB	DSF Knowledge Base
LMB	Lower Mekong River Basin
MQUAD	Data preparation tool for generating catchment average estimates of rainfall from point estimate rainfall.
MRB	Mekong River Basin
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
PET	Potential Evapotranspiration
PRECIS	Providing Regional Climates for Impacts Studies, a regional climate model system developed by Hadley Centre, UK.
RCM	Regional Climate Model
SEA START RC	Southeast Asia SysTem for Analysis, Research and Training Regional Center
SRES	Special Report on Emission Scenarios
SWAT	Soil and Water Assessment Tool, US Department of Agriculture
UMB	Upper Mekong Basin
VR	Volume Ratio
WUP	Water Utilisation Programme

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