Variations in water resources in the Vietnamese Mekong Delta in response to climate change and their impacts on rice production

Nguyen Duy KHANG*,**, Akihiko KOTERA*, Toshichika IIZUMI*, Toshihiro SAKAMOTO*, and Masayuki YOKOZAWA*

(*National Institute for Agro-Environmental Sciences, Kannondai 3-1-3, Tsukuba, Ibaraki, 305-8604, Japan
**Southern Institute of Water Resources Research, 28 Ham Tu, District 5, Hochiminh city, Vietnam)

Abstract

A numerical hydraulic model was developed and used to investigate the spread of salinity intrusion and the propagation of flooding in the Vietnamese Mekong Delta under two proposed scenarios: “baseline” (2000s) and “future” (2090s). The baseline scenario was based on observed hydrological and salinity intrusion data from 1998 to 2006. The changes in upstream flow discharge in the future scenario (increased for most of the year) were derived from previous research results obtained using the Japan Meteorological Agency atmospheric general circulation model output for the IPCC SRES A1B scenario. The sea level rise in the A1B scenario (a projected 53-cm increase) was also included in the future scenario. The resulting salinity intrusion and flood water levels were then used to roughly estimate possible rice cropping durations. We found that large adverse changes in duration of rice cultivation in the future scenario were caused mainly by floods with greater peaks, larger areal extents, and longer durations. The area potentially suitable for growing triple rice crops decreased from 31% of the total delta area currently to 5%, whereas that potentially suitable for a single rice crop increased from 21% currently to 62%. Using GIS techniques, we divided the delta into three areas with different levels of rice vulnerability levels. Areas of high and medium vulnerability covered approximately 31 and 36% of the total delta area, respectively.

Key words: Climate change impacts, Flooding, Rice cultivation, Salinity intrusion, Vietnamese Mekong Delta.

1. Introduction

The Vietnamese Mekong Delta is located in the lower reaches of the Mekong River (Fig. 1). It plays a key role in the socioeconomics of Vietnam, as a highly productive and densely populated area. Rice is the main crop, and the delta annually contributes significant amounts for export. Rice cultivation in the delta is greatly dependent on water resources and quality, and these parameters are strongly governed by salinity intrusion during the dry season and flooding during the rainy months.

In the IPCC Fourth Assessment Report: Climate Change 2007 (IPCC, 2007), precipitation during the 21st century is projected to increase across the Mekong Basin during the rainy season, and possibly even during the dry season in some areas. Consequently, the annual flow discharge is projected to increase for most of the year, with larger increases during the rainy season. Extreme flood events are likely to occur with higher frequency, greater peaks, and longer duration (Hoanh et al., 2003; Kiem et al., 2008; Eastham et al., 2008). In addition, the sea level is projected to increase, possibly causing more severe saline intrusion in coastal areas of the delta. The sea level rise will also adversely affect flooding in upstream areas of the delta (Wassmann et al., 2004).

We examined the potential impacts of the projected sea level rise and variations in the upstream river flow caused by climate change on the delta’s hydrological regime and water resources. We also developed the River and Channel network Analysis System (RiCAS) hydraulic model to investigate the changes in salinity...
intrusion and flooding in the delta in terms of their levels, areal extent, and duration. We subsequently used the simulation results to compute the possible rice cultivation duration as a function of variations in the available water resources, and used this change to perform a risk assessment for the study area.

2. Study area

The Vietnamese Mekong Delta covers an area of 3.9 million ha, which is approximately 79% of the overall Mekong Delta. Approximately 80% of the delta is less than 1.0 m above mean sea level, and only 1% is higher than 3.0 m. For this reason, the delta has been identified as one of the world’s most vulnerable areas under predicted future climate change (World Bank, 2007; IPCC, 2007)

The delta is divided into several parts by a complex system of interconnected rivers and channels. The delta’s hydrological regime is influenced by the flow discharge of the Mekong River, the diurnal tides in the South China Sea, and the semi-diurnal tides in the Gulf of Thailand. Climate in the delta is governed by monsoon winds, resulting in two clear seasons: a rainy season from May to November, and a dry season during the rest of the year.

By 2007, the delta’s total population had reached about 17.5 million, of which 13.8 million lived in rural areas and were involved in agriculture or related activities, with rice as a major crop. The delta contributes approximately 50% of Vietnam’s total cereal production and more than 80% of the rice produced for export, positioning Vietnam as the world’s second-largest rice exporter (GSOV, 2007). Rice cultivation in the delta is classified into three crops: “dong xuan” (the winter-spring crop), “he thu” (the summer-autumn crop), and “mua” (the rain-fed crop). Variations in the available water resources and in water quality, which are strongly governed by salinity intrusion during the dry season and flooding during rainy months, are the key factors determining the cultivation calendar and number of crops (i.e. single, double, or triple) in various parts of the delta (Wassmann et al., 2004; Kotera et al., 2008).

3. Model development and set up

We developed the RiCAS hydraulic model to simulate water flows and salinity intrusion in the complex connected river and channel network of the Vietnamese Mekong Delta. RiCAS was designed to be part of an integrated model in which RiCAS is coupled with a crop model via a water-balance module. This integrated model is being developed as a tool to investigate the overall possible impacts of climate change on the delta’s rice crop.

RiCAS was developed by numerically solving the Saint-Venant equations (Cunge et al., 1980) for water flow and the advection-dispersion equation for solute transport. The model can be divided into two modules: the solution for water flow is initially obtained using a hydrodynamic module, and this flow is then used...
as input for the simulation of solute transport using an advection-dispersion module. In this section, we briefly introduce the development of the model based on the governing equations and numerical methods, and then present the model verification and validation results. The construction of a computational scheme to simulate the flow and salinity intrusion in the delta is also presented.

3.1 Governing equations

The hydrodynamic module of RiCAS is based on the full set of Saint-Venant equations (Cunge et al., 1980, Abbot and Minns, 1998) that describe one-dimensional flow in an open-channel network:

- Mass conservation equation:
  \[
  \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad \text{or} \quad \frac{\partial q}{\partial t} + \frac{1}{b} \frac{\partial Q}{\partial x} = q \tag{1}
  \]

- Momentum conservation equation:
  \[
  \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \alpha \frac{Q^2}{A} \right) + gA \frac{\partial z}{\partial x} + gA \left( \frac{Q}{K} \right)^2 = 0 \tag{2}
  \]

where \( A \) is the cross-section area of the river or channel, \( Q \) is the flow discharge, \( z \) is the water surface level, \( b \) is the storage width, \( \alpha \) is the momentum distribution coefficient, \( q \) is the lateral flow, and \( K \) is the conveyance, which is calculated as \( K = \frac{AR^{2/3}}{n} \), where \( n \) is the Manning coefficient and \( R \) is the hydraulic radius

The advection-dispersion module of RiCAS is based on the following mass conservation equation:

\[
\frac{\partial A C}{\partial t} + \frac{\partial Q C}{\partial x} - \frac{\partial}{\partial x} \left( AD \frac{\partial C}{\partial x} \right) = AK_d C + qC_o \tag{3}
\]

where \( C \) is the solute concentration, \( D \) is the dispersion coefficient, \( K_d \) is the first-order decay rate, and \( C_o \) is the source concentration of the lateral flow

3.2 Numerical methods

a) The Abbot-Ionescu scheme for the Saint-Venant equations

The Saint Venant equations (1 and 2) are solved by using the finite difference method with the six-point implicit Abbott-Ionescu scheme on a staggered grid combined with the double-sweep algorithm. Details of this method are described by Cunge et al. (1980) and Abbott and Minns (1998)

b) The MUSCL-TVD scheme for the advection-dispersion equation

An implicit finite difference MUSCL-TVD type scheme was designed to solve the advection-dispersion equation. This scheme is a well-known high-resolution numerical method which has been derived for hyperbolic conservation equations. The MUSCL part of the approach implies a high-order of accuracy obtained by the data reconstruction, which is constrained so as to avoid spurious numerical oscillations, while the TVD method ensures that the total numerical variation does not increase over time, which means that the numerical scheme is convergent (Toro, 1999 and references therein). The derivation of the scheme can be briefly introduced as follows:

Most of the MUSCL-TVD type schemes in the literature are presented in terms of the linear advection equation. For the purpose of simplicity in constructing a numerical scheme, we wrote equation (3) in the following form:

\[
\frac{\partial C'}{\partial t} + \frac{\partial \nu C'}{\partial x} - \frac{\partial}{\partial x} \left( D \frac{\partial C'}{\partial x} \right) = AK_d C' + qC_o \tag{4}
\]

where \( C' = AC \) is the new representative variable for the solute concentration, \( \nu = \frac{Q}{A} \) is the cross-sectional averaged flow velocity, and \( \nu' = \nu + \frac{D}{A} \frac{\partial A}{\partial x} \) is named as the “geometrical velocity”, which implies that it implicitly includes channel geometry variations. Based on equation (4), with the new variable \( C' \) and the geometrical velocity \( \nu' \), the finite-difference scheme can be derived by considering the mass flux into a control element situated around a grid point, as illustrated in Fig. 2. The scheme’s formulation can be expressed as follows:

\[
\nu_{i+1/2} \frac{C_{i+1} - C_{i}}{\Delta t} + F_{i+1/2}^{+1/2} - F_{i-1/2}^{+1/2} = q_{i+1/2}^{+1/2} C_{o}^{+1/2} \tag{5}
\]

Fig. 2. Illustration of a control element in the advection-dispersion model.
where $V_{s+1/2}^{n+1/2}$ is the storage volume, $F_{s+1/2}^{n+1/2} = h_{s+1/2}^{n+1/2} + p_{s+1/2}^{n+1/2}$ is the mass flux at the downstream face of the $i$-th control element, and the symbols $h$ and $p$ stand for the advection and dispersion fluxes, respectively. The subscript $n+1/2$ indicates that the functions are evaluated at the centre time level $n+1$.

The dispersion flux term is approximated by using the central scheme as shown in the equation (6):

$$ p_{s+1/2}^{n+1/2} = - D_{s+1/2}^{n+1/2} \left( C_{s+1/2}^{n+1/2} - A_{s+1/2}^{n+1/2} C_{s+1/2}^{n+1/2} + A_{s+1/2}^{n+1/2} C_{s-1/2}^{n+1/2} - A_{s-1/2}^{n+1/2} C_{s+1/2}^{n+1/2} \right) / 2Ax_{s+1/2}, \tag{6} $$

Despite the introduction of the new variable $C_i$, the solute concentration $C_i$ is still explicitly presented in the derived numerical formulations hereafter, because all values of the cross-section area $A$, even at time step level $n+1$, are known before the advection-dispersion equation is solved.

The MUSCL-TVD type scheme is derived for the advection flux by using the slope-limiter method in data reconstruction and the flux-limiter for the monotone flux respectively. The final expression of the scheme is written as below

$$ h_{s+1/2}^{n+1/2} = \frac{1}{4} \left[ \beta_s^{n+1/2} (1 + \alpha_s^{n+1/2}) \phi_s^{n+1/2} + \beta_s^{n+1/2} (1 - \alpha_s^{n+1/2}) \phi_s^{n+1/2} \right], \tag{7} $$

Where

$$ \beta_s^{n+1/2} = 1 - \text{sign} (\phi_s^{n+1/2}) \phi_s^{n+1/2}, $$

$$ \beta_s^{n+1/2} = 1 - \text{sign} (\phi_s^{n+1/2}) \phi_s^{n+1/2}, $$

$$ \phi_s^{n+1/2} = \beta_s^{n+1/2} \left[ (1 + \omega) A_{s+1/2}^{n+1/2} + (1 - \omega) A_{s-1/2}^{n+1/2} \right], $$

$$ \Delta_i = \zeta(r_i) \Delta_i, $$

$$ \Delta_i = \frac{1}{2} \left[ (1 + \omega) A_{i+1/2}^{n+1/2} + (1 - \omega) A_{i-1/2}^{n+1/2} \right], $$

$$ r_i = \frac{A_{i+1/2}^{n+1/2}}{A_{i+1/2}^{n+1/2}} = \left\{ \begin{array}{ll}
A_i & \text{if } \phi_s^{n+1/2} > 0 \\
A_{i+1/2}^{n+1/2} & \text{if } \phi_s^{n+1/2} < 0
\end{array} \right. $$

$\zeta(r_i)$ is the slope-limiter function, $\phi_{s+1/2}$ is the flux-limiter function.

Substituting (6) and (7) into (5) yields the following linear algebraic equation:

$$ \begin{align*}
\alpha_i C_i^{n+1/2} + \beta_i z_i^{n+1/2} + \gamma_i Q_i^{n+1/2} & = \delta_i, \tag{8}
\end{align*} $$

where the coefficients $\alpha_i, \beta_i, \gamma_i$, and $\delta_i$ are estimated during iterations. Obtaining (8) for all grid points results in a system of algebraic equations that can be solved by using the double-sweep approach (Cunge et al., 1980; Abbott and Minns, 1998).

### 3.3 Model verification and validation

RiCAS was verified by comparing its simulation results with the analytical solutions available for some benchmark problems to check the model’s scheme. Besides, a comparison between the simulation results and observed data at several hydrological stations in the Vietnamese Mekong Delta, as presented in section 3.4, is another verification example. In addition, in order to confirm that the model was free of logical errors, the RiCAS results were compared with the solutions produced by the MIKE11 model, which is popular and widely used for rivers and estuaries and was developed by DHI Water & Environment (DHI, 2004). These analyses were conducted for several simulation cases with wide-ranging complexity of channel network connections, cross-sectional geometries, grid-size variations, and hydraulic structure operations, as well as with various boundary conditions. Due to space limitations within this paper, only some of the verification examples are presented here to illustrate the approach.
Fig. 3 is a simple example used to verify the advection-dispersion module. The simulation results are compared with the analytical solutions of the constant-parameter advection-dispersion equation, subject to a continuous load of infinite duration (Runkel, 1996). The longitudinal concentration profiles obtained by applying a rather coarse grid size of 1000 m using both RiCAS and the MIKE11 model are displayed for comparison. Both models predicted the longitudinal profile well for both small and large values of the dispersion coefficient (i.e., for $D=10$ and 30 m$^2$/s, respectively). However, RiCAS did not generate any overshoot or undershoot solutions, even with a small dispersion coefficient, unlike MIKE11. The numerical solutions produced by MIKE11 seemed to be smoother than those obtained using RiCAS, indicating a larger “numerical dispersion”. Similar numerical analyses were also performed for several sets of model parameters, such as flow velocity, dispersion coefficient, and grid size. The results (not shown here) confirmed that with a finer grid resolution and a larger dispersion coefficient both models produced similar concentration profiles that fitted the respective analytical solutions well.

Fig. 4 is another example of verification of both the hydrodynamic module and the advection-dispersion module. Simulated solutions for water level (Fig. 4a), flow discharge (Fig. 4b), and salinity intrusion (Fig. 5) showed similarly good results for RiCAS and MIKE11. The computational scheme is described in section 3.4. In this comparison, we assigned the observed hydrological and saline concentration data in 2000 to the respective boundaries. To avoid any discrepancies that might have been caused by differences in the interpolation techniques employed for assigning model parameters to grid points, we used a single parameter set for each river or channel branch. The water level at Long Xuyen and the flow discharge at My Thuan produced by RiCAS agreed well with those obtained by using MIKE11 (Fig. 4). RiCAS also predicted saline concentrations similar to those predicted by MIKE11 at Dai Ngai and My Hoa (Fig. 5). These results suggest that we can confidently use RiCAS to simulate the flows and salinity intrusion in the delta’s river and channel network.

3.4 Model setup and calibration for the Vietnamese Mekong Delta

The model’s computational scheme extends from Kratie in Cambodia to the South China Sea and the Gulf of Thailand. The model includes the Tonle Sap Lake, floodplains in both Cambodia and Vietnam, and most of the main rivers and channels in the Vietnamese Mekong Delta. Flow discharges are assigned to upstream boundaries and sea water levels imposed as downstream boundaries. The river and channel network was constructed using a topographical map at a scale of 1:100,000, published by Map Publishing House in 2003. The Google Earth tool was also effectively used in constructing the model scheme. The cross-section data of the rivers and channels were provided by Southern Institute of Water Resources Research, while those on the configuration and operation of the sluice...
gate and bridge system, and the main road and dyke system were collected from provincial Departments of Agricultural and Rural Development and Departments of Transport. The flood plains were schematized by using “artificial” channels with specific storage areas. Interchange flows between channels and floodplains were computed by using the energy equation (Cunge et al., 1980; DHI, 2004), which provided a quasi-two-dimensional description of the flood plains.

Model calibration and validation were performed by using the observed hydrological and salinity intrusion data from 1998 and 2000. The observed hydrological data was provided by Southern Center for Hydro-Meteorology, while observed salinity intrusion data was collected from the Southern Institute of Water Resources Research. In addition, daily maps of the flooding extent derived from MODIS satellite images in 2000 (Sakamoto et al., 2007) were used in the model setup and calibration and to validate the flood simulation. Some calibration results have been provided as illustrations in this report. The simulated water levels at key locations along the main branches of the Mekong River fitted well with the observed data, both during the dry season and during months with flooding (Fig. 6). Good agreement was also found between the simulated and observed values of the daily maximum saline concentration at Tra Kha (Fig. 7).

### 4. Simulation scenarios

After calibration and validation, we used the model to simulate flows and salinity intrusion for the two proposed scenarios: the “baseline” scenario (for the 2000s) and the “future” scenario (for the 2090s). In the baseline scenario, the upstream flow discharge of the Mekong River was taken as the annual averaged flow rate from 1998 to 2006. Tidal levels and saline concentrations of sea water were imposed as the downstream boundaries using data from 2005. We selected 2005 for this data because the upstream discharge variations during the dry season that year were similar to the annual averaged flow rate from 1998 to 2006.

According to IPCC (2007) under the SRES A1B scenario, by the end of this century, the global average sea level was projected to rise by up to 48 cm above 1990s levels. The local changes in sea level due to changes in ocean density and circulation relative to the global average in the South China Sea and the Gulf of Thailand are approximately 0 to 5 cm, which means that the sea level in the South China Sea and the Gulf of Thailand is projected to rise by up to 53 cm by the end of the 21st century under this scenario. We adopted this sea level rise in our model simulation for the future scenario.

### Table 1. Monthly rates of change in flow discharge of the Mekong River and sea level rise value used in the future (2090s) scenario. Flow data were obtained from Kiem et al. (2008).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of change in flow discharge (%)</td>
<td>+6.8</td>
<td>+8.4</td>
<td>+15</td>
<td>+20.9</td>
<td>-14.4</td>
<td>+2.8</td>
<td>+63.0</td>
<td>+60.4</td>
<td>+24.4</td>
<td>+14.8</td>
<td>+19.4</td>
<td>+61.1</td>
</tr>
<tr>
<td>Sea level rise (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>52</td>
</tr>
</tbody>
</table>

Fig. 6. Comparison of the observed and simulated water levels at (a) Chau Doc and (b) Tan Chau in year 2000 (see Fig. 1 for the locations of the stations).

Fig. 7. Comparison of the observed and simulated daily maximum salinity concentration values at Tra Kha in 2000 (see Fig. 1 for the locations of the stations).
Kiem et al. (2008) studied the impact of climate change on the hydroclimatology and water resources of the Mekong River Basin by using the Yamanishi hydrological model. Their analysis was based on the output of the high-resolution Japan Meteorological Agency atmospheric general circulation model for the SRES A1B scenario. Their findings suggest that the monthly average flow discharge of the Lower Mekong Delta sub-basin (the parts in Cambodia and Vietnam) from 2080 to 2099 will increase for most of the year, especially during the rainy season (Table 1), compared with the levels from 1979 to 1998. We used these values of the changes in monthly average discharge to derive the upstream boundary for the future scenario in our study.

5. Results and Discussions

5.1 Impacts on irrigation water available for rice crops during the dry season

Using a salinity value of 2.5 g/L as the threshold for irrigation water (Khang et al., 2008), we calculated the duration of the period when the irrigation water was available for rice crops during the dry season at every grid point. The results were then transferred into a GIS dataset and used to interpolate the values at any given point in the delta. Given that sufficient rain water was available to permit rice cultivation during the wet season, the duration of the period when irrigation water was available throughout the year was computed as the duration during the dry season plus all months of the rainy season.

The increased upstream flow discharge during the dry months in the future scenario (as presented in Table 1) was expected to reduce salinity intrusion, whereas the sea level rise simultaneously caused saline water to intrude farther inland. The positive impacts that resulted from the increased upstream flow discharge outweighed the negative impacts caused by the sea level rise (Fig. 8). This also indicated the effectiveness of the sluice gate system in protecting paddy fields against salinity intrusion. It can be seen that the positive impacts also outweigh the negative in coastal areas along the South China Sea, particularly in Tra Vinh and Long An provinces. However, such positive impacts accounted only for irrigation water and did not counteract the negative effects of flooding (discussed in section 5.2).

5.2 Effects on flooding and possible durations for rice cropping

Fig. 9 depicts the combined impacts of the sea level rise and the increase in flow rates of the Mekong River during the rainy season. In the future scenario, flooding was clearly much greater than in the baseline scenario in terms of both flood levels and areas inundated. Flooding extended strongly towards the sea, especially in Kien Giang, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, and Ca Mau provinces, where it had rarely been observed in the past, even during extreme flood events such as those having occurred in 2000. The area inundated to a depth exceeding 0.5 m increased by approximately 23% of the delta’s total area, and the area with a flood depth exceeding 2 m increased from 4% of the total delta area in the baseline scenario to 25% in the future scenario (Table 2). Extreme flooding...
Fig. 9. Spatial distribution of flood depths at the time of maximum flood extent (on 19 October in the baseline scenario and 21 September in the future scenario).

Table 2. Areas flooded to different flood depths in the baseline (2000s) and future (2090s) scenarios.

<table>
<thead>
<tr>
<th>Flood inundation area at maximum flood extend (ha)</th>
<th>&lt;0.5</th>
<th>0.5-1</th>
<th>1-2</th>
<th>2-3</th>
<th>&gt;3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>None</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>Extremely high</td>
</tr>
<tr>
<td>“Baseline” (2000s)</td>
<td>2,170,825 (54%)</td>
<td>770,000 (19%)</td>
<td>933,175 (23%)</td>
<td>157,950 (4%)</td>
<td></td>
</tr>
<tr>
<td>“Future” (2090s)</td>
<td>1,239,975 (31%)</td>
<td>821,125 (20%)</td>
<td>971,200 (24%)</td>
<td>846,925 (21%)</td>
<td>152,725 (4%)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are percentages of the delta's total area.

Fig. 10. Spatial distribution of the number of possible rice crops as a result of salinity intrusion and flooding in the baseline and future scenarios.

(a flood depth exceeding 3.0 m) was not found in the baseline scenario, but covered 4% of the delta’s total area in the future scenario, primarily in An Giang and Long An provinces.

Furthermore, the rise in sea level and the increase in upstream flow discharge would also increase the flooding duration. Using a flood depth of 0.5 m as the threshold value at which failure of the rice crop is likely (Kotera et al., 2005, Kotera et al., 2007), we computed the flood durations for areas that exceeded
this threshold. These values, together with the results obtained in section 5.1 concerning the duration of availability of irrigation water, were then used to estimate the possible durations of rice cultivation. From field data, the region's average period of 110 days was adopted for the duration of a single rice crop. The results implied significant changes in possible cultivation durations in almost all provinces, from the upstream region to the delta's coastal area. The area potentially available for triple rice crops was estimated to decrease from 31% of the total area to 5%, whereas the area potentially suitable for a single rice crop increased from 21% of the delta's total area to 62% respectively. As we noted in section 5.1, the beneficial impacts on rice cultivation in terms of water availability for irrigation were outweighed by the large decreases that would result from flooding. Therefore, the cumulative changes in the length of time available for rice cultivation and its spatial distribution in the future scenario (Fig. 10) were caused mainly by the longer flooding duration, deeper flooding, and larger flood extent.

5.3 Vulnerability assessment for rice cultivation
To analyze the wide-ranging impact of the sea level rise and the variation of the Mekong River flow on rice cultivation, we used a rice crop vulnerability index (RCVI), which was computed as follows:

$$RCVI = \begin{cases} \frac{\Delta_i}{S_{RC}} & \text{if } \Delta_i > S_{RC} \\ 1 & \text{if } \Delta_i < S_{RC} \end{cases}$$

where $\Delta_i$ (days) the decrease in the potential duration of rice cultivation in the future scenario compared with the duration in the baseline scenario, and $S_{RC}$ (days) is the length of time required to cultivate a single rice crop (110 days). If $RCVI \geq 1$, this means that at least one rice crop may fail. Fig. 10 depicts the spatial distribution of crop vulnerability in the delta, based on the vulnerability indices in the future scenario. Similar to the classification criteria of Khang et al. (2008), we defined three broad vulnerability classes: areas with high ($RCVI \geq 0.66$), medium (0.66$ > RCVI > 0.33$), and low ($RCVI \leq 0.33$) vulnerabilities respectively.

The areas with high and medium vulnerabilities covered most of the central part of the delta, as well as parts of the coastal areas in Kien Giang, Ca Mau, and Soc Trang provinces. Areas with high and medium vulnerability accounted for approximately 31% and 36% of the delta's total area, respectively.

6. Concluding remarks
We used a future (2090s) scenario derived from the IPCC SRES A1B climate change projections to investigate the potential impacts of the projected climate-change-related sea level rise and variations in the upstream river flow of the Mekong River on salinity intrusion and flooding in the Vietnamese Mekong Delta. We used the results to assess the effects of these changes on the potential duration of rice cultivation. We observed significant changes in cultivation durations in most provinces, from the upstream reaches to the coastal area of the delta. The area potentially suitable for cultivating three rice crops decreased from 31% of the delta’s total area to 5%, whereas the area potentially suitable for a single rice crop increased from 21% of the area to 62% respectively. These significant changes were caused mainly by increased flooding, with a greater peak, larger areal extent, and longer duration.

Vulnerability assessments were conducted on the basis of the assumption that no adaptation measures would be applied to mitigate the impacts of climate change. As a result, approximately 67% of the delta’s total area would be significantly adversely affected by climate change.

However, because our assessment was based on salinity intrusion and flooding for a single scenario,
derived by using output from only one AGCM, the results can be considered to provide only an initial estimation of the possible impacts. It is obvious that a more comprehensive study of the impacts of climate change on rice production should be founded on multiple AGCM outputs. Furthermore, such a study should account for the impacts of climate change on other factors directly affecting rice production, such as solar radiation, precipitation, and temperature. For this purpose, a crop model should be combined with the hydraulic model developed here to provide an integrated model. Development of this model is underway. Despite these shortcomings and the uncertainties in the climate change projections, our results suggest that adaptation measures and mitigation strategies should be developed and implemented as soon as possible to protect against the negative effects of climate change -especially the combined impacts of increased flooding and the projected future sea level rise. Such impacts must be accounted for in the planning and management of the region’s water resources and infrastructures as well as in any strategy for regional socioeconomic development.

Acknowledgments

This study was supported by the Global Environment Research Fund (S-4) of the Ministry of the Environment, Japan

References


**N. D. Khang et al.: Water resources and rice production in VMD subject to climate change**

ベトナム・メコンデルタの水資源変動
—気候変化の影響とその変動がコメ生産に及ぼす影響—

Nguyen Duy KHANG*・**・小寺昭彦*・飯泉仁之直*・坂本利弘*・横沢正幸*

（*農業環境技術研究所**ベトナム南部水資源研究所）

要 約

ベトナム・メコンデルタにおける塩水週上現象と洪水現象を高精度で再現する水理モデルを開発し、"現在" (2000年代) および"将来" (2090年代) シナリオを適用することで水資源環境およびその変動がコメ生産に及ぼす影響を評価した。デルタ上流域における河川流量変化は、"現在" シナリオでは1998-2006年の水文観測データを適用し、"将来" シナリオではSRES A1Bの排出シナリオに基づきJMA-AGCMによって予測された値を用いて作成した。また、将来の海面上昇量はA1B排出シナリオに基づいて予測された値 (+52 cm) を用いた。モデルで予測された塩水週上期間と洪水期間から、水稲の作付が可能となる期間を推計したところ、"将来"における作付可能期間は "現在" よりも大きく短縮する傾向が示された。これは "将来" において洪水期の最大潜水深、潜水域、潜水期間が共に "現在" よりも増大すると予測されたことが主な要因である。その結果、3期作可能地域の面積はデルタ全体の31%から5%に減少するとともに、1期作のみ可能な地域の面積は21%から62%に増加すると推計された。さらに、作付可能期間の減少度を表す指標を用いて気候変化によるコメ生産の脆弱性を評価しGISを用いて分類したところ、脆弱性が高いおよび中程度と評価された地域はそれぞれデルタ面積の31%，36%に及ぶと推計された。

キーワード：稲作、塩水週上、気候変化影響、洪水、ベトナム・メコンデルタ