IMRR Project
Integrated and sustainable water Management
of Red-Thai Binh River System in a changing climate

Report D7.2
Estimating the effects of Climate Change
and designing adaptation policies

Authors:
Matteo Giuliani - DEIB Polimi
Daniela Anghileri - DEIB Polimi
Andrea Castelletti - DEIB Polimi
Phuong Nam Vu - IWRP

Project Coordinator: Prof. R. Soncini Sessa

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Please notice that all the figures in this report are in colors and are unreadable in a black and white printed copy (an online version with colored figures is available on the project web-site http://xake.elet.polimi.it/mediawiki-1.19.1/index.php/Main_Page).
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1 Introduction

The study of the effects of climate change on the management of the Red River system along with the associated design of adaptation policies required the introduction of some modeling assumptions with respect to the problem formulation adopted in report D7.1:

1. Hydropower objective: the formulation of the objective function accounting for the interests of EVN has been modified with respect to the one adopted in report D7.1 (i.e., minimize the average daily loss of energy production) because, the available energy demand as well as the associated weights are representative for the historical conditions only and cannot be assumed to be valid in the future. As a consequence, the new objective function is defined as the maximization of the hydropower production in the system (for details see Section 3.1).

2. Number of objectives: the objectives functions considered in this analysis do not include the evaluation of the performance in terms of flood control and water supply under extreme conditions, so the problem formulation includes only three objective functions. The rationale for limiting the study to “normal” conditions is related to the limited statistical significance of the projected streamflow trajectories, which prevented the generation of synthetic time series comprising extreme events as described in Chapter 6 of report D7.1.

3. Policy inputs: given the increased variability in the projected hydroclimatic conditions, the information used to condition the policy has been augmented by adding to the state of the system, namely time index and reservoirs’ storage, the total previous day observation of the inflow (for details see Section 3.1).

2 Water storage operations under climate change

Globally, more than half of the world’s rivers are regulated by dams (Nilsson et al., 2005), forming a cumulative storing capacity greater than 20% of the total annual runoff (Vorosmarty et al., 1997). While the opportunities for constructing new dams in developed countries are coming to an end (Gleick and Palaniappan, 2010), with some cases already experiencing dams’ removal (e.g., Doyle et al., 2003; Kibler et al., 2011), developing countries still offer untapped potential. According to the World Bank, the estimated total hydropower capacity in Africa and South East Asia exceeds 1,900 GW, which is nearly four times the currently installed capacity in Europe and North America (World Bank, 2009).

Large storage projects contribute positively to regional growth and development by increasing water availability for different economic sectors, producing relatively carbon-neutral energy, and reducing flood risk (e.g., Biemans et al., 2011; Fernandez et al., 2013; Giuliani et al., 2014; Van Vliet and Aerts, 2015). Yet, dams alter the natural hydrologic regimes by moving water volumes in space and time (Haddeland et al., 2014) with potentially negative impacts on ecosystem services (e.g., Ziv et al., 2012; Castelletti et al., 2014), habitat fragmentation (e.g., Grill et al., 2015), and sediment transport and dynamics (e.g., Wild and Loucks, 2014). Pressure on water resources is further growing as a consequence of climate change and growing populations, which are expected to severely affect freshwater availability in many regions of the world (IPCC, 2013). This increasing stress emphasizes the need to rethink how large storages are operated by enlarging the scope of their operations across sectors and by adopting effective tools to analyze the potential
of alternative operating policies under current and projected conditions (Arnell and Lloyd-Hughes, 2014; Harrison et al., 2015). Re-designing the existing storages’ operations has indeed a strong potential for enlarging the flexibility and the adaptive capacity of water systems, without the need of structural upgrades and their associated financial outlays (Anghileri et al., 2011; Georgakakos et al., 2012).

The Red River system represents as a paradigmatic study site to analyze the effects of climate change on the operations of water reservoirs. The Red River is the second largest river basin in Vietnam, the 5th largest in South East Asia, and its delta is populated by nearly 20 millions of people, which makes it one of the most densely populated areas of the world (Devienne, 2006). As part of the medium-long term energy and food security national strategy, a number of large dams have been constructed on the Red River tributaries, for a cumulated storing capacity of 19.86 billion m$^3$, and other three dams are under construction for an additional total capacity of 3 billion m$^3$. The regulation of these dams has been designed on the basis of the observed hydrologic variability and the historical demands to ensure adequate levels of hydropower production, guarantee water supply to the activities in the Red River delta, and mitigate downstream flood, primarily in the Vietnamese capital Hanoi (Le Ngo et al., 2008; Vinh Hung et al., 2010; Castelletti et al., 2012a). Yet, no guarantee exists that policies optimized over the past will not fail in coming years under the additional pressures deriving from the rapid economic and demographic development of the country (Toan et al., 2011), along with the expected detrimental effects of climate change (see Arndt et al. (2015) and references therein). Determining the potential of the existing network of large reservoirs for securing energy and food under change requires exploring the following main questions: Are the current system operations vulnerable with respect to the projected climate change impacts? Which is the sector expected to be more exposed to negative impacts? Which is the cost if no adaptation is implemented?

With the purpose of replying to the these questions, in this report we explore the impacts of a perturbed physics ensemble of climate projections on the multi-purpose operations of the large reservoirs in the Red River basin, focusing on Son La and Hoa Binh on the Da River and Tuyen Quang on the Gam River. Although a number of works have already studied climate change impacts in Vietnam focusing on specific sectors (e.g., Adger, 1999; Booth et al., 1999; Yu et al., 2010; Gebretsadik et al., 2012; Chinowsky et al., 2015; Neumann et al., 2015), their restricted scope, generally, provided limited support in designing inter-sector adaptation strategies. This report contributes an assessment of the role of large storages in compensating the adverse effects of climate change and considers different climate models projections and different future time horizons to estimate the changes in the overall system performance as well as in the tradeoffs across the Red River system multi-sector services. This scenario-led approach (Wilby and Dessai, 2010) allows identifying the main vulnerabilities of the current storage operations, understanding the risk of failure across the sectors, quantifying the uncertainty associated to the climate scenarios, and assessing the expected costs if no adaptation is implemented (Prudhomme et al., 2010). In particular, we investigate the evolution of the system’s tradeoffs by discussing how the same operating policy can perform differently in terms of fairness and equity of water resources sharing (Sokona and Denton, 2001; Thomas and Twyman, 2005), just because of changed climatic conditions. Finally, we identify the operational adaptive capacity of the Red River system, namely the theoretical upper limit for adaptation via improved and more informed storage operations, in order to support prioritizing policy responses and adaptation strategies.
3 Framing the system

The Red River basin (Figure 2) is an international basin covering an area of 169,000 km² between Vietnam (51.3%), China (48%), and Laos (0.7%). The three main tributaries of the Red River (Da, Lo, and Thao) rise in the northern part of the basin and join before reaching a large flood plain in the Red River delta region. The region is characterized by a tropical monsoon climate with two well distinct seasons: the wet season, from May to October, and the dry season from November to April. The average flow in the Red River delta varies from 8,000 m³/s during the monsoon peak to 1,500 m³/s in the dry months.

The catchment has been experiencing a rapid development in terms of population and economic growth (Devienne, 2006). People are moving from the rural areas to the main cities and the capital Hanoi producing an increase in water and energy demands, and also in the potential impact of extreme floods (Vinh Hung et al., 2010). Around 20 million of people currently live in the delta region, with 6.5 million living in the Hanoi metropolitan area where the population density is higher than 2,000 inhabitants per km². To cope with these demands, over the last 20 years three large multi-purpose reservoirs have been constructed in the Vietnamese part of the catchment, namely Son La and Hoa Binh on the Da River and Tuyen Quang on the Gam River, along with some small reservoirs on the Lo River and other three dams under construction in the upstream part of the Da River catchment. These three large reservoirs, which provide an overall storing capacity of 19.86 billion m³, are operated to satisfy three main interests:

- hydropower production in the three power plants connected to the dams, which account for a total installed power capacity of 6,246 MW (i.e., 43.6% of the national capacity);
- flood control, particularly in the city of Hanoi, which suffered a number of catastrophic floods events during the monsoon season (De Kort and Booij, 2007);
- water supply to support a variety of water related activities in the Red River delta, where agriculture accounts for 58% of the total water demand and involves around 50% of the local workers in 501,000 ha of cultivated fields, distributed among 22 irrigation districts and fed by a dense artificial canal network. After the Mekong River delta, the Red River delta is indeed the second largest rice production area of the entire Vietnam, which is the second-largest rice exporter in the world (Yu et al., 2010).

All these sectors are expected to be affected by climate change, associated to positive and negative variation of the hydropower production by more than 5% depending on the climate scenario, 10% decrease of the average yields for annual crops, and increased risk of flooding due to higher frequency of extreme events (Arndt et al., 2015). The variability in these projections, depending on the sectors and the climate scenario considered, emphasizes the need of enlarging the perspective in climate change analysis by assessing the changes in the overall system performance as well as in the tradeoffs across the Red River system multi-sector services.

3.1 Model and objectives formulations

The integrated model of the Red River system (Figure 3) relies on a combination of conceptual and data-driven models. The four sub-catchments of Da, Thao, Lo, and Gam rivers are described by means of four HBV models (Bergstrom, 1976), which simulate the soil water balance and subsequent rainfall-runoff processes to estimate the daily streamflow in the rivers ($q^D_t$, $q^T_t$, $q^L_t$, $q^G_t$).
Figure 2: Map of the Red River system.
These models were calibrated using satellite data from the APHRODITE project (Research Institute for Humanity and Nature, Japan) due to the lack of information on the Chinese part of the catchment (Li and Bui, 2012).

The dynamics of the three main reservoirs, namely Hoa Binh (HB), Son La (SL), and Tuyen Quang (TQ), is described by the mass balance equations of the water volumes $s_j^t$ stored in each reservoir ($j = SL, HB, TQ$), i.e.

$$s_{SL}^{t+1} = s_{SL}^t + q_{D}^{SL} - r_{SL}^{SL} - E_{SL}^t$$  \hspace{1cm} (1a)

$$s_{HB}^{t+1} = s_{HB}^t + r_{SL}^{HB} - r_{HB}^{HB} - E_{HB}^t$$  \hspace{1cm} (1b)

$$s_{TQ}^{t+1} = s_{TQ}^t + q_{G}^{TQ} - r_{TQ}^{TQ} - E_{TQ}^t$$  \hspace{1cm} (1c)

where $t$ is the time, $q_{D}^{j}$ and $q_{G}^{j}$ are the water volumes of the Da and the Gam rivers flowing into Son La and Tuyen Quang reservoirs, respectively, in the time interval $[t, t+1)$, and $E_{j}^t$ represent the mean daily losses for evaporation in each reservoir. The daily release of the $j$-th reservoir is defined as $r_{j}^{t+1} = f(s_{j}^t, u_{j}^t)$, where $f(\cdot)$ describes the nonlinear, stochastic relation between the decision $u_{j}^t$, and the actual release $r_{j}^{t+1}$ (Soncini-Sessa et al., 2007). The release $r_{j}^{t+1}$ coincides with the release decision $u_{j}^t$ unless a correction is needed in order to take into account the legal and physical constraints on the reservoir level and release, including spills when the reservoir level exceeds the maximum capacity. In the adopted notation, the time subscript of a variable indicates the instant when its value is deterministically known.

The flow routing in the Red River delta, namely the routing of the water flow downstream the Day diversion to Hanoi and the irrigation districts, is approximated by a dynamic emulator (see Castelletti et al. (2012b) and references therein) based on two data-driven artificial neural networks (ANNs) constructed on the results of the simulations of the MIKE11 model of the Red River delta. This provides a simplified representation of the 22 irrigation districts, along with nearly 337 rivers and canals, 303 pumps, and 89 sluice gates, for a total length of the network of 4,200 km (for further details, see Dinh (2015)). These two ANN models approximate the distributed water volume available in the irrigation canals ($CWV_i$) and the water level in Hanoi ($h_{i}^{HN}$), i.e.

$$CWV_{i+1} = ANN(q_{i+1}^{\text{delta}}, W_i, tide_{i-1}, CWV_i)$$  \hspace{1cm} (2a)

$$h_{i+1}^{HN} = ANN(q_{i+1}^{\text{delta}}, tide_{i-1}, h_{i}^{HN})$$  \hspace{1cm} (2b)

where $q_{i+1}^{\text{delta}} = q_{i}^{ST} - q_{i}^{DD}$ is the water entering the downstream system, accounting for a one-day delay travel time from the upstream system at Son Tay ($q_{i}^{ST} = r_{i}^{HB} + q_{i}^{L} + r_{i}^{TQ}$) to the delta and the potential diversion of water in the Day diversion ($q_{i}^{DD}$), which is opened only in case of extreme floods events (i.e., when the predicted level in Hanoi is higher than 13.4 m); $W_i$ is the total water demand in the Red River delta, comprising different water uses (e.g., irrigation, fisheries, urban supply, environment); $tide_{i-1}$ is the previous day tide level to account for the seawater intrusion in the delta.

By direct interaction with the stakeholders during the IMRR project (see report D4.2), three main water-related interests were identified and associated to the following operating objectives’ formulations, evaluated over the simulation horizon $H$: 

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Figure 3: Schematic representation of the Red River system model.

- **Hydropower production** ($J^{hyd}$): the daily average energy production (GWh/day), to be maximized, defined as

$$J^{hyd} = \sum_{j=1}^{3} \left( \frac{1}{H} \sum_{t=0}^{H-1} HP_{t+1}^j \right)$$

where $HP_{t+1}^j$ is the daily energy produced by the power plant connected to the $j$-th reservoir. In particular, the energy production of each power plant is estimated by a data-driven artificial neural network, which approximates the optimal hourly operation of the turbines given the net hydraulic head (i.e., the reservoir level minus the tailwater level) and the daily reservoir release.

- **Flood control** ($J^{flood}$): the daily average flood damage in Hanoi ($-$), estimated by a non-
linear cost function (Figure 4) estimated by direct stakeholders consultation, which depends on the corresponding water level in Hanoi $h_{HN+1}$, i.e.

$$J_{\text{flood}} = \frac{1}{H} \sum_{t=0}^{H-1} F(h_{t+1}^{HN})$$

(4)

- Water supply ($J_{\text{supply}}$): the daily average squared water deficit (m$^3$/s)$^2$ with respect to the total water demand of the Red River delta (Figure 5), defined as

$$J_{\text{supply}} = \frac{1}{H} \sum_{t=0}^{H-1} (\text{ANN}(q_{\text{delta},t+1}, W_t, \text{tide}_{t-1}, CWV_t))^2$$

(5)

where the deficit is estimated by a data-driven artificial neural network to account for the water distribution processes in the delta region. This ANN model represents a non-dynamic emulator (Castelletti et al., 2011), also called response surface, which approximates the water deficit obtained via simulation of the MIKE11 model of the Red River delta. In particular, the adopted quadratic formulation aims to penalize severe deficits in a single time step, while allowing for more frequent, small shortages (Hashimoto et al., 1982).

The set of Pareto optimal operating policies is obtained via Evolutionary Multi-Objective Direct Policy Search (Giuliani et al., 2015), an approximate dynamic programming approach (Castelletti et al., 2008) which combines direct policy search, nonlinear approximating networks, and multi-objective evolutionary algorithms. The operating policies, which provides the release
decisions vector $u_t = [u_{SL}^t, u_{HB}^t, u_{TQ}^t]$ as a function of the day of the year ($t$), the current reservoir storages ($s_{SL}^t, s_{HB}^t, s_{TQ}^t$), and the total previous day inflow ($q_{D}^t + q_{T}^t + q_{L}^t + q_{G}^t$), are parameterized as Gaussian radial basis functions, which are capable of representing functions for a large class of problems (Busoniu et al., 2011) and have been demonstrated to be effective in solving multi-objective policy design problems (Giuliani et al., 2014; Biglarbeigi et al., 2014; Giuliani et al., 2015).

The set of Pareto approximate operating policies $p_\theta$ can be obtained by solving the following multi-objective problem:

$$p_\theta^* = \arg\min_{p_\theta} | -J_{\text{hyd}}, J_{\text{flood}}, J_{\text{supply}} |$$

where $\theta \in \Theta$, the objectives functions are defined in eqs. (3-5), and the problem is constrained by the dynamics of the system (see eqs. 1-2). To perform the optimization, we use the self-adaptive Borg MOEA (Hadka and Reed, 2013), which has been shown to be highly robust across a diverse suite of challenging multi-objective problems, where it met or exceeded the performance of other state-of-the-art MOEAs (Hadka and Reed, 2012). Each optimization was run for 2 million function evaluations. To improve solution diversity and avoid dependence on randomness, the final set of Pareto optimal policies is obtained as the set of nondominated solutions identified from the results of 20 random optimization trials. In total, we run 120 million simulations (i.e., 2 million times 20 seeds times 3 formulations, namely over history and full adaptation over two extreme scenarios), requiring around 36,000 computing hours. Each optimization run was parallelized over 256 processing cores of The Cube Cluster of Cornell University, a 512 processing cores system with a 120 Terabyte Terascale file system.
4 Climate change scenarios

We consider five climate change scenarios of projected temperature and precipitation over the entire river basin, provided by the Vietnam Institute of Meteorology, Hydrology and Environment (IMHEN). They are obtained from the HadCM3 General Circulation Model (Gordon et al., 2000) forced with the A1B emission scenario (IPCC, 2000). In particular, we use a 5-member perturbed physics ensemble, comprising a standard scenario (Q0), two scenarios with smaller and larger temperature increases (Q3 and Q13, respectively), and two scenarios with negative and positive precipitation changes leading to drier (Q10) and wetter (Q11) conditions respectively.

These scenarios are downscaled, first, using the PRECIS regional modeling system (Jones et al., 2004) and, then, using the Quantile Mapping statistical downscaling technique (D` equ` e et al., 2007). The control scenario covers the period 1990-2010, while the future scenario spans the entire century. Figure 6 shows the spatial variations of precipitation and temperature in the two considered future periods under the standard scenario Q0, namely 2040-2060 and 2078-2098, with respect to the control period. Total annual precipitation is expected to increase in the entire catchment with a monotonic trend in almost all the sub-basins. Also mean daily temperature is projected to increase in time over the entire basin, reaching +4°C by the end of the century.

Figure 7 shows some features of the other four ensemble members. Scenario Q10 predicts overall almost no change in the precipitation volume, although there can be some spatial differences from regions with a decrease around 5-10% and regions with an increase of 5-10%. Scenario Q11, instead, predicts a clear increase in precipitation, which can reach also +30% in some areas of the Delta. These are the scenarios referred to as dry and wet, respectively. Scenario Q3 predicts a small increase in temperature, between 3.5°C and 4°C depending on the location, whereas scenario Q13 predicts a larger increase, between 3.7°C and 4.4°C. For this reason, they are referred to as small increase and large increase scenarios, respectively.

The projected streamflow trajectories in the Da, Thao, Lo, and Gam rivers are obtained via simulation of four HBV models (Bergstrom, 1976). Figure 8 compares the streamflow trajectories obtained from the observed temperature and precipitation and the patterns simulated with the standard scenario Q0 in the control period as well as in the two periods in the future. The control period is able to reproduce the historical hydrology closely, although some biases still exist, particularly in the early monsoon season when the climate model tends to produce an early flow peak, which is not present in the historical trajectory. The streamflow tends to increase in the monsoon season although not always monotonically. Also the seasonal flow variability changes in time, with generally higher peaks in the tail of the monsoon in the period 2040-2060.

Figure 9 and Table 1 compare the historical flow of the four rivers with the simulations over the horizon 2078-2098, as projected by the 5 scenarios. According to these projections, the future streamflow pattern will be characterized by a longer monsoon season, which generally increases the average annual flow, followed by a shorter but drier period as quantified by the low values of the 10th percentile (see Table 1). Under the standard scenario Q0, we expect an average increase of the streamflow (i.e., +33.4% and +17.9% in the median and total annual flow) associated with high variability both in terms of dry and wet conditions (i.e., -29.1% in the 10th percentile and +14.7% in the 90th percentile). Coherently with their definitions, scenario Q10 is the one producing the lowest flows, resulting in the smallest average annual flow, while scenario Q11 is producing the highest streamflow peaks, captured by the highest 99th percentile. Finally, Q3 and Q13 show more variable flows, with the former more similar to Q10 and the latter to Q0.
Figure 6: Climate change variations in precipitation (P) and temperature (T) over the Red-Thai Binh river basin using the standard scenario Q0. Upper panels: total annual precipitation change in the period 2040-2060 (left) and 2078-2098 (right) relative to the control period 1990-2010. Lower panels: mean daily temperature change in the period 2040-2060 (left) and 2078-2098 (right) relative to the control period 1990-2010.
Figure 7: Climate change induced variations in precipitation (P) and temperature (T) over the Red-Thai Binh river basin. Upper panels: total annual precipitation change in the period 2078-2098 relative to the period 1990-2010, in the scenarios Q10 (left) and Q11 (right). Lower panels: mean daily temperature change in the period 2078-2098 relative to the period 1990-2010, in the scenarios Q3 (left) and Q13 (right).
Figure 8: Comparison between historical streamflow patterns observed in the period 1990-2010 in the four main rivers Da, Thao, Lo, and Gam and simulations of HBV models forced with the standard scenario Q0 in the period 2078-2098 (5 days cyclostationary moving average).
Figure 9: Comparison between historical streamflow patterns observed in the period 1990-2010 in the Da, Thao, Lo, and Gam rivers and simulations of HBV models forced with the climate change scenarios in the period 2078-2098 (5 days cyclostationary moving average).
Table 1: Summary of changes in the projected streamflow under the climate change scenarios in the period 2078-2098 with respect to the historical observations in the period 1990-2010 (average over the four rivers).

<table>
<thead>
<tr>
<th>Percentage (%)</th>
<th>Q0</th>
<th>Q10</th>
<th>Q11</th>
<th>Q3</th>
<th>Q13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual flow</td>
<td>+17.9</td>
<td>+6.8</td>
<td>+19.9</td>
<td>+10.5</td>
<td>+21.5</td>
</tr>
<tr>
<td>10th percentile</td>
<td>-29.1</td>
<td>-29.8</td>
<td>-17.8</td>
<td>-24.6</td>
<td>-9.0</td>
</tr>
<tr>
<td>50th percentile</td>
<td>+33.4</td>
<td>+22.9</td>
<td>+31.7</td>
<td>+24.9</td>
<td>+41.6</td>
</tr>
<tr>
<td>90th percentile</td>
<td>+14.7</td>
<td>+1.3</td>
<td>+13.0</td>
<td>+8.7</td>
<td>+18.3</td>
</tr>
<tr>
<td>99th percentile</td>
<td>+27.7</td>
<td>+19.7</td>
<td>+34.9</td>
<td>+15.8</td>
<td>+21.1</td>
</tr>
</tbody>
</table>

5 Policy design under climate change

5.1 Policy performance under historical conditions

The aim of this section is the inter-sector analysis of the system performance, measured in terms of hydropower production, flood damages, and water supply deficit (see Section 3.1), achievable under historical hydroclimatic conditions by adopting alternative operations of the existing network of reservoirs. This analysis allows quantifying the space for a negotiated agreement representing a fair compromise between the conflicting interests involved. Figure 10a illustrates the performance of the Pareto optimal operating policies designed over the historical horizon 1990-2010, where hydropower production $J_{hyd}$ (GWh/day) and flood damages $J_{flood}$ (-) are plotted on the primary axes, while the water supply deficit $J_{supply}$ (m$^3$/s)$^2$ is represented by the dimension of the circles. The black arrows indicate the directions of increasing preference, with the ideal solution that would be represented by a small circle in the top-left corner of the figure, while each circle represents a different tradeoff between the three objectives. Results show that a clear conflict exists between the maximization of hydropower production and the prevention of flood damages. The best performance in terms of $J_{flood}$ (solution PF in the bottom-left corner of the figure) is obtained by maintaining the reservoirs level as low as possible to buffer the monsoon peak of the inflows (see the solid lines in Figure 10b). This negatively impacts on the energy production due to the reduction in the water turbined during the dry season, when the reservoir is almost empty, as well as the losses in terms of hydraulic head. On the contrary, given the dimensions of the reservoirs and the large power capacity installed, the best performance in terms of $J_{hyd}$ (solution PH in the top-right corner of the figure) tries to keep the reservoirs at their maximum level and to release the turbine capacity for the entire year (see the dashed lines in Figure 10b). Beside reducing the buffering capacity during the monsoon season, this energy-driven operating policy increases the vulnerability of the water supply in the delta, with these solutions attaining very high values of water deficit (i.e., large circles). The conflict between flooding and water supply is instead weaker, because the drawdown of the reservoirs’ level during the monsoon season is indirectly making available large water volumes in the Red River delta. However, the temporal difference between the peak of the monsoon and the water demand peak in February, which is associated to the submersion of the rice fields, requires an ad hoc operations of the reservoirs to attain the minimum values of $J_{supply}$ (solution PS, associated to the dotted lines in Figure 10b), ultimately degrading the performance in terms of $J_{hyd}$ and $J_{flood}$.
Figure 10: Performance of the Pareto optimal policies over history (1990-2010), where hydropower production and flood damages are plotted on the primary axes, while the circles’ size represents water supply (top panel). Average storage trajectories of Son La, Hoa Binh, and Tuyen Quang reservoirs obtained with policies PF, PH, and PS (bottom panels).
Overall, when evaluated over the historical hydroclimatic conditions, the set of Pareto optimal operating policies illustrated in Figure 10 provides a rich context for understanding complex management tradeoffs and dynamics in the Red River system and has the potential for supporting the identification of candidate compromise solutions. Just as an example, we select a candidate compromise policy (CP, identified by the green cross in Figure 10) according to the criterion of the minimum distance with respect to the Utopia point (Eschenauer et al., 1990), which identifies the absolute optima of the three objectives. The CP performance is \( J^{\text{hyd}} = 59 \) (GWh/day), \( J^{\text{flo}} = 8634.7 \) (-), \( J^{\text{irr}} = 55.01 \) (m\(^3\)/s)\(^2\), which is better than 49% of the solutions in the Pareto optimal set in terms of hydropower production, 59% in terms of flood damages, and 45% in terms of water supply.

5.2 Policy performance under climate change

The variation of the hydrologic regime due to climate change (Figure 9) is likely to alter the medium and long term performance of the baseline operating policies illustrated in Figure 10 as well as their tradeoffs between the operating objectives. To assess the vulnerabilities under projected climate of the baseline operating policies, which are designed over historical conditions, we re-evaluated them via simulation over the period 2078-2098 under the five scenarios described in Section 4. Figure 11 shows that climate change is expected to produce a general degradation of the system performance in all the sectors. The major concern is associated to the projected increase in the flood damages, which are increasing (the circles move to the right) in all the scenarios except Q3, from 70% to 200%. In fact, the duration of the monsoon is expected to increase, with higher streamflow in September and October (Figure 9). The baseline policies, however, tend to keep the reservoirs’ level high in this period because the flood risk is supposed to be low and, consequently, they fail in controlling the floods in Hanoi when exposed to this non-stationary alteration of the hydrologic regime. Ensuring flood protection under the projected scenarios results to be particularly challenging due to the projected increase in the Thao River streamflow during the monsoon season (Figure 9), which is critical as this river is not regulated and directly contributes to the floods in Hanoi.

Our results also show negative climate change impacts on water supply vulnerability in all the scenarios (the colored circles are larger than the black ones), with the values of \( J^{\text{supply}} \) that increase from 15% to 160% due to the expected decrease of the streamflow during the dry season. Given the importance of the Red River delta in terms of rice production, this climate change impact may represent a significant challenge for the future national food security. Finally, the smaller variability in the average water availability (see the average annual flow in Table 1) produces less pronounced impacts on the hydropower production, with variations in the values of \( J^{\text{hyd}} \) from -7% to +5.5%. Although the two drier scenarios (i.e., Q10 and Q3) induce modest reductions in hydropower production, the other three scenarios (i.e., Q0, Q11, and Q13) allow attaining even better performance in this objective. Yet, we expect increasing climate change impacts on hydropower when an energy market will be introduced in Vietnam (Nguyen, 2007) and the energy production will be more valuable in different periods of the year.

The analysis of the system performance under different climate scenarios allows exploring the full range of potential benefits and risk induced by the changing climate and contributes in understanding how the uncertainty in these scenarios is transferred to the operating policy performance. Figure 11 shows that the set of Pareto optimal operating policies over history can perform significantly differently in the future, depending on the climate scenario that will realize,
Figure 11: Re-evaluation of the baseline operating policies (black circles) over the period 2078-2098 under the five climate change scenarios (colored circles).
ultimately affecting the equity and fairness of the solutions. According to the standard scenario (Q0), the entire baseline Pareto optimal set is projected to degrade its performance in terms of flood control and water supply, while allowing higher hydropower production. However, the same set of solutions can maintain almost the same performance in terms of flood damages, while loosing around 8% of hydropower production under Q10 or Q3. The climate change impacts predicted by Q13 are similar to the ones under Q0, with slightly higher hydropower production but also larger values of water supply deficit. Finally, Q11 suggests that the historical policies will produce from 4 to 10 times higher flood damages, while maintaining the same levels of hydropower production and water supply deficit. The variability associated to the five scenarios also affects the evolution of the system tradeoffs. The conflict between $J_{\text{hyd}}$ and $J_{\text{flood}}$ against $J_{\text{supply}}$ is exacerbated under the projected climate, with most of the colored circles in Figure 11 that are larger than the ones under historical conditions. Moreover, the clear tradeoff between hydropower and flooding illustrated in Figure 10 maintains the same shape only under Q10, though translated toward the bottom-right part of the objective space. This tradeoff curve becomes instead more vertical under Q0, Q13, and Q3, meaning that a small improvement in $J_{\text{flood}}$ induces a large loss in $J_{\text{hyd}}$. Under Q11, it instead evolves toward a horizontal slope, where a small increase in hydropower production produces large flood damages. This evolution of the tradeoffs towards more pronounced conflicts, combined with the uncertainty in the long-term policy performance, hampers the identification of negotiated compromise solutions.

5.3 Climate change adaptation

The results discussed in the previous section refers to a business-as-usual situation where, despite the evident changes in the hydroclimatic conditions, no adaptation measures are implemented. More realistically, the operations of the system will be adapted to the new conditions. In order to better understand the system vulnerabilities at different future time horizons and to assess the potential adaptive capacity of the system achievable by modifying the operations of the three reservoirs, we analyze the policy performance attained under the assumption of full adaptation to the projected future, i.e. we assume that the system operator recognize the change and optimally re-operates the system based on the new hydrological conditions. The analysis is focused on scenarios Q10 and Q11, as these latter are the ones showing the largest impacts on the performance of the baseline operating policies. In particular, Q10 is the driest scenario and has negative impacts both on hydropower production and water supply. Conversely Q11, which is the wettest scenario, produces the largest flood damages. Figure 12 contrasts the performance of the baseline solutions over the period 1990-2010 (black circles) first with their re-evaluation in the medium (i.e., 2040-2060, shown in grey) and long (i.e., 2078-2098, shown in orange) term and, then, with respect to a set of fully adapted operating policies over the period 2078-2098 (red circles). Again, the green crosses identify the performance of the candidate Compromise Policy, selected according to criterion of the minimum distance from the Utopia point in the baseline Pareto optimal set and evaluated over the historical period ($CP_h$) as well as its re-evaluation in the medium ($CP_{Q10M}, CP_{Q11M}$) and long ($CP_{Q10L}, CP_{Q11L}$) term. Using the same criterion, we also selected an Adapted Compromise Policy ($ACP_{Q10}, ACP_{Q11}$) within the fully adapted Pareto optimal set.

Results suggest that the impacts on the policy performance are characterized by a non-stationary and non-monotonic trend. Over the period 2040-2060 under Q10 (Figure 12a), we observe significant reductions in hydropower production and larger water supply deficit, while
Figure 12: Comparison of the baseline operating policies’ performance evaluated over different horizons, namely 1990-2010, 2040-2060, and 2078-2098, with the performance of fully adapted solutions over the long-term horizon 2078-2098 under Q10 (panel (a)) and Q11 (panel (b)) scenarios.
lower flood damages. The difference in the performance of \( CP_{Q10M} \) with respect to \( CP_h \) (measured in terms of \( \Delta J^{hyd} \), \( \Delta J^{flo} \), and \( \Delta J^{irr} \)) are indeed equal to -12%, +280%, and -28%, respectively. On the long term, characterized by a relatively increase in average annual water availability combined with large streamflow reductions in the dry period (see Table 1), the baseline operating policy amplifies climate change impacts and produces definitely larger flood damages and lower water supply deficit (+71% and +153% under \( CP_{Q10L} \) with respect to \( CP_h \)), along with a 7% reduction in hydropower production. The adaptation of the operating policies to the changed climate has the potential for contributing in the mitigation of these negative impacts. Results in Figure 12a show that the performance potentially achievable over the period 2078-2098 under full adaptation (red circles) allows bouncing back to adequate levels of performance in all the three objectives. The degradation of performance adopting the compromise policy \( ACP_{Q10} \) with respect to the historical performance of \( CP_h \) is indeed reduced to -5% in terms of hydropower production, +9% in water supply, and +17% in flood damages, corresponding to a difference in the same objectives relative to policy \( CP_{Q10L} \) equal to +2%, -57%, and -31%.

Similar results are obtained on the Q11 scenario (Figure 12b), with the non-stationary and non-monotonic climate trend associated to decreasing hydropower production and increasing water supply deficit on the medium term, followed by an average long term increase of 20% in the annual streamflow, combined with a +34.9% in the peaks, which is projected to produce huge flood damages if no adaptation options are implemented. Under this wet scenario, the projected impacts on the performance of \( CP_{Q11M} \) and \( CP_{Q11L} \) with respect to \( CP_h \) are equal to -7%, +112%, -12% in the medium term and +2%, +25%, +508% in the long term. However, results show that the performance of the Pareto optimal policies assuming full adaptation successfully exploit this additional water availability to attain better performance in hydropower (i.e., the maximum production increases from 60.62 GWh/day in the historical set to 62.73 GWh/day in the fully adapted set) and water supply deficit (i.e., the minimum deficit decreases from 18.55 (m³/s)² to 17.64 (m³/s)²). Relatively to \( CP_{Q11L} \), the fully adapted \( ACP_{Q11} \) attains +3% in hydropower production and -60% in flood damages, with a small decrease in the water supply deficit (-4%). Overall, these results demonstrate that the modification of the reservoirs regulation has a strong adaptive capacity for mitigating the adverse climate change impacts on the system performance.

5.4 Analysis of the operating policies

Figure 13 illustrates how the benefits discussed in the previous section can be obtained by relatively simple adaptation of the baseline reservoirs operations to the changed climate conditions. The adaptation to Q10 consists in larger drawdown of Son La and Hoa Binh during the winter period, followed by the possibility of maintaining a higher average storage during the monsoon season, which is predicted to be drier than historically, thus allowing higher hydropower production. The adaptation on Tuyen Quang is more evident and suggests maintaining a higher storage during the first months of the year to better ensure water supply to the Red River delta, while keeping a larger flood pool from August to November to buffer the longer monsoon season, which is particularly evident in the projected streamflow of the Gam River (Figure 9). In the case of Q11, effective adaptation is obtained by balancing the storages in Son La and Hoa Binh in order to improve the hydropower production by increasing the hydraulic head at the Son La power plant without degrading flood control. This strategy is acceptable in terms of flood control because, despite Q11 is the wettest scenario, the projected streamflows in the Da River consists in a longer monsoon
Figure 13: Comparison of the average storage trajectories of Son La, Hoa Binh, and Tuyen Quang reservoirs obtained with the history-based compromise policy (CP, black line) and the fully adapted compromise policy (ACP, red line) over the period 2078-2098 under Q10 (panel (a)) and Q11 (panel (b)) scenarios.
season with a reduced peak. The fall peaks predicted both in the Lo and the Gam rivers suggest, instead, to reduce the storage in the Tuyen Quang reservoir to increase the flood protection with respect to the historical operations.

6 Conclusions

The role of large storage operations is expected to play a key role for increasing water, energy, and food security under changing climate and society. Since the rapid economic and demographic development of the Red River basin is already challenging the existing water storages’ capability of meeting multiple and competing water demands, in this report we explore the impacts of climate change on the operations of Son La, Hoa Binh, and Tuyen Quang, as well as their potential in terms of adaptive capacity.

Our analysis of the Pareto optimal operating policies under historical hydroclimatic conditions provides a rich context for supporting the identification of candidate compromise solutions, which better address the tradeoffs across the three primary conflicting sectors in the system. The re-evaluation of these solutions under a perturbed physics ensemble of climate change scenarios contributes to the identification of the main system’s vulnerabilities. Depending on the climate scenario and the time horizon considered, the history-based solutions are predicted to degrade up to 12% in terms of hydropower production, 280% in terms of water supply, and 508% in terms of flood control, in the worst case situation. The variability associated to the considered future, non-stationary, uncertain scenarios is therefore amplified by the reservoirs’ operations, as the impacts on the statistics describing the projected streamflows pattern are lower than 30%. In addition, our results show that the uncertainty associated to the climate scenarios produces an evolution in the system’s tradeoffs, with the same solutions performing differently depending on the scenario that will realize. Finally, the adaptive capacity offered by changing the operations of the three reservoirs is demonstrated to be effective in mitigating these negative impacts of climate change.

Under the assumption of full adaptation, the system performance is significantly improved with respect to the non-adaptation baseline both under dry conditions (Q10), with the fully adapted policy recovering 7% of the hydropower production and 57% in terms of water supply deficit, as well as under wet conditions (Q11), with the adaptation of the reservoirs operations saving 60% of the flood damages.

The conclusion from this work is that large storage operations can potentially amplify the impacts of climate change on water, energy, and food security, potentially expanding the uncertainty associated to the future climate scenarios and modifying the systems tradeoffs. These negative impacts can be partially mitigated without any financial cost or risk by capitalizing on the flexibility offered by the adaptation of the reservoirs operations to the future hydroclimatic conditions. In particular, in the Red River system climate change is expected to impact more on flood control and water supply than hydropower production. Still, the predicted 7% reduction of hydropower production by the end of the century under Q10 raises significant concerns about securing energy to support the rapid development of the country, where hydropower currently accounts for 28,542 GWh/year, which corresponds to around 29.3% of the national energy production (Vietnam Electricity (EVN), 2012). With no adaptation of the storage operations, the risk of loosing 1,998 GWh/year would imply spending around 120 million US$\$/year for buying the same amount of energy on the South East energy market, assuming the current price of 0.06 US$\$/kWh. The adaptation of the storage operations partially mitigates this effect by reducing
the loss of hydropower to 5%, thus potentially saving around 34.4 million US$/year.

References


Castelletti, A., F. Pianosi, and R. Soncini-Sessa (2008), Water reservoir control under economic, social and environmental constraints, Automatica, 44(6), 1595–1607, doi:{10.1016/j.automatica.2008.03.003}.


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Sokona, Y., and F. Denton (2001), Climate change impacts: can africa cope with the challenges?, Climate Policy, 1(1), 117–123.


Vietnam Electricity (EVN) (2012), Corporate Profile 2010-2011.

Vinh Hung, H., R. Shaw, and M. Kobayashi (2010), Flood risk management for the riverside urban areas of hanoi: The need for synergy in urban development and risk management policies, Disaster Prevention and Management: An International Journal, 19(1), 103–118.


