MODELLING JOINT RIVER BASINS MANAGEMENTS FOR MITIGATING THE DROUGHT AND FLOOD - A CASE STUDY IN UPPER CHAO PHRAYA RIVER BASIN THAILAND

Supattra Visessri¹, Sucharit Koontanakulvong² and Ming-Daw Su³

ABSTRACT

Thailand has frequently experienced floods and droughts during S-W monsoon and dry period, respectively. In recent decades, the severity of both has intensified from rapid economy/urban developments and climate change impacts. This study uses an optimization model as a simulation tool to explore different alternative scenarios for possible approaches to improve water system management.

A monthly optimization model was built with LINGO representing the system framework of Nan and Yom river systems of the upper Chao Phraya River Basin, Thailand. All necessary components, representing inflow, outflow and storage of water were included in the model. Water demands were estimated for municipal, irrigation and environmental water use sectors. The model was built with the consideration of easiness for scenario setup to simulate different drought/flood mitigation measures. Eight scenarios were tested based on the combinations of three alternatives, i.e. transferring water between the Yom and Nan River basins using bypass canals, constructing a new reservoir on the upstream of the Yom River, and reducing paddy area in the Yom and Nan River basins. As water transferring between the Yom and Nan River basins was enabled or when a virtual reservoir was added on the upstream of the Yom River, downstream flow was sufficient, and deficit in agriculture was smaller compared to base case which has no bypass and no reservoir on the Yom River. When both bypass canals and virtual reservoir were used in combination, downstream flow was sufficient with no deficit for agriculture.

Though a monthly operating model might not be able to catch the variation within shorter time period, it can be easily modified to weekly or daily models as input data becomes available. This study demonstrates the use of an optimization model as simulation tool for evaluating different scenarios, or as a tool to discuss with stakeholders for better management decisions.

Keywords: Nan basin, Yom basin, Chao Phraya River, Thailand, Joint river basins water management.

1. INTRODUCTION

Water is a crucial natural resource. Water management is a complex issue. Imbalance between limited water supply and increasing demand due to rapid population and economic growth has been a conventional issue for water and disaster management. A contemporary issue associated with climate change and uncertainty makes water management in present day more challenging. Thailand has frequently experienced floods and droughts. In 2011, a catastrophic flood caused a

¹ Water Resources Engineering Department, Chulalongkorn University, Bangkok, Thailand 10330; E-mail: supattra.vi@chula.ac.th
² Water Resources Engineering Department, Chulalongkorn University, Bangkok, Thailand 10330; E-mail: sucharit.k@chula.ac.th
³ Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei, Taiwan 10617; E-mail:sumd@ntu.edu.tw
major loss of 1,425,544 million Baht (World Bank 2012). Floods usually occur during the Southwest monsoon between mid-May and mid-October while droughts are common from mid-October to mid-May which is the dry period. In 2015, Thailand faced an off-season drought due to a dry rainy season caused by El Nino. Annual rainfall in 2015 was below the 30-year average. The levels of water in major reservoirs as of 11 June 2015 were low at 20% of Thailand's reservoir capacity (WMSC 2016). The worst drought in 50 years is being predicted for Thailand in 2016 as a result of prolonged El Nino. It is evident that the severity of flood and drought in recent decades has been intensified from climate change impacts and rapid economy/urban development. This calls for an urgent step to explore alternatives for water system management to alleviate the impacts of extreme events. Optimization model and simulation tool are widely-used for water resource management and reservoir operation. This study therefore uses an optimization model as a simulation tool to explore different alternative scenarios for possible approaches to improve water system management. The objectives of this study are to assess the value of management alternatives to prevent water deficit in all sectors and to provide a flexible modelling framework for joint reservoir operations. Rigorous planning and management of water resources is a key for achieving sustainability.

Reservoir systems operation is complicated as it involves i.e. managing limited water resources to meet increasing water demand from stakeholders, flood mitigation, drought prevention and climate uncertainty. The optimization of reservoir systems operation is commonly modelled using linear programing in which the relations among all variables are linear (e.g. Cai et al. 2001; Reis et al. 2005; Xie and Xue 2005; Reis et al. 2006; Heydari et al. 2015).

2. THE UPPER CHAO PHAYA RIVER BASIN

The optimization model and simulation tool were applied to the study area in the Yom and Nan River basins which are two of the four basins contributing to the Chao Phraya River basin where the capital city, Bangkok, is located. Different scenarios for joint river basins management can be investigated through modelling. This may offer improved efficiency of reservoir operation and mitigate the drought and flood in the Yom and Nan basin and also the Chao Phraya basin and the nation as a whole.

2.1 Location and topography

The Yom and Nan basins are located in the north of Thailand lying vertically between the latitudes 15°40'-19°40' N and the longitudes 99°15'-101°25' E (Figure 1). The total area of the Yom and Nan basin is approximately 58,476 km². The Khong basin and Laos are located on the north and extend to the northeast of the Yom-Nan basin. The Pasak basin is to the southeast. South of the basin is the Chao Phraya basin. The Ping and Wang basins are to the southwest and northwest. The elevations range from msl to 2118 m amsl. Middle of the basin is river plains enclosed by mountains (Figure 1).

2.2 Stream network and water resources

Major rivers are the Yom and Nan Rivers draining water from the north to the south of the basin and merges with the Ping, and Wang Rivers forming the Chao Phraya River in the lower part of the country. There are no reservoir in the Yom basin but two reservoirs, the Sirikit and KwaeNoi reservoirs in the Nan basin. Normal pool storages of the Sirikit and Kwae Noi reservoirs are 9,510 Mm³ and 939 M m³. The peak inflows to the reservoirs strongly match with the storm events. The reservoir system is operated for multi-purposes including flood controls and water supply to municipal,
irrigation, and salinity control. The releases from the Sirikit and Kwae Noi are important factors of flooding in the Chao Phraya basin during wet season while in the dry season, the releases must be carefully managed based on low reservoir storage to meet the demand for development and ecological conservation. Figure 2 shows the schematic of the upper Chao Phraya River basin.

Figure 1. Location plan with elevations, river network and the Sirikit reservoir

2.3 Climate and hydrology

The climate of the Yom-Nan basin is characterized by the Southwest and Northeast monsoons resulting in three seasons: rainy from mid-May to mid-October, winter from mid-October to mid-February, and summer from mid-February to mid-May. Rainfall and flows in the Yom-Nan basin are highly variable both in space and time. Flood occurs in May, September and October during the period of heavy rainfall while drought occurs in other months. The Yom-Nan basin has experienced the problem of climate and land use change (Sriariyawat et al. 2013; Sucharit et al. 2013), thus resulting in hydrological change. This increases difficulty in regional water management and in reservoir operations.
Figure 2. Schematic of the upper Chao Phraya River basin comprising the Ping, Wang, Yom, and Nan River basins (based on RID 2016)

3. METHODS

A large number of optimization modelling tools such as LINDO, LINGO, GAMS, CPLEX, and MATLAB are available and applicable to the reservoir operation problem. LINGO software with LINDO (Linear, INteractive, and Discrete Optimizer) solver (LINGOSystems, Inc.2003) was chosen for this study because it has been widely used for a number of reservoir operation studies (e.g. Xie and Xue 2005; Sharif and Swamy 2014; Heydari et al. 2015). Major advantages of the LINGO model are simplicity, robustness, low computational resource (Heydari et al. 2015), free from dimensionality problem, flexibility to transport from existing reservoir system to others with minimum modification (Sharif and Swamy 2014).
3.1 The development of objective function and constraints

The Sirikit and KwaeNoi are multi-purposes reservoirs (domestic use, irrigation, and salinity control). Insufficient release may obstruct economic development of the country and deteriorate downstream condition. The improved reservoir operation was therefore evaluated through an objective function that minimize water deficit for all sectors. Penalties for failing to supply the required water were used with highest weight given to potable demand in domestic sector as it is the first priority to be met. Least penalty weight was for irrigation. The objective function is:

\[
\text{Minimize } S_{\text{DEF}} = \sum_{i=1}^{I} W_i DEF_i \quad \text{ Eq.(1)}
\]

Where \( S_{\text{DEF}} \) is total deficit in the basin
\( I \) is number of sectors
\( W_i \) is penalty weight for failing to meet the demand in sector \( i \)
\( DEF_i \) is total water deficit in sector \( i \)

\[
DEF_i = \sum_{k=1}^{K} \sum_{t=1}^{T} D_{i,k}(t) - R_{i,k}(t) \quad \text{ Eq.(2)}
\]

Where \( K \) is number of components in each sectors i.e. number of provinces and agricultural command areas for domestic and agriculture sectors accordingly. For salinity control, a fixed amount of minimum flow requirement is set at downstream channel and no number required as its components.
\( D_{i,k}(t) \) is the demand in component \( k \) of sector \( i \) at time step \( t \)
\( R_{i,k}(t) \) is reservoir release for component \( k \) of sector \( i \) at time step \( t \)

A set of constraints or the limits of the values of the variables were formulated as listed below. Possible reservoir storage was set between maximum and minimum reservoir capacity (Eq. (3) and (4)). The restriction on environmental flow is set as minimum flow requirement at downstream as shown in Eq. (5). Reservoir water balance equation (Eq. (6)) was developed for the continuity considering in/out flow and the storage change. Flows at each node of analysis where channels/canals join together or water is diverted from the channels/canals were checked for water balance considering inflow, outflow, and side flow at the node.

\[
S_k(t) < S_{\text{MAX}}_k \quad \text{ Eq.(3)}
\]

\[
S_k(t) > S_{\text{MIN}}_k \quad \text{ Eq.(4)}
\]

\[
Q(t) > Q_{\text{MIN}}_t \quad \text{ Eq.(5)}
\]

\[
S_k(t+1) = S_k(t) + I_k(t) - R_k(t) - SP_k(t) \quad \text{ Eq.(6)}
\]

Where \( S_k(t) \) is storage of the reservoir \( k \) at time step \( t \)
\( S_{\text{MAX}}_k \) is maximum capacity of the reservoir \( k \)
\( S_{\text{MIN}}_k \) is minimum capacity (or dead storage) of the reservoir \( k \)
\( Q(t) \) is flow in the channel at time step \( t \)
\( Q_{\text{MIN}}_t \) is minimum flow requirement at the downstream channel at time step \( t \)
\( I_k(t) \) is inflow to the reservoir \( k \) at time step \( t \)
\( R_k(t) \) is release from the reservoir \( k \) at time step \( t \)
\( SP_k(t) \) is spill from the reservoir \( k \) at time step \( t \)
3.2 The application of LINGO to the Yom-Nan basin

A monthly optimization model was set up for the Yom-Nan basin with LINGO. Input variables were average monthly inflow to Sirikit and KwaiNoi reservoirs in 2003-2012, and maximum and minimum capacities of Sirikit and KwaiNoi reservoirs. The objective function to minimize total deficit (S\_DEF) and related equations, i.e. deficits in domestic (DEFP), deficits in agriculture (DEFA), and deficits in low flow requirement (DEFDQ) are shown in Eq. (7) – Eq. (10). Deficits would be found when demands were not met by the releases (RP). Domestic demand (DP) was estimated by multiplying the number of populations in each of the four provinces of Sukhothai, Phitsanulok, Phichit, and Uttaradit, with the estimated per capita daily water use. Agricultural demand (DA) was calculated based on crop types (paddy or upland) and areas. There were 14 irrigation areas in the Yom-Nan basin. Downstream low flow requirement (DQ) was assumed as 0.10% of mean monthly maximum flow for this study and can be changed as needed in future simulations. Water balance equations were formulated for 12 nodes in natural channels and 10 nodes for bypass canals (as shown in Figure 3) using inflow, outflow, and side flow data. The side flow data were taken from previous study of Chaowiwat (2010).

\[
\begin{align*}
\text{Minimize } S_{\text{DEF}} &= 99 \times DEFP(t) + DEFA(t) + DQ(t) \quad \text{Eq.(7)} \\
DEFP(t) &= \sum_{k=1}^{4} \sum_{t=1}^{12} DP_k(t) - RP_k(t) \quad \text{Eq.(8)} \\
DEFA(t) &= \sum_{k=1}^{14} \sum_{t=1}^{12} DP_k(t) - RP_k(t) \quad \text{Eq.(9)} \\
DEFDQ(t) &= \sum_{k=1}^{12} DQ_k(t) - Q_k(t) \quad \text{Eq.(10)}
\end{align*}
\]

![Figure 3. Schematic of the Yom and Nan River basins](image)

This study evaluated eight scenarios developed based on the combinations of three alternatives which are 1) transferring water between the Yom and Nan River basins using bypass canals, 2) constructing a new reservoir on the upstream of the Yom River with storage capacities shown in Table 1., and 3) reducing paddy cultivation area in the Yom and Nan River basins in half. Scenarios were coded using three letters; each one represents the application (Y = Yes and N = No) of each alternative (1 to 3) in order as mentioned above. For example, YNY referred to the scenario that
allowed transferring water between the Yom and Nan River basins, no virtual reservoir, and reduced paddy agriculture.

### Table 1. Capacities of Sirikit, KwaeNoi, and a virtual reservoirs.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Min.capacity (Mm$^3$)</th>
<th>Max.capacity (Mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirikit</td>
<td>9,510</td>
<td>2,850</td>
</tr>
<tr>
<td>KwaeNoi</td>
<td>939</td>
<td>43</td>
</tr>
<tr>
<td>Virtual (upstream of the Yom River)</td>
<td>0</td>
<td>9,000</td>
</tr>
</tbody>
</table>

### 4. RESULTS AND DISCUSSION

Results of optimization are summarized in Table 2. Deficit of 65.2 million m$^3$ in agriculture was found if none of the measures was implemented (baseline scenario NNN). Without bypass, deficit of 20.5 million m$^3$ in agriculture remained even if the paddy cultivation area were cut in half (scenario NNY). The above mentioned deficits in agriculture were removed, if either the bypass system was enabled (scenarios NYY, YYN, YNY, and YYY) or a reservoir was assumed at the upstream of the Yom River (scenarios NYN, YYN, NYY, and YYY). This implies that joint management of the river network allowing water transfer between basins is more efficient than managing each individual river separately as excess of water from one basin can be supplied to another basin fading water shortage. This also shows that the bypass network project for joining Nan and Yom basins is a successful implementation.

Similarly, in flood period, excess of water from flood prone area can be transferred to adjacent basins with lower risk or damage. In all scenarios, the downstream flow requirements were met. This might be due to low downstream requirements. Sensitivity of the downstream requirements was also tested by increasing the minimum to average requirements as shown in Table 3. If the downstream flow requirements were increased from minimum to average, the downstream flow requirements were not met in all scenarios. Either when water transfer was allowed through bypass canals (scenario YNN, YYN, YNY, and YYY) or paddy cultivation area was cut to half (scenario NNY, NYY, YNY, and YYY), deficits in agriculture and downstream flow requirements decreased.

The virtual reservoir was found to contribute most to reducing deficit in agriculture from 65.2 Mm$^3$ to zero (comparing baseline scenario NNN to NYN) but cannot improve deficit in downstream flow requirements as the deficit downstream remained at 2121.7 Mm$^3$ (both for baseline scenario NNN and NYN). This is probably because water from the new reservoir was distributed to agriculture and left small amount for downstream release. When compared the performance of single measure of adding a new reservoir (scenario NYN) to a combined measure of adding new reservoir together with bypass (scenario YYN), the latter caused a slight increase in agriculture deficit from zero to 0.2 Mm$^3$ but contributed more in decreasing downstream requirement deficit from 2121.7 Mm$^3$ to 1057.1 Mm$^3$.

The combination of all three measures (scenario YYY) was considered as the best with its lowest objective function contributed by zero deficits in domestic and agriculture and lowest deficit in downstream requirements. If single alternative can be implemented, priority should be given to constructing bypass canals as improved efficiency in water resources management can be achieved through joint reservoir operations. Reducing paddy agriculture and constructing a new reservoir should be next priority accordingly.
Table 2. Optimization results when downstream flow requirements were set at minimum. This table shows values of objective function, deficit in domestic (S_DEFP), deficit in agriculture (S_DEFA), and deficit in low flow requirement (S_DEFDQ). Unit shown in million m$^3$.

<table>
<thead>
<tr>
<th>D/S flow requirement</th>
<th>Minimum</th>
<th>Half paddy/Half fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full paddy</td>
<td></td>
</tr>
<tr>
<td>Bypass/Virtual reservoir</td>
<td>NNN</td>
<td>NYY</td>
</tr>
<tr>
<td>Objective function</td>
<td>65.2</td>
<td>0</td>
</tr>
<tr>
<td>S_DEFA</td>
<td>65.2</td>
<td>0</td>
</tr>
<tr>
<td>S_DEFP</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S_DEFDQ</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Optimization results when downstream low flow requirements were set at average. This table shows values of objective function, deficit in domestic (S_DEFP), deficit in agriculture (S_DEFA), and deficit in low flow requirement (S_DEFDQ).

<table>
<thead>
<tr>
<th>D/S flow requirement</th>
<th>Minimum</th>
<th>Half paddy/Half fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full paddy</td>
<td></td>
</tr>
<tr>
<td>Bypass/Virtual reservoir</td>
<td>NNN</td>
<td>NYY</td>
</tr>
<tr>
<td>Objective function</td>
<td>2186.9</td>
<td>2121.7</td>
</tr>
<tr>
<td>S_DEFA</td>
<td>65.2</td>
<td>0</td>
</tr>
<tr>
<td>S_DEFP</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S_DEFDQ</td>
<td>2121.7</td>
<td>2121.7</td>
</tr>
</tbody>
</table>

The main limitation of this work is that the conclusion is drawn based on subjective penalty values putting more weight (99 in Eq. (7)) for domestic deficit than for agriculture and downstream flow deficits. Changing the penalties values may lead to different results and conclusion. Recommendation for further research is to improve the accuracy of penalty values i.e. by using damage cost associated with each sector. This work also took average as input data for the hydrological data. Detailed analysis of wet and dry years could potentially offer better information for the management. More scenarios, such as implementing a rain water harvesting system, changing crop patterns, and introducing a new technology to lower crop water requirements, can be evaluated to search for better options in regional water management.

5. CONCLUSIONS

This study has demonstrated the merits of the optimization model as a simulation tool for reservoirs system operations. The use of the optimization model as a simulation tool for comparison studies among different planning and management scenarios may give the planner/manager a more insightful and holistic knowledge to improve the regional water management efficiency and effectiveness.

The model results based on eight scenarios have delivered useful information for joint reservoir operations to balance limited water supply and high demand, to mitigate water deficit in all sectors, and to support decision making. The proposed framework demonstrated through a case study of the Yom and Nan basins can be extended to...
cover adjacent basins such as Ping and Wang for broader picture of applied to other joints reservoir systems for regional water resources planning. The proposed model was run at monthly time step but it can be easily modified to a finer or coarser time steps as data are available.

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