Decision Support for Complicated Irrigation System: A Case Study of Lower Pak Phanang River Basin

Natapon Kaewthong¹ and Pakorn Ditthakit², *

¹Graduate Student, School of Engineering and Resources, Walailak University.
²Assistant professor, School of Engineering and Resources, Walailak University.
*Correspondence: dpakorn@hotmail.com

Abstract. Decision support for complicated irrigation system is presented in this article. The optimization mathematical model was developed mainly based on water balance concept for both command areas and coupled river and canal delivery system to suitably determine planted area for each plant species under constraints of available water supplies and limited areas to meet the maximization of economic value for the lower Pak Phanang river basin, Southern Thailand. Due to very complex problem-solving type with many decision variables of 410 and constraints of 861, an open source Excel add-in, widely known as Open Solver, was applied to solve nonlinear mixed-integer problems. The developed model was calibrated by comparison of the required inflow quantities to satisfy the calculated agricultural water demand in the study and the observed runoff quantities at X.105 runoff station, upstream of study area, during dry season (Jan to Apr). Land use data in 2012 obtained from the Land Development Department of Thailand (LDD) was interpreted to determine agricultural water demand. It was found that there was satisfying agreement between both considered values with agricultural water requirement quantities of 21.54 MCM and observed runoff quantities of 20.98 MCM. We hence applied the developed model with 8 scenarios for guidance for irrigation management in the study area.

1. Introduction

As rapidly growing urbanization, more and more water resources are required as a fundamental manufacture factor. However, many regions have been facing water shortage problem due to the effects of climate change, land use change, mismanagement, no enough water supply and other uncontrollable factors [1-5]. With limited area of developing large water infrastructure projects such as dam or reservoir and current environmental concerns, development of small water resources projects or rainwater harvesting project have been widely acceptable in water resources management [6, 7]. In addition to water supply management as mentioned previously, water demand management like optimal cropping pattern determination in irrigated area is commonly applied [8]. For those suitable managements and maximization of possible benefit, mathematical model development for water resources planning and management is an important decision support tool for irrigation engineer. It is a coupled model of water balance analysis model and optimization model [9, 10].

The area of the lower Pak Panang river basin may be claimed as one of the most complex irrigated areas in Thailand. In spite of having Huay Nam Sai reservoir located the upper Pak Panang river basin, there is no sufficient amount of water for agricultural activities in the lower Pak Panang river basin. Additionally, because of flatted area with nearly-zero bed slope of river and most irrigated area having
level higher than water surface level in river and canals, the pumping irrigation system was used in this area. The river and canals are inevitably used as major water storage, especially during dry season. We might call this storage system as river and canal storage system. The irrigated pumping stations were built along with Pak Phanang River and tributary canals by Royal Irrigation Department (RID). Water in river or canals can flow arbitrarily depending on hydraulic gradient direction due to pumping by farmer group. At present, only gentle agreement was assigned for pumping, that is, all farmer groups can independently pump the water used for their agriculture until water level in Pak Phanang river reaching to +0.3 m MSL.

Therefore, the model for water resource planning and management considered an important tool in reducing future conflicts in the Lower Pak Panang Basin. This model uses the principle of the highest economic value to be derived from the management of water resources under limited resources. The results of this research will use as a model for practical implementation in the future for other watersheds experiencing similar problems. To manage water shortage problem for agricultural activities during dry season, this article presents determination of suitable planted area for each plant species under constraints of available water supplies and limited areas to meet the maximization of economic value.

2. Literature

At present, several mathematical modelling based on optimization techniques have been being developed to support decision-making in irrigation management [11-14] and water resources development [15, 16]. Although linear equations are widely used in solving management-type problems, mixed-integer nonlinear programming (MINLP) are more suitable for complex problem-solving type as considering in this research work. Nonlinear programming (NLP) have been applying for solving in water resource management problems, such as reservoir operation and surface water management [17]. MINLP was used for identifying optimal locations of pressure reducing valves in water distribution systems [18], optimal storm sewer system design [19] and water resource management [20, 21]. An open source Excel add-in, widely known as Open Solver developed by Mason [22, 23] in the Department of Engineering Science at the University of Auckland, was selected for this research work since it has been successfully applied for many fields of application, such as chemical engineering [24], airline business [25], and complex university timetabling problem [26].

3. Methodology

3.1 Water balance and water flow network

To comprehend the complicated irrigation system in lower Pak Phanang river basin, the schematic diagram was intentionally delineated under consultant of irrigation officers from Royal Irrigation Department (RID) and local stakeholders as shown in figure 1. It shows components of the system including main river (Pak Phanang river), canals, command area, locations of pumping station, agricultural water demand in each command area, water flow direction, return flow, and water storage or community pond in each command area. Main Canal (MC) command area is the area which irrigation water is obtained from pumping water from river or canals into gravitational irrigation canal system, whilst Main Drainage (MD) command area which irrigation water is obtained from pumping water from river or canals into drainage canal system (water flowing with adverse slope). Water balance analysis was firstly considered for each command areas and then for the whole system with coupled river and canal delivery network.

Figure 2 shows more details for a coupled model of water balance analysis and optimization model. Water supply in the study area are obtained mainly from river storage and canal storage and some from surface runoff. The community ponds in each command area are alternative water sources and could be more considered in present and near future since no enough water source meet more growing demand. Water surface runoff was evaluated by the SCS model, which transfer rainfall to runoff. The water in river storage and canal storage is delivered to the command areas by gravitational irrigation.
canal system and some is pumped to the command areas. Land use data in 2012 obtained from the Land Development Department of Thailand (LDD) was interpreted to determine agricultural water demand based on Hargreaves equation and estimation of water storage (community pond) in each command area. The data of electricity charge and crop price were used to evaluate benefit for the lower Pak Phanang river basin.

Tables 1 and 2 show water storage volume in the river, main canals, and community ponds in each command area, and the amount of water flowing into the study area. The amount of water in these water storage were assumed to be full since rainy season or flooding event has just encountered in December. These values were assigned as initial values for the simulation run. As presented previously, mixed-integer nonlinear optimization mathematical model was developed for solving complex problem-solving type with many decision variables of 410 and constraints of 861. To simplify the model and relaxation for a large optimization problem, one time period of 4 months (Jan to Apr) in dry season was considered herein. The details of the objective equation and the constraint equation are discussed in the next section.

**Figure 1.** Schematic diagram of lower Pak Phanang river basin
Figure 2. A coupled model of water balance analysis and optimization model

Table 1 Water storage volume in the river and main canals and the amount of water flowing into the study area (MCM)

| Inflow from Upper Pakpanang River | Inflow from Upper SaoThong Canal | Pakpanang River storage | Chauat Prakmuang Canal storage | Ban Klang Canal storage | Chian Yai Canal storage | Bang Sai Canal storage | Sukhum Canal storage | Maisiab Canal storage |
|----------------------------------|---------------------------------|-------------------------|-------------------------------|------------------------|------------------------|------------------------|---------------------|------------------------|
| 20.79                            | 4                               | 25                      | 5                             | 3.2                    | 3                      | 2.3                    | 2                   | 0.5                    |

Table 2 Water storage volume in community pond (MCM)

| water storage area | MC1 | MC2 | MD1 | MD2 | MD3 | MD4 | MD5 | MD6 | MD7 | MD8 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| MC1                | 0.50| 0.71| 0.94| 0.34| 0.50| 0.69| 0.22| 0.13| 0.23| 0.14|

3.2. Objective function and constraints

3.2.1. Objective function. The objective function was developed for maximizing economic value for the lower Pak Phanang river basin. The decision variables include planted area for each plant species in each command area, time taken for pumping water from river or irrigation canals at each pumping station, water flow direction in river and canals. In this work, we only considered in dry season (January to April) due to being the period of time having limited water sources. The objective function can be written as follows.

$$Max \ Z = \sum (A_{c,m} \cdot P_c) - \sum (O_i)$$ (1)

$$Max \ Z =$$ net benefit obtained from agricultural crops (baht)

$$A_{c,m} =$$ planted area for each plant species (c) in each command area (m) (m$^2$)

$$P_c =$$ selling price of agricultural crop for each plant species (c) (baht/ m$^2$)

$$O_i =$$ pumping costs for electric irrigation pumps depending on time taken for pumping water at each pumping station (i) (baht)
3.2.2. **Constraints.** Constraint equations can be implemented by introducing parametric constraints to determine the relationship of nonlinear inequalities to the limits of the objective equation generated by the variant of the problem. The plant species involving in this study were paddy field, palm oil, rubber, grapefruit, orchard, vegetable, ruzy, and biennial crop. The considered constraints in the study can be alphabetically explained as follows.

- planted area in each command area ≤ total area of each command area
- total agricultural water demand ≤ amount of available water storage in river and canals
- water allocated to each command area ≤ available pump capacity at each command area
- sum of water inflow at junction node = sum of water outflow at junction node
- some water flow direction in river or canals must be assigned to be corresponding the natural water flow direction of study

4. **Model Calibration**

To calibrate the model, planted areas and time taken for pumping water in each command area as decision variable were determined. The planted areas obtained from simulation run were not more than those derived from interpretation of land use data in 2012 given by Land Development Department of Thailand (LDD). Such areas then were used for calculation of agricultural water demand. The exact time taken for pumping water in each command area was ambiguous due to no official record. However, we obtained those values, which were not exceed 20 hrs per day, from interviewing irrigation officers. The comparison between the required inflow quantities to satisfy the calculated agricultural water demand in the study and observed runoff quantities at X.105 runoff station, upstream of study area, during dry season (Jan to Apr) was undertaken. It was found that there was satisfying agreement between both considered values with agricultural water requirement quantities of 21.54 MCM and observed runoff quantities of 20.98 MCM.

5. **Scenarios Analysis for water management in Lower Pak Panang basin**

Two main scenarios analysis were considered herein, depending on variable of inflow from upper Pak Phanang river, that is, it was one of decision variables as defined in scenario#01 or it was constant variable of 20.79 MCM as defined in scenario#02. Each sub-scenarios under main scenarios were established with altering cases of planted area variable as well as pump control variable as shown in table 3. The detained information can be explicitly explained as follows.

| Scenarios | Inflow from upper Pak Phanang river | Planted Area | Pump Control |
|-----------|------------------------------------|--------------|--------------|
|           | land use in 2012 | consisently decreased | Increased abandoned areas of paddy fields and orchards | new planted area allocation | realistic in-situ | allowing additional capacity point |
| 1.1       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 1.2       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 1.3       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 1.4       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 2.1       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 2.2       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 2.3       | 0                     | 0             | 0             | 0              | 0              | 0              |
| 2.4       | 0                     | 0             | 0             | 0              | 0              | 0              |

* fixed value  o = decision valiable
Scenario#01: The aim of this scenario was to determine amount of required inflow from the upper Pak Phanang river under various consideration of planted area and pump control variables with maximizing net benefit of area.

- 1.1 Using land use data in 2012 and pump control with realistic in-situ, no more than 20 hrs a day
- 1.2 Using land use data in 2012 and allowing additional pump control
- 1.3 Using land use data in 2012, allowing to increase planted areas in abandoned areas of paddy fields and orchards and allowing additional pump control
- 1.4 New planted area allocation under total planted areas obtained land use data in 2012, but not allowing to increase planted areas in abandoned areas of paddy fields and orchards, and pump control with realistic in-situ, no more than 20 hrs a day

Scenario#02: The aim of this scenario was to analyse net-benefit maximization of area under recorded data of inflow from the Upper Pak Phanang river.

- 2.1 Allowing to reduce planted areas based on land use data in 2012 and pump control with realistic in-situ, no more than 20 hrs a day
- 2.2 Allowing to reduce planted areas based on land use data in 2012 and allowing additional pump control
- 2.3 New planted area allocation, the considered total area including total planted areas obtained land use data in 2012 and planted areas in abandoned areas of paddy fields and orchards, and pump control with realistic in-situ
- 2.4 Allowing to reduce planted areas based on land use data in 2012, pump control with realistic in-situ, and allowing community pond based on 10% of the planted areas in each command area.

6. Results and Discussion
The various study results for two main scenarios are presented in table 4. It gave the information concerning water inflow for upper basin, economic value or net benefit, agricultural water demand, and planted areas for each plant species, i.e. paddy filed, palm oil, para rubber, grapefruit or pomelo, orchard, vegetable, biennial plant. They can be explained and discussed as follows.

| Case study | Water inflow from Upper basin | Economic value | Water Demand | Area MCI in MDM (hectare) |
|------------|--------------------------------|----------------|--------------|--------------------------|
|            |                                |                | paddy field | palm oil | rubber | grapefruit | orchard | vegetable | ruzy | biennial | Total |
| Case 1.1   |                                | 30.272         | 12.101      | 1.374     | 1.096  | 4.568    | 2.281   | 5.839     | 242  | 66,772.35 |
| Case 1.2   |                                | 209,307,609    | 1,677,667,863 | 326,574,028 | 39.272 | 12.101 | 1.374 | 1.096 | 4.568 | 2.281 | 5.839 | 242 | 66,772.33 |
| Case 1.3   |                                | 216,845,570    | 1,820,084,433 | 334,771,298 | 39.272 | 12.101 | 1.380 | 1.096 | 4.602 | 2.162 | 6.586 | 267 | 69,466.17 |
| Case 1.4   |                                | 21,005,507     | 1,005,378,896 | 134,416,843 | 881     | 513    | 4,122 | 2.705 | 6,027 | 6,843 | 17,516 | 578 | 39,184.5 |
| Case 2.1   |                                | 20,790,000     | 983,164,644  | 138,075,252 | 14,842  | 1.134 | 1.374 | 1.096 | 4.568 | 2.281 | 5.839 | 242 | 31,675.07 |
| Case 2.2   |                                | 20,790,000     | 983,164,644  | 138,075,252 | 14,842  | 1.134 | 1.374 | 1.096 | 4.568 | 2.281 | 5.839 | 242 | 31,675.07 |
| Case 2.3   |                                | 20,790,000     | 1,004,589,819 | 128,371,994 | 843     | 513    | 4,122 | 2.705 | 6,027 | 6,843 | 17,516 | 578 | 39,146.18 |
| Case 2.4   |                                | 20,790,000     | 1,701,978,223 | 326,574,032 | 39.272 | 12.101 | 1.374 | 1.096 | 4.568 | 2.281 | 5.839 | 242 | 66,772.33 |

Case 1.1 indicated that it was no feasible solution found due to insufficiently existing pump capacity for agricultural water demand. Although amounts of water inflow from upper basin were plentiful, they were not be able to be used to meet water requirement. It was obviously shown as in case1.2 that allowing additional pump control could conquer the limitations as found in case 1.1. In this scenario, it required agricultural water demand of 326.57 MCM, which was from upper basin 209.31 MCM and water storage in area 117.26 MCM, for the agricultural area of 66,772.32 hectares. Undoubtedly, the maximum net benefit of 1.82 thousand billion baht (more than 42.41 million
baht as compared to case 1.2) was found in case 1.3 due to allowing to increase planted areas in abandoned areas of paddy fields and orchards and allowing additional pump control. It required agricultural water demand of 334.77 MCM, which was from upper basin 216.85 MCM and water storage in area 117.92 MCM, for the agricultural area of 69,466.17 hectares. Case study 1.4 showed altering of planted area under pump capacity limitation. This proposed scenario was to test the reduction of agricultural water demand by increasing the planted area of low water demand plant (para rubber and ruzy) and decreasing the planted area of high water demand plant (paddy filed and palm oil). As shown in table 4, minimum agricultural water demand of 134.42 MCM was found. In addition, it required water from the upper basin only 21.01 MCM with the economic return of 1.01 thousand billion baht.

The results of cases 2.1 and 2.2 were very similar, but not the same values, for planted areas of each plant species, but it could not be shown in table 4 due having difference in the 5th digits decimal. It can be explained that reduction measure of planted areas were more effective than measure of additional pump control under the limitation of amount of water supply form the upper basin. The total planted area of approximately 31,675.07 hectares with the economic return between 983.16 and 984.73 million baht for cases 2.1 and 2.2, respectively. It was found that cases 2.3 and 1.4 was similar concept for irrigation management, that is, increasing the planted area of low water demand plant (para rubber, grapefruit, orchard, vegetable, and ruzy) with high income and decreasing the planted area of high water demand plant (paddy filed and palm oil). The total planted area of approximately 39,146.18 hectares with the economic return of 1.00 thousand billion baht. Both total planted area and the economic return were more than case 2.2 with 7,471.11 hectares and 19.83 million baht. For the final case study of 2.4 with allowing community pond based on 10% of the planted areas in each command area, the maximum economic return of 1.70 thousand billion baht and the maximum total planted area of 66,772.32 hectares, when considering only case 2, was obtained. Moreover, it indicated that when water supply sources were plentiful, growing rice gave the maximum benefit for the Lower Pak Phanang River Basin.

7. Conclusions
This study illustrated the application of mixed integer nonlinear programming as decision support tool for complicated irrigation management. The Lower Pak Phanang River Basin, located Nakhon Si Thammarat province, Southern part of Thailand was used as a study area with limited water supply sources during dry season. To solve the water shortage problem, we proposed water demand management by determination of suitably plated area for each plant species. The abandon areas of paddy field and orchard were additionally considered to increase planted areas for more obtained net benefit. Not only were water supply sources limited, but also the operations of pump control for each command areas at present were restricted and obstructed to get more net benefit. The additional pump control, which is water supply management, then was proposed to release this restriction. Finally, the community pond, which applies the concept of rainfall harvesting, supplementally undertaken in this study. All above scenarios analysis could be used as guidance for irrigation management of the Lower Pak Phanang River Basin.

References
[1] Erica DeNicola, Omar S. Aburizaiza, Azhar Siddique, Haider Khwaja, and David O. Carpenter, 2015. Climate Change and Water Scarcity: The Case of Saudi Arabia, Annals of Global Health (2015), VOL.81, NO.3, MayeJune 2015: 342–353.
[2] Anil Kumar Misra 2014. Climate change and challenges of water and food security, International Journal of Sustainable Built Environment (2014), 3, 153–165.
[3] J. A. Duran-Encalada, A. Paucar-Caceres, E. R. Bandala, and G. H. Wright 2017. The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region, European Journal of Operational Research 256 (2017) 567–581.
[4] Jawad Taleb Al-Bakri, Mohammad Salahat, Ayman Suleiman, Marwan Sulfan, Mohammad R. Hamdan, Saeb Khrsat and Tarek Kandakji 2017. Impact of Climate and Land Use Changes on Water and Food Security in Jordan: Implications for Transcending “The Tragedy of the Commons”, Sustainability (2013), 5, 724-748.
[5] Sujay S. Kaushal, Arthur J. Gold, and Paul M. Mayer 2017. Land Use, Climate, and Water Resources-Global Stages of Interaction, Water 2017, 9, 815.
[6] Md. Tariqul Islam, Md. Mohabbat Ullah, M. G. Mostofa Amin, and Sahadat Hossain 2016. Rainwater harvesting potential for farming system development in a hilly watershed of Bangladesh, Appl Water Sci (2017) 7:2523–2532.

[7] N. Areerachakul 2013. Overviews of Rainwater Harvesting and Utilization in Thailand: Bangsaiy Municipality, International Journal of Environmental and Ecological Engineering (2013), Vol7, No:7.

[8] Ehsan NeamatollahiJ, Vafabakhshi M.R, Jahansuz, F.Sharifzadeh 2017. Agricultural Optimal Cropping Pattern Determination Based on Fuzzy System, Fuzzy Information and Engineering (2017), 9(4), 479-491.

[9] Min Goo Kang, A.M.ASCE; and Seung Woo Park 2014. Combined Simulation-Optimization Model for Assessing Irrigation Water Supply Capacities of Reservoirs, Journal of Irrigation and Drainage Engineering (2014), Volume 140 Issue 5 - May 2014.

[10] Wafa Difallah, Khelifa Benahmed, Belkacem Draoui, and Fatch Bounaama 2017. Linear Optimization Model for Efficient Use of Irrigation Water, International Journal of Environmental and Ecological Engineering (2017), Volume 2017, Article ID 5353648.

[11] Laxmi Narayan Sethi, D. Nagesh Kumar, Sudhindra Nath Panda and Bimal Chandra Mal 2002. Optimal Crop Planning and Conjunctive Use of Water Resources in a Coastal River Basin, Water Resources Management (2002), 16, 145–169.

[12] Laxmi Narayan Sethi, Sudhindra N. Panda and Manoj K. Nayak 2006. Optimal crop planning and water resources allocation in a coastal groundwater basin, Orissa, India, agricultural water management 83 (2006), 209–220.

[13] Takeshi Itoh, Hiroaki Ishii and Teruki Nanseki 2003. A model of crop planning under uncertaintyin agricultural management, Int. J. Production Economics 81–82 (2003) 555–558.

[14] Angel Galan-Martín, Carlos Pozo, Gonzalo Guillén-Gosálbez, Assumpció Anton Vallejo and Laureano Jimenez Esteller 2015. Multi-stage linear programming model for optimizing cropping plan decisions under the new Common Agricultural Policy, Land Use Policy (2015), 515–524.

[15] Zhanqi Wang, Jun Yang, Xiangzheng Deng and Xi Lan 2015. Optimal Water Resources Allocation under the Constraint of Land Use in the Heihe River Basin of China, Sustainability (2015), 7, 1558-1575.

[16] M. W. Rose grant, C. Ringler, D. C. McKinney, X. Cai, A. Keller and G. Dono so 2000. Integrated economic-hydrologic water modeling at the basin scale: the Maipo river basin, Agricultural Economics 24 (2000) 33-46.

[17] Anongrit Kangrang, and Cetthaphan 2013. Optimal Reservoir Rule Curve Considering Ant Colony Optimization with Simulation Model, Journal of Applied Sciences (2013), 13(1): 154-160.

[18] Pham Duc Dai, and Pu Li 2014. Optimal Localization of Pressure Reducing Valves in Water Distribution Systems by a Reformulation Approach, Water Resour Manage (2014) 28:3057–3074.

[19] Omer Karovic, and Larry W. Mays 2014. Sewer System Design Using Simulated Annealing in Excel, Water Resour Manage (2014) 28:4551–4565.

[20] POFF, N.L…et al 2016. Sustainable water management under future uncertainty with eco-engineering decision scaling, Nature Climate Change (2016), 6(1),pp.25-34.

[21] Ajay Singh 2013. Irrigation Planning and Management Through Optimization Modelling, Water Resour Manage (2014) 28:1–14.

[22] Andrew J Mason 2010. OpenSolver: Open Source Optimisation for Excel, Proceedings of the 45th Annual Conference of the ORSNZ, November 2010, pp.181-190.

[23] Andrew J Mason 2011. OpenSolver: An Open Source Add-in to Solver Linear and Integer Programmes in Excel, Operations Research Proceeding (2011), pp.401-406.

[24] Jorge R. Paloschi 2001. Improving robustness using homotopy as an open solver in dynamic simulation package, Computer Aided Chemical Engineering (2001), Volume 9, Pages 255-260.

[25] Zachary Cesarotti, Matthew Reyers, Reiko Tominaga, and Samantha Zimmerman 2017. Airline Schedule Planning: Optimization Approaches, Analytics Now 2015-2016 Edition, Pages 2-10.

[26] R.A.Runga Prabodanie 2016. An Integer Programming Model for a Complex University Timetabling Problem: A Case Study, Industrial Engineering & Management Systems, Vol 16, No 1, March 2017, pp 141-153.