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Optimization Model for Irrigation Planning in Heterogenous Area

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Abstract: This study proposes an allocation LP model that can take into account heterogeneity of land area. The divided scenario into several sub-areas based on suitable soil type for each crops was used to represent the heterogeneous character in term of water requirement and crop yield. The proposed model was applied to find the dry-season (January-May) crop pattern of the Nong Wei Irrigation Project which located in the Northeast Region of Thailand. The records of seasonal flow, requested areas, crop water requirements, evaporation and effective rainfalls of the project were used for this illustrative application. Results showed that the proposed LP model gave the optimum crop pattern with net seasonal profit which corresponding seasonal available water and required area. It provided the highest profit as compare to the existing LP model that considering homogeneous project. The obtained patterns of considering heterogeneity corresponded to the available land areas of the suitable soil type.

Key words: Optimization model, Linear Programming (LP), irrigation planning, crop pattern

INTRODUCTION

Irrigation planning under limited available resources is the one of the classical problems in water resource management. In particular, given the total available resources such as water, land area and production cost, one would like to know a crop pattern of the irrigation project in order to maximize the total profit. At the starting of each irrigation season, the required land-areas are required from a farmer, while the seasonal inflow is given from the reservoir administration for serving the irrigation project. For this reason, the farmer needs to have the optimum cropping pattern which will maximize the economic return. A Linear Programming (LP) is an optimization technique which widely used to allocate the limited resources because of the proportionate characteristic of the allocation problem. One popular application of the technique in the water resource literature is to find an optimal seasonal crop pattern subjected to limited available resources. The maximization benefit was set as the objective function based on the resource constraints. The constraint functions are linear equation for finding optimum crop pattern when given available water (Haouari and Azaiez, 2001; Singh *et al*., 2001; Babatunde *et al*., 2007). A different portion of treated water from waste water treatment and ground water is included into the water constraints of the LP model (Panda *et al*., 1996; Sethi *et al*., 2006). Moreover, water quality parameters (salinity and suspended solid) are incorporated into the LP model as well (Sethi *et al*., 2002). Also, a pricing of irrigation water is considered in the constraints of LP model (Salman *et al*., 2001; Quba' *et al*., 2002).

Most previous studies assumed homogeneity in crop water requirement and crop yield for all soil types of considered irrigation project. The crop yield is usually affected by crop water requirement and physical soil type that has suitable condition for cultivating crop such as sufficient fertile, moisture content and porosity. As a result, the obtained pattern is inappropriate with the soil type having suitable condition for cultivating, so consequences are increasing production cost, using chemical fertilizer and pesticide and increasing pollution. Hence, planners or engineers need management tools to find an optimum crop pattern. The divided scenario into several sub-areas or block can be represented the heterogeneous character of the large scenario in term of water requirement and crop yield (Paudyal and Gupta, 1990; Evans *et al*., 2003). However, the heterogeneous character in irrigation planning is not considered in term of suitable soil type for cultivation of each crop.

The purpose of this study is to propose an allocation LP model that can take into account heterogeneity of land area. The heterogeneous character of the irrigation project will be represented by dividing the land area into several sub-areas based on suitable soil type for cultivation of each crop.

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MODEL FORMULATION

The linear programming is used as a based model for finding optimal seasonal crop pattern. The model will be formulated to maximize profit subjected to the limited resources on available seasonal water and suitable soil types of each crop. The obtained crop pattern can be used for seasonal planning which considering the heterogeneous character of the scenario. The objective function of the model can be presented as:

$$\text{Max } Z_j = \sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{k=1}^{K}(Y_{hik}P_{hik} - C_{hik})X_{hijk} \quad (1)$$

Where:

- Z_j = Gross profit of the scenario during the season j
- h = Sub-area index of the scenario (h = 1, 2, 3,...,H)
- i = Soil type index (i = 1, 2, 3,...,I)
- j = Seasonal index j
- k = Crop type (k = 1, 2, 3,…,K)
- Y_{hik} = Crop yield of crop k in sub-area h for soil type i (kg ha^{-1})
- P_{hik} = Crop price of crop k in sub-area h for soil type i (baht kg^{-1})
- C_{hik} = Production cost of crop k in sub-area h for soil type i (baht ha^{-1})
- X_{hijk} = Irrigated area of crop k in sub-area h for soil type i during season j (ha)

The constraints of the model can be divided into two categories including water constraint and land area constraint. The water constraint considered the constant irrigation efficiency (RID, 2004). The net crop water requirement is not greater than the total available water of the irrigation system multiplying the irrigation efficiency of the irrigation project, which described as:

$$\sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{k=1}^{K}\sigma_{hijk}X_{hijk} \le \phi Vd_j \quad (2)$$

Where:

- σ = Crop water requirement rate of crop k in sub-area h for soil type i during season j (mm ha^{-1})
- Vd_j = Total available water of the irrigation system during season j (Mm^3)
- φ = Irrigation efficiency of the irrigation project

The seasonal available water of each zone (q_{hj}) is calculated by multiplying the net available water of the irrigation system with a proportion of each zone area and total area (T_j), which presented as:

$$q_{hj} = \phi Vd_j\left(\frac{X_{hj}}{T_j}\right) \quad (3)$$

$$\sum_{i}^{I}\sum_{k}^{K}\sigma_{hijk}X_{hijk} \le q_{hj} \quad (4)$$

For the land area constraint, the summation of all zone area is not greater than the available total area of scenario during season j, which described as:

$$\sum_{h=1}^{H}X_{hj} \le T_j \quad (5)$$

In each zone is divided into several sub-areas suitably to soil type. The total land area of all soil type is not larger than the available area of the zone, which presented as:

$$\sum_{i=1}^{I}\sum_{k=1}^{K}X_{hijk} \le X_{hj};\ \text{for } h = 1,...,H \quad (6)$$

The net irrigated area of all crops is not greater than the land area of each soil type. The irrigated area of each crop is not larger than the suitable area for its cultivation. These constraints are of the following form:

$$\sum_{k=1}^{K}X_{hijk} \le X_{hij};\ \text{for } h = 1,...,H \text{ and } i = 1,...,I \quad (7)$$

$$X_{hijk} \le S_{hijk};\ \text{for } h = 1,...,H \text{ and } i = 1,...,I \text{ and } k = 1,...,K \quad (8)$$

$$X_{hijk} \ge 0 \quad (9)$$

Where:

- S_{hijk} = Amount of suitable land for the cultivation of crop k in sub-area h for soil type i during season j

In order to consider the heterogeneous character of the suitable soil type for cultivation each crop, the zone area is divided into several suitable soil types (Fig. 1).

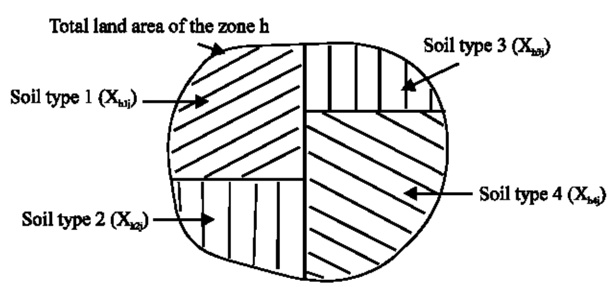

Fig. 1: The suitable soil type for the cultivation in a zone area

ILLUSTRATIVE APPLICATION

The 27 year (1977-2003) of seasonal flow, irrigated area, crop water-requirement, related evaporation and effective rainfall of the Nong Wei Irrigation Project during dry season (January-May) were considered for illustrating the application of the proposed approach. Figure 2 presents the location of the Nong Wei Irrigation Project in the Northeast region of Thailand.

The developed LP model is applied to find an optimum crop pattern of the Nong Wei Irrigation Project subjected to restriction on water availability and land area. There are four land use types (rice, corn, vegetable and fish pond) in the considered project. However, fish ponds are not included to allocate because they are fixed. The total area of scenario is 41,814 ha (1 ha = 10,000 m^2) and is divided into 7 zones.

In addition, the crop yield and benefit rate of each crop in those cases are presented. It indicates that crop water requirements in unsuitable area of cultivation are smaller than in suitable land because of the unsuitable soil type. Similarly, the crop yield and benefit rate are too small because crop yield is affected by physical soil type and water requirement. The suitable condition of soil type for cultivating crop (S1) indicates that all crops are grown in the suitable soil type area. On the other hand, unsuitable soil type for cultivation (S2) means the unfertile area (Table 1).

In order to test the effectiveness of the approach model in the homogeneity of the irrigation system, a sensitivity analysis was conducted. The analysis tested a variation of the benefit of the considered scenario by changing the homogeneity character under the same resources.

In this study, the efficiency of the proposed LP model that takes into account heterogeneity of land area is presented. For this reason, the homogeneous character of the irrigation project is considered in order to compare the case studies. When the irrigation project was considered as a homogeneous character, crop water requirement and crop yield were calculated accordingly with each suitable soil type of the zone. They depended on available land size of each suitable soil type as well as their values of suitable and unsuitable soil types, which described as:

$$\hat{\sigma}_k = \frac{\sigma_k^1 \times X_k + \sigma_k^2 \times X_{\bar{k}}}{\sum_{k=1}^{K} X_k} \tag{10}$$

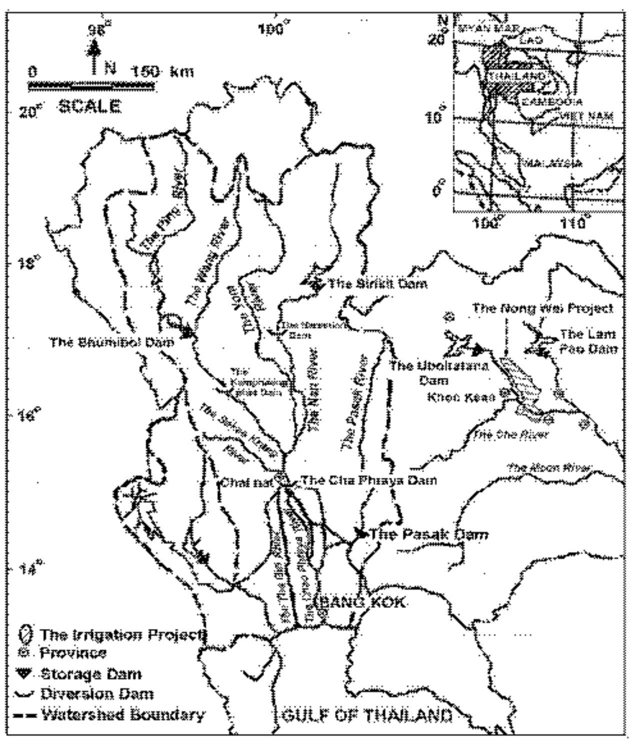

Fig. 2: Locations of the Nong Wei Irrigation project

Table 1: Crop water-requirement rate of each crop in suitable and unsuitable cases for cultivation

	Crop water requirement		Yield				Benefit	
Suitable soil type for cultivation crop	S1 (mm ha^{-1})	S2 (mm ha^{-1})	S1 (kg ha^{-1})	S2 (kg ha^{-1})	Production cost (baht ha^{-1})	Crop price (baht kg^{-1})	S1 (baht ha^{-1})	S2 (baht ha^{-1})
Rice	7,317	6,272	2,900	2,320	9,175	4	2,860	453
Corn	4,814	3,349	1,400	1,120	7,950	8	2,999	808
Vegetable	4,096	2,891	3,413	3,071	56,250	18	6,847	537
Fish pond	9,125	-	-	-	-	-	-	-

S1: Suitable for cultivation, S2: Unsuitable for cultivation, 1 US \$ ~ 35 Baht

$$\hat{Y}_k = \frac{Y_k^1 \times X_k + Y_k^2 \times X_{\tilde{k}}}{\sum_{k=1}^{K} X_k} \qquad (11)$$

Where:

$\hat{\sigma}_k$ = Crop water requirement rate of crop k when considering project as homogeneous (mm ha^{-1})

σ_k^1 and σ_k^2 = Crop water requirement rate of crop k in the suitable and the unsuitable soil type, respectively (mm ha^{-1})

k = Crop index for crop k

$\tilde{k}$ = Crop index for the others

X_k = Irrigated area for crop k

$X_{\tilde{k}}$ = Total irrigated area of all crop except crop k

$\hat{Y}_k$ = Crop yield of crop k when considering project as homogeneous (kg ha^{-1})

Y_k = Crop yield of crop k in the suitable soil type (kg ha^{-1})

Y_k^1 and Y_k^2 = Crop yield of crop k in the suitable and unsuitable soil type, respectively (kg ha^{-1})

The crop water requirement rate and crop yield from (10) and (11) will be used to replace their values in (1) and (2) to find the crop pattern in homogeneous consideration cases (existing LP model). The calculated values for homogeneous consideration are presented as the following.

Table 2 indicates that crop yields of all crops in the considered scenario as homogeneous character are smaller than their heterogeneous. Moreover, the crop water requirement rates of the homogeneous consideration are less than the heterogeneous one. For this reason, the benefits per hectare of the homogeneous consideration for all crops are small as compare with those of suitable soil type for heterogeneous consideration. However, these values are higher than their values of unsuitable for cultivation case. These crop water requirement rate, yield and benefit in Table 2 will be used in the existing LP model for finding optimal crop pattern.

Table 2: Crop water requirement rate, yield and benefit, when the irrigation project was considered as homogeneous character

Suitable soil type for cultivation crop of the zones	Crop water requirement (mm ha^{-1})	Yield (kg ha^{-1})	Benefit (baht ha^{-1})
Rice	6,922	2,680	1,949
Corn	3,857	1,217	1,568
Vegetable	2,930	3,082	739,000
Fish pond	9,125	-	-

Figure 3 shows the optimal crop pattern of the proposed and existing LP models for the available water of 100, 300 and 500 Mm^3. The crop patterns of the proposed LP model are approximately the targeted irrigation area of the project for all provided water. The crop patterns of the existing LP model are unsuitable for the targeted irrigation area because the obtained patterns are larger than the suitable size for cultivation especially the vegetable area of 500 Mm^3. The results of Table 3 shows that the model using heterogeneous character of project provided more net benefit than the model using homogeneous characters of project. In addition the obtained patterns of considering heterogeneity are corresponding to the available land areas of the suitable soil type, while the obtained patterns of homogeneous consideration are not suitable for the availability of land areas. Moreover, the obtained patterns during low available water of heterogeneous considering are given more benefit than homogeneous consideration. It indicates that heterogeneous considering is necessary for allocating during water shortage. As a result homogeneity of the irrigation project in LP model is the merit of planning.

The varied request area and available inflow from 3,200 to 40,000 ha and 50 to 500 Mm^3, respectively were used to test the efficiency of the proposed model. The results show that the proposed model provides higher net benefit than the existing model for all cases. In addition, the sum of net benefit for heterogeneous case (1,361.34 Million baht) is larger than the sum of homogeneous case (815.04 Million baht). It indicates that the variation of heterogeneous character has a large impact on the optimal solution. For this reason, LP model with heterogeneous character of land area is appropriate for finding optimum crop pattern (Table 4).

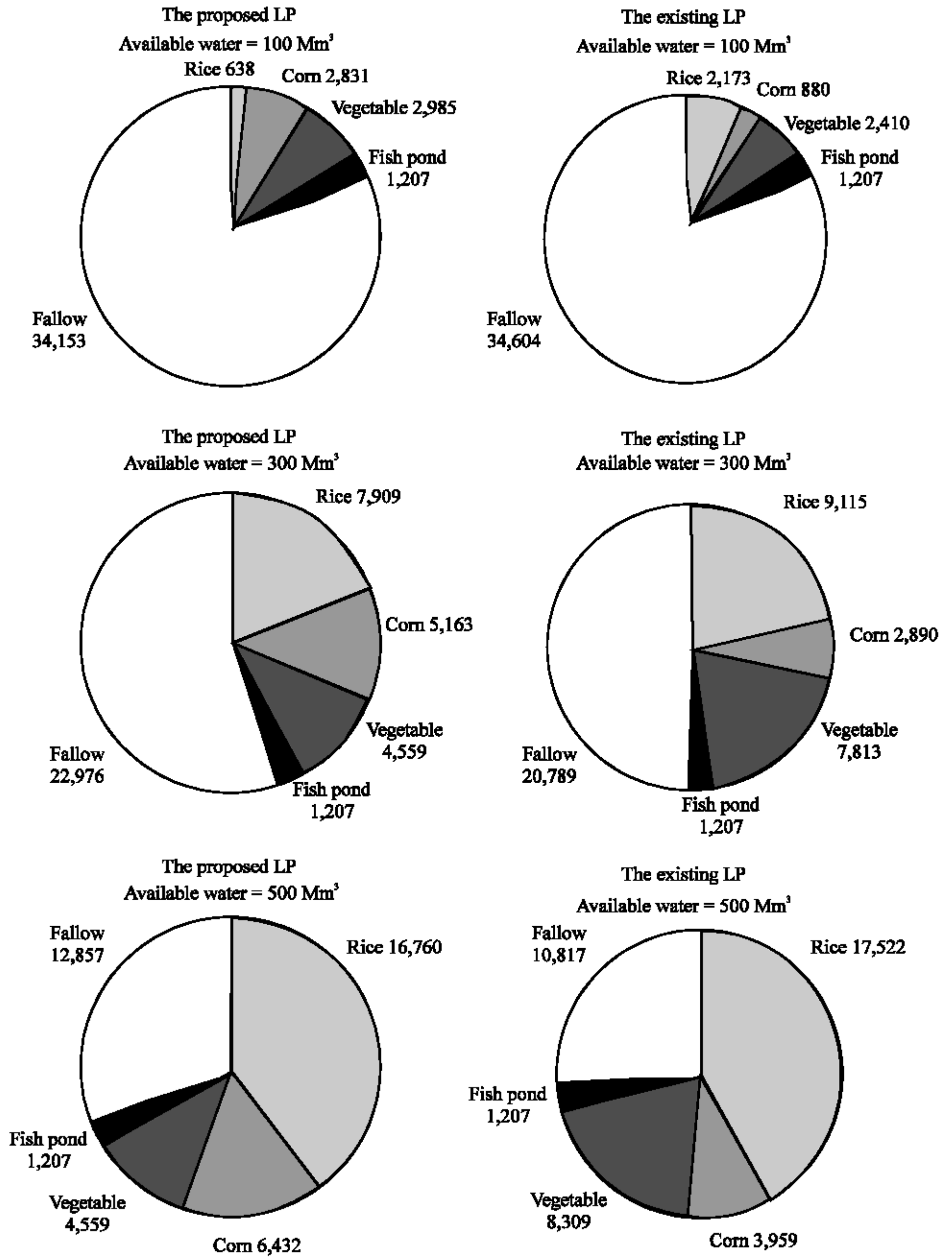

Fig. 3: Optimal crop pattern of the proposed and existing LP models

Table 3: Gross benefit and optimum crop pattern of the scenario using the developed LP model with heterogeneous and homogeneous characters of project

Suitable soil type for crop	Available land area (ha)	Available water (Mm^3) 100 Non	100 Homo	300 Non	300 Homo	500 Non	500 Homo
Rice	40,056	638,000	2,713	7,909	9,115	16,760	17,522
Corn	6,432	2,831	880,000	5,163	2,890	6,432	3,959
Vegetable	4,559	2,985	2,410	4,559	7,813	4,559	8,309
Fish pond	1,207	1,207	1,207	1,207	1,207	1,207	1,207
Total benefit (Million baht)		30.750	12.980	69.320	42.990	98.440	66.890

Non: Heterogeneous. Homo: Homogeneous

Table 4: Net benefit of the scenario using the proposed LP model (heterogeneous character of project) and the existing model (homogeneous characters of project)

Request area (ha)	Available water (Mm^3)	Total benefit (Million baht) Heterogeneous	Homogeneous
3,200	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
8,000	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
16,000	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
24,000	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
32,000	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
40,000	50	16.34	5.48
	150	42.79	20.48
	300	69.32	42.99
	500	98.44	66.89
SUM		1,361.34	815.04

CONCLUSION

This research proposed a LP model considering heterogeneity of soil type for allocating the available land area and the limited water supply. The divided scenario into several sub-areas based on suitable soil type for each crops can be represented the heterogeneous character of the large scenario in term of water requirement and crop yield. The proposed LP model gave the optimum crop pattern with net seasonal benefit which corresponding seasonal available water and required area. It provided the highest benefit as compare to the existing LP model that considering homogeneous project. The obtained patterns of considering heterogeneity corresponded to the available land areas of the suitable soil type. The heterogeneous character of scenario in term of crop water requirement and crop yield in the LP model has a large impact on the cropping pattern.

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