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Decision support system for irrigation maintenance in Indonesia: a multi-objective optimization study

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Abstract

Maintenance of irrigation infrastructure is essential to sustain food production and farmers' earnings. Given the shortage of funds for maintenance in developing countries, it is critical to understand the degradation of the function of irrigation systems so that optimal budget allocations can be made. A case study of Indonesia proposes an Infrastructure Density Index that can be used to justify budgets for regions with distinct characteristics. Current policy and practice in Indonesia is to allocate the budget uniformly, based on unit cost per hectare. Thus, the existing system provides unvarying budgets without considering the irrigation assets in each network system of a region. Regional differences should be taken into consideration during budget allocations since each region has different infrastructure characteristics related to the density of hydraulic structures, length of irrigation canals, and area of the irrigation system. A budgeting model has been developed by using non-linear programming and an analytic hierarchy process to promote more reasonable budgeting allocation policy. The case study focuses on seven irrigation regions in West Java Province, Indonesia. Fair budgeting strategy is illustrated by the relationship between structure density and the Budgeting Index.

Keywords: Analytical hierarchy process; Budgeting strategy model; Nonlinear programming; Structure budgeting index

Introduction

In developing countries, promoting food production is often a national priority and 70–80% of available fresh water is used for agriculture (Serageldin, 1995). Rehabilitation, training and education, new applied technologies, management information and decision support systems, and other

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improvements in policy managerial and technical aspects related to operation and maintenance, are all emphasized, while construction and irrigation systems expand continuously (Rosegrant, 1997). The participation of water user associations (with farmer participation) in government projects was established in order to encourage the collection of water charges from farmers, in response to the additional resources required for operation and maintenance (O&M) activities. However, in the long run it would be as the full resources for (O&M) at least in tertiary system arranged by the water user association (farmer).

Allocating funds for maintenance and renewal of systems is a classic budget problem, and an optimal allocation plan directs funds toward areas of greatest need and return on investment (Grigg, 1996). In Java, Indonesia, the agricultural regions as such are typically indistinguishable to rural development in mostly poor areas and local people cannot pay the full price for food. This situation illustrates that most farmers, even now, have a low income, and this encourages an unwillingness and inability to pay for water charge collection for O&M (charged in addition to the government's O&M allocation). In addition, there are other problems related to low collection rates for water charges, low fee levels which are rarely increased (due to the reluctance of politicians to charge for water), with no connection between amount of charge collected and the amount allocated for O&M. Furthermore, most irrigation projects, policy and research reports concern the enhancing of irrigation maintenance with relation to technical and managerial remedies, due to problems such as under-finance and deferred maintenance. Small budgets for O&M, the unwillingness of dissatisfied water users to pay water charges, and the expectation of future subsidies for rehabilitation all contribute to the deferral of maintenance work. Deferred maintenance brings about the need for premature rehabilitation, or rehabilitation which occurs before the end of the design life of the system (Vermillion, 2000).

It has been evaluated that the average budgetary requirement for maintenance in Indonesia's public irrigation systems varies between US$18 and US$28 per hectare, in contrast to real expenditures of between US$5 and US$13 per hectare. Low declining rates of budget allocation and collection of O&M charges provide significant pressure on the sustainability of irrigation systems. Skutch (1998) noted that maintenance operating costs classically stand around a mere 20% of total O&M budgets. Clearly, maintenance is given low priority and limited budget allocation (Vermillion, 2000).

The major maintenance and renewal of systems in Indonesia requires a capital budgeting system which should be based on a rationale of needs, such as modern management assets, identified in Operation and Maintenance Real Number (OMRN) Reports annually for irrigation maintenance. However, for some reason, Indonesia has difficulties in making annual (periodic) inspections, since there is a limited operation cost identified for the infrastructure irrigation database system (usually, updating of the database is carried out on a project basis). This problem promotes an inadequate budget proposal and lack of any accuracy in submitting actual budget allocations to the government, especially on a national scale.

In addition, the existing policy of O&M budget allocation is normally calculated based on the total area of the irrigation region without considering the density of its hydraulic structures or the length of canal in each irrigation region. Consequently, the amount of funds received by each regional authority to maintain its irrigation system depends only on the total area of the irrigation network. In other words, the Water Resources Agency allocates uniform budgets for each irrigation region in rupiah (IDR) (US$ 1 = IDR 9,090.90 as at 28 March 2010 per hectare when, in fact, water delivery in longer distribution systems (canals) need greater budget allocations compared to water delivery in shorter canals, even if both irrigation areas are the same (Hadihardaja, 2005). Clearly, a uniform allocation plan produces sub-optimal returns in terms of the same budgeting policy for all irrigation areas, despite irrigation areas varying in characteristic and supporting facilities.

This study focuses on routine maintenance since there is a problem related to the limited budget for maintenance from the government, and an unwillingness amongst dissatisfied water users (or an inability) to pay water charges. This study is also intended to determine an equitable budgeting strategy for optimal O&M budget allocation for each irrigation region. The need for maintenance and renewal are functions of system characteristics which include a list of variables (i.e. the area), and the length and number of components, etc.; there should be a budget allocation plan that recognizes these variables. In order to resolve the problems between the OMRN system and a simple allocation policy by definition (in rupiah per hectare), then, assuming the rate of function degradation of the irrigation system is relatively constant in the irrigation region, the length of the irrigation canal and the number of hydraulic structures are the main variables taken into consideration in this study.

Given that the variables which will provide a fair allocation are known, and to solve the budget problem, an optimization and multicriteria analysis technique such as nonlinear programming (NLP) and analytic hierarchy process (AHP), respectively, will be adopted to reach an optimal decision for an equitable budgeting strategy. A budgeting index in conjunction with the density of the infrastructure is also introduced as an important parameter and evaluated for correlation. Pattern analysis of the budget allocation is also introduced in this study to evaluate the typical O&M budget for each irrigation region. The case study is related to seven irrigation regions in the West Java province, Indonesia.

Case study

The case study is related to the various physical characteristics of seven irrigation regions in hilly, transition or plain areas. The physical characteristics considered include, for example, the topographical condition, density of hydraulic structure, length of the canal, and other supporting facilities corresponding to the irrigated region. The seven irrigation regions are South Lakbok (SL), West Lutung (WL), East Lutung (EL), Cihea (Ch), Ciletuh (Ct), Rangoon (Rgn) and Telagasari (Tgs).

Figure 1 shows the typical characteristics of the seven irrigation regions. Irrigation regions with a higher value on the normalization scale will have a greater area, longer length of canal(s), and more hydraulic structure units. The variability of physical characteristics is demonstrated, with the Telagasari

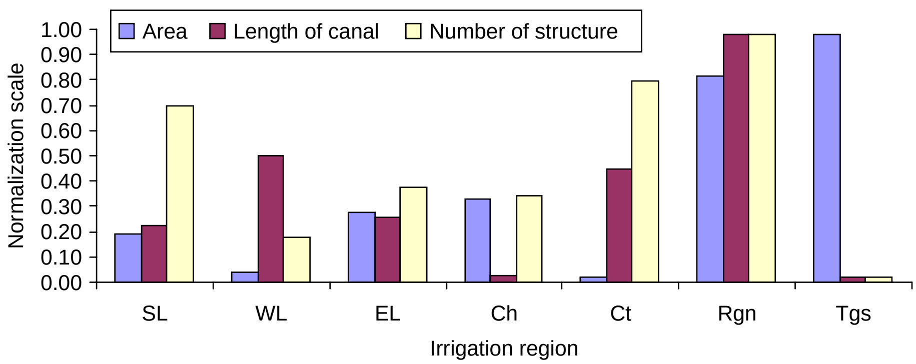

Fig. 1. Variability of physical characteristics, in terms of area, length of canals and number of hydraulic structures (after normalization).

irrigation region, having the largest area but the shortest canal and least number of hydraulic structures compared to the other regions.

The concept of fair budgeting strategy and basic assumptions

Engineer-managers emphasize the significance of financial management in their institutions. Financial management is applied by using tools such as financial planning, budgeting, accounting, reporting and auditing. The most valuable of these financial tools to support the entire management process is budgeting. Budgeting is the link between planning, operation and control. A budget is an implemented plan for expenditure and revenue, structured to monitor the programs and divisions of an institution such as a water resources agency (Grigg, 1988).

Managers or decision-makers in a water resources agency in Indonesia provide budget allocations in terms of rupiah per hectare for all irrigation regions within the same budget allocation. This approach is taken in order to estimate the budgeting needs for irrigation maintenance by using the easiest method possible but, unfortunately, it lacks accuracy as it fails to consider the number of assets of each irrigation region. The maintenance budgeting system is in fact derived based on evaluation and assessment of management assets through monitoring. This evaluation and assessment is usually not appropriately carried out, hence the difficulty in providing an accurate estimate of the required maintenance budget. In addition, the level of O&M usually varies from one irrigation region to another and, once again, the average budget should differ between irrigation regions, as it depends on previous maintenance activities carried out.

The Water Resources Institution makes decisions at provincial level concerning irrigation O&M related to the budgeting strategy of an irrigation region system. The Institution needs to establish a fair schedule to account for the distribution, length of water delivery, and for the area of each irrigation region. Water delivery over a longer distribution/canal may require more budget than a shorter one. Moreover, a higher density in the hydraulic structure per hectare will entail a larger budget allocation. Circumstances such as these must be taken into consideration to ensure a fair budgeting strategy for appropriate cost allocation for each irrigation region.

Budget allocation for irrigation maintenance and an easier implementation is usually determined based on the area of the irrigation region. The larger the irrigation region, the more budget allocation will be granted without considering the length of the canal and the number (volume) of hydraulic structures to be maintained. Therefore, this situation is unfair for a small area of irrigation with a very long canal and plenty of hydraulic structures, compared to a large area of irrigation with a shorter canal and less hydraulic structures.

Budgeting strategy for maintenance using an NLP model

A fair budgeting system is considered to be one that minimizes the variance of O&M costs due to the density of hydraulic structures and length of canal per area of the irrigation region, as well as O&M activities for the irrigation system, by using NLP. An NLP model may be used to optimize (minimize) deviation, divergence, shortage or to close the gap between supply and demand to obtain optimal decision policy, especially (in this case) related to variance (Hadihardaja, 2009). Based on this, the measure of effectiveness, or the weighted variance equation, for the budgeting strategy can be derived and modified to be, for example (Ossenbruggen, 1984):

$$V = \frac{1}{A}\sum_{i=1}^{N} a_i[B_i - \bar{B}]^2 \quad (1)$$

in which V is the variance, A is the total area for all irrigation region, N is the number of selected irrigation regions, a_i is the area of each irrigation region, B_i is the allocated budget for each irrigation region i, and $\bar{B}$ is the budget allocated by government related to average cost for maintenance. Both B_i and $\bar{B}$ have the same unit in rupiah per hectare.

If B_i is defined as $B_i = [L_i P_{ICi} + H_i P_{HSi}]$, in order to establish an optimal budgeting strategy derived from the average for all irrigation regions, the objective function, therefore, is to minimize

$$V = \frac{1}{A}\sum_{i=1}^{N} a_i[L_i P_{ICi} + H_i P_{HSi} - \bar{B}]^2 \quad (2)$$

subject to the constraints that consist of $\frac{1}{A}\sum_{i=1}^{N}[a_i L_i P_{ICi} + a_i H_i P_{HSi}] = \bar{B}$, $D_{ICi}P_{IC} = P_{ICi}$, $D_{HSi}P_{HS} = P_{HSi}$, and the non-negativity constraints, such as $P_{IC} \geq 0$ and $P_{HS} \geq 0$, in which L_i is the length of irrigation canal for an irrigation region i, P_{ICi} is the irrigation canal index for irrigation region i, P_{IC} is the irrigation canal index for all irrigation regions, and D_{ICi} is the length density coefficient of the irrigation canal for irrigation region i, defined as the ratio between the length of canal at region i and total length of the canal in all regions, or $D_{ICi} = L_i/\sum L_i \quad \text{for} \quad i = 1, \ldots, N$.

P_{HSi} is the irrigation hydraulic structure index for irrigation region i, P_{HS} is the irrigation hydraulic structure index for all irrigation regions, and D_{HSi} is the unit density coefficient of irrigation hydraulic structure for irrigation region i and defined as the ratio between the number of hydraulic structures in region i and the total number of hydraulic structures in all irrigation regions, or $D_{HSi} = H_i/\sum H_i \quad \text{for} \quad i = 1, \ldots, N$. (in which H_i is the number of hydraulic structure at irrigation region i). Two decision variables have been selected for the mathematical model to solve the optimal budgeting strategy: P_{IC} and P_{HC}. Further derivation shows that the equation can be derived and verified by using the simple equation:

$$\bar{B}A = \sum B_i a_i \quad \text{for} \quad i = 1, \ldots, N$$

Budgeting strategy for maintenance using a multi-objective, multi-criteria model

The principles and requirements of developing a water resources management system are related to decision-making aimed at the evaluation of the water management processes. This evaluation involves a complexity of structures including processes, multiple subsystems with complex mechanisms interacting as internal or external parts, time and geographical dependencies, a great volume of data acquired from the processes, multi-criteria decision-making, and the interaction of processes and a complexity of legal information (Dzemydiene *et al.*, 2008). The multi-objective multi-criteria model used in this study is the AHP. This model is based on hierarchical additive weighting, employing the pair-wise comparison method to compare the alternative options and estimate decision weights.

Once the alternative options are ranked, the decision-maker can easily choose the most suitable alternative for the decision needs. In this study, the decision weights are determined in order to obtain the justified weight for each alternative, i.e. each irrigation region. Therefore, the justified weights are the new weights and they are called, then, the budgeting indexes.

The seven irrigation regions are employed as the alternatives in the AHP model. In addition, three criteria are used to evaluate the seven alternatives: the length of the irrigation canal, the area of irrigation region, and the number of hydraulic structures. The execution of the AHP models shows that the proportional value of the decision weights is transformed to justified weights by using the equation:

$$\bar{B}A = C_W \sum W_i a_i \quad \text{for} \quad i = 1, \ldots, N \tag{3}$$

in which W_i is the decision weight based on global priority for the AHP solution. Finally, the value of $C_W W_i$ can be calculated, representing the justified weights, which are identical to the budgeting indexes.

Results and discussion

Based on the execution of the model, the analysis and discussion of the study will focus on the relationship between infrastructure density and the budgeting index developed by using the NLP and AHP methods. In addition, modified budgeting strategy for each region of irrigation maintenance is introduced to evaluate the existing budget and alternative budget allocation using both methods.

Infrastructure density index

The infrastructure density index is the combination index linking the irrigation canal and hydraulic structure indexes. This index is generated by normalizing the length of the canal or number of hydraulic structures in each region per total length of canal or number of hydraulic structures for the entire selected irrigation regions. The density index is presented in Figure 2.

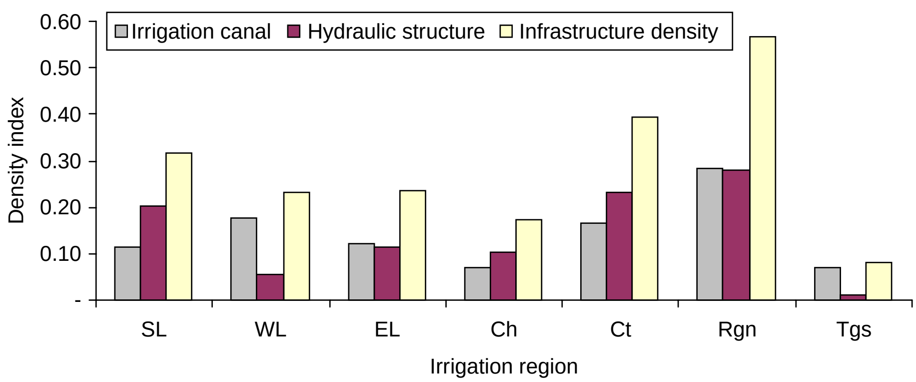

Fig. 2. Density indexes for irrigation canals, hydraulic structures and their combination, the infrastructure density index.

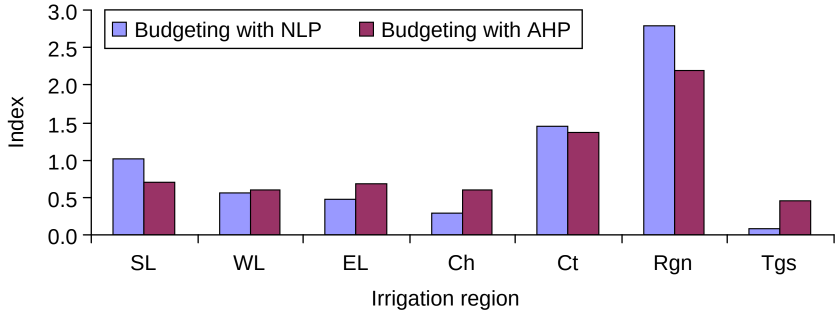

Fig. 3. Budgeting indexes (based on NLP and AHP) for each irrigation region.

Budgeting index

The budgeting index is determined by calculating the ratio between the budgeting strategy (proposed model) and the budget allocation for each irrigation region. The modified budget allocation is derived by considering the density of the canal and/or the number of hydraulic structures in each region, and combined to obtain the density index. The resulting budgeting indexes derived from both methods are presented in Figure 3.

The results for the AHP model are obtained from the value of budgeting indexes, $C_W W_i$, in which the global weight coefficient for all irrigation regions, C_W, is 6.63.

Relationship between infrastructure density and budgeting index

The characteristics of infrastructure density and budgeting index are presented to show the patterns of each irrigation region. Rangoon (Rgn) has the largest budget since it has the largest density index. In contrast, Telagasari (Tgs) has the smallest budget allocation because of the smallest value of density index, as presented in Figure 4. In addition, after the relationship between the infrastructure density and the budgeting index is developed, then the budgeting index can be determined when the infrastructure density index is known (Figure 5).

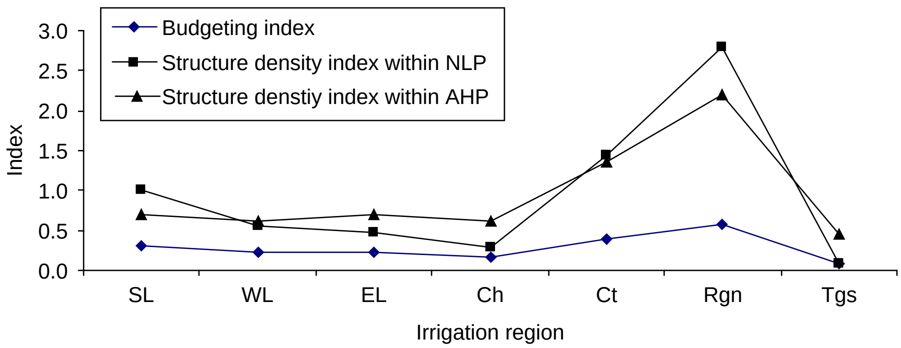

Fig. 4. Characteristics of infrastructure density and budgeting index for each irrigation region.

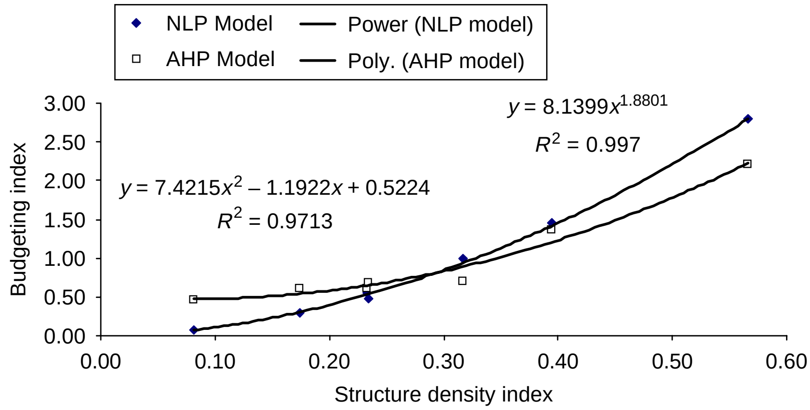

Fig. 5. Relationship between infrastructure density and budgeting index.

The relationship between infrastructure density and the budgeting index for both the NLP and AHP methods can be formulated, respectively, as follows:

$$B_{Ii} = 8.14[P_{\mathrm{IC}i} + P_{\mathrm{HS}i}]^{1.88} \tag{4}$$

$$B_{Ii} = 7.42[P_{\mathrm{IC}i} + P_{\mathrm{HS}i}]^{2} - 1.19[P_{\mathrm{IC}i} + P_{\mathrm{HS}i}] + 0.5 \tag{5}$$

in which B_{Ii} is the budgeting index. The relationship between infrastructure density and the budgeting index, evaluated for the NLP and AHP methods, gives $R^2 = 0.997$ and $R^2 = 0.971$, respectively. Therefore, the modified budgeting strategy, NB_i, can be obtained by using a simple equation such as:

$$\mathrm{NB}_i = B_{Ii}\bar{B} \tag{6}$$

in which NB_i is the new budget related to optimal budgeting for each irrigation region i, in rupiah per hectare.

Modified budgeting strategy for irrigation maintenance

A fair budgeting strategy can be determined easily once government decides the allocation for an irrigation maintenance fee. After that, this decision can be re-evaluated by using our proposed methods. Suppose that the government decides the fee for maintenance is IDR 200,000 per hectare. The new budget allocation for each irrigation region can be determined, as in Figure 6, which shows the variations of the modified budget allocation (optimal allocation) compared to the common existing budget allocation (uniform government policy) for each irrigation region. Based on the results of the proposed models, NB_i (developed by using the density index) is a more reasonable budget strategy in each irrigation region, i, and is more realistic than the existing budget allocation. However, using the AHP method is more appropriate than NLP, since the NLP method has a value approaching zero when the density index has a very small value i.e. less than 0.5 (See Figure 5). The different approach of the

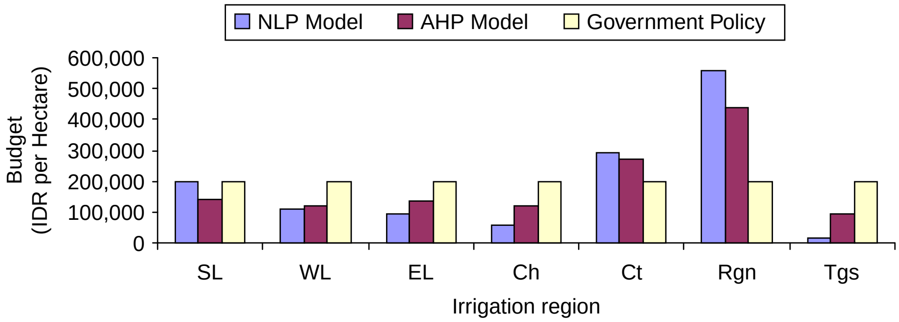

Fig. 6. Typical budgeting strategy within the NLP and AHP models, compared to government uniform allocation of IDR 200,000 per hectare.

AHP method shows that, for a small value of density index (less than 0.15), the budgeting index is relatively constant at 0.5. This condition indicates that, in practice, basic maintenance is still required even though an irrigation region has a shorter canal and less hydraulic structures, etc.

Conclusions

The study was carried out in order to develop a new fair strategy model for an appropriate budgeting strategy, by taking into consideration the density of hydraulic structures, length of irrigation canals, and based on the area of each irrigation region. The common policy of a uniform budgeting allocation system per hectare can be adjusted using the infrastructure density index and applying the relationship between budgeting and the infrastructure index to obtain a more reasonable budget allocation.

The modified budgeting allocation system using the NLP and AHP models has been developed in order to assist decision-makers in determining an appropriate budget allocation and policy at provincial level, without ignoring the uniform policy of budgeting system. The uniform budget allocation may still be used for easier budgeting planning at the strategic level, or for decision making at national level. At national level, it is easier for central government to establish a budget planning strategy related to total maintenance costs, on a uniform basis for the whole irrigation region of the country. The proposed models are useful in giving autonomy at province level, allowing local governments to modify and justify the existing budget allocation, especially when the budget is very limited.

For practical purposes, the AHP method provides a more reasonable and fair budgeting strategy than does the NLP method. This is because the AHP model provides a base budgeting allocation for small values of the structure density index instead of the zero allocation of the NLP method. The AHP method would be a benefit for basic maintenance, such as routine inspection and other minor maintenance activities.

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