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ARTICLE

Allocating the costs of multi-purpose water resource development: a case study of Chi-Chi Weir in Taiwan

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Abstract Most multi-purpose water resources have been planned and constructed by governments in Taiwan to meet the water demands of different users. However, economic and solvency differences among parties using water create conflicts regarding the reasonable and equitable allocation of investment and operational costs. The Chi-Chi Weir in Nantou County, which was completed in 2002, meets the high water demand of residents and the needs of industrial growth in central Taiwan. Thus, multi-purpose water reservoirs are designed to serve agriculture, the public and industry. Three analytical methods, the quantity-based method, marginal cost method, and separable cost remaining benefit method (SCRB), are employed to compare the cost allocation for different parties using water. The quantity-based method indicates that proportional costs allocated to agriculture, the public, industry and new irrigated areas are 88.02, 3.63, 7.86, and 0.49%, respectively. Via the marginal cost method, the proportional costs allocated to agriculture, the public, hydropower, industry and new irrigated areas are 68.44, 2.51, 28.71, and 0.34%, respectively. The marginal cost price of water is NT\$ 2.97 ton^{-1}; industrial use has the highest price. Based on the SCRB method, the proportional costs allocated to agriculture, the public, hydropower, and new irrigated areas are 18.2, 22.2, 51.8, 4.8, and 2.9%, respectively.

Keywords Water resource · Cost allocation · Separable cost remaining benefit method · Quantity-based method · Marginal cost method

Introduction

Reservoirs and weirs are constructed continually to meet the increasing demand for water from the industrial sector and urban population, which is growing rapidly in Taiwan. Owing to the massive cost of multi-purpose water facilities, allocating costs among the beneficiaries of the water users is difficult. The authorities overseeing water resources not only have to face the issue of efficient resource allocation but must equitably allocate water and cost among all parties. In the past, water was primarily allocated for agricultural irrigation and household use, followed by industrial development. The annual water consumption by the industrial sector has increased annually during recent years. Thus, the allocation of water to different users must meet production and consumption needs; that is, the proportion of water allocated should change over time to satisfy household and industrial demands.

According to the principle of efficiency, the social welfare created is typically greater than that when water is allocated inefficiently (Hsiao 1999). Swallow and Marin (1998) mentioned that the efficient allocation of water would result in a 2% increase in social welfare when water is allocated efficiently. Renzetti (1992) concluded a 4% increase in social welfare can be obtained if water is

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allocated according to seasonal characteristics. Dinar and Howitt (1997) developed different cost-allocation schemes based on different scales, financial structures or geographic locations. Notably, a cost-allocation method should be determined through negotiation among use parties. The costs of developing and maintaining water resource facilities vary with location. Therefore, a cost-allocation scheme should reflect the different costs of water. Boardman (2001) demonstrated that efficient allocation of water can maximize the "Pareto Efficiency" of social welfare. Thus, the government has recently constructed different water facilities in different areas to meet the ever-increasing demand for water by different sectors, including the high-tech sector. One must consider the efficiency and equity principle when generating a rational cost-allocation scheme. In practice, water authorities should consider the characteristics, ability to pay, and social appraisal of beneficiaries, and even subsidize some users (Hsiao 1999). The equity principle means that the allocation of water among different sectors must be equitable; however, the equity principle is always in conflict with efficiency. If a public utility is overseeing water resource facilities, then the basic consideration in cost allocation is that total income must cover total cost to avoid the creation of profit. In addition, if the price of water is set by a governing agency such that total cost is covered, this is called the "Average Cost Method," which is widely used most agencies allocating water (Hanke and Davis 1973; Loughlin 1977). Based on the principle of efficiency, each party must pay the cost of the water, and this cost should reflect the marginal cost (MC) of water; this is the so-called MC method, meaning that the price paid by a water user should reflect the MC rather than average cost (Billings and Agthe 1980; Colander and Haltivanger 1979; Gibbs 1978). Although, past study primarily focused on the price of water incurred by a public utility, it can also be utilized for cost allocation of multi-purpose water resource facilities (Dinar and Howitt 1997).

Based on a case study of Taiwan's Chi-Chi Weir, this study attempts to compare three different analytical methods, the quantity-based method, marginal cost method, and separable cost remaining benefit (SCRB) method, to determine the reasonable cost allocation regarding multipurpose water resources development for solving cost allocation problems existing between beneficiaries of public construction.

Materials and methods

Cost of water resource facilities can be allocated using three methods: quantity, priority, and benefit-based methods. Quantity-based methods are comparatively simple and easily understood. In the past, cost was allocated based on the estimated of entities. Priority-based methods are generally used to allocate the cost of multi-purpose public projects; these methods first consider the most important water users, and then users of secondary importance. Based on this hierarchy, the largest proportion of cost should be allocated to the most important water users. The benefit-based method has many benefits; for example, it can determine the actual benefit to each user, and ascertain the corresponding cost. Notably, the SCRB method is derived from this benefit-based method. When applying the SCRB method, each water user is allocated a specific cost, and each user is allocated the remaining cost proportionally based on the net benefit.

Quantity-based method

The quantity-based method is the simplest cost-allocation method; cost is allocated based on the actual amount of water received by different parties. Two cost-allocation methods exist. The first method directly calculates based on the actual amount of water received or quota-based amount of water received annually by different users, as shown in Eq. 1. The second method first deducts the separable cost of different parties, then, according to the actual amount of water received, total cost is allocated to different user proportionally, as shown in Eq. 2).

$$c_j = f^N \frac{q_j}{\sum_{j=1}^{N} q_j} \tag{1}$$

$$c_j = (f^N - \Sigma_N m_j) \cdot \frac{q_j}{\sum_{j=1}^{N} q_j} + m_j \tag{2}$$

where c_j partial cost allocated to user j ($), f^N total facility cost ($), m_j separable cost allocated to different users j ($), q_j represents the actual amount of water received or quota-based amount of water received user j (m^3), N total number of water users.

Marginal cost method

Marginal cost analysis is the changeable amount of total cost generated by each additional unit of water, which is allocated to water user by the water supplier. In the measuring economic efficiency, social optimization and the allocation of water, costs allocated should equal the MC of the water supply, as shown in Eqs. 3 and 4.

$$\mathrm{MC}_j^* = \mathrm{AC}^* + \frac{\partial \mathrm{AC}^*}{\partial q_j} \times \sum_{j=1}^{N} q_j \tag{3}$$

$$\mathrm{AC}^* = \frac{\partial f^N}{\partial \sum_{j=1}^{N} q_j} \tag{4}$$

where f^N total cost ($), q_j additional water supply sent to a specified water user j (m^3), AC^* average cost ($), MC^* marginal cost ($), N total number of users.

Equation 3 indicates that MC is not equal to the cost allocated to each water user. In cost allocation of multi-purpose water resource facilities, the unit price allocated to raw water varies among water resource facilities with or without planned water supply purpose. In the MC method, which is the most efficient method, marginal benefit equals marginal cost (MR = MC), and this method can avoid under-estimating the cost of water. Because the common cost function is a scale economy, the income derived from the marginal cost method; thus, all costs cannot be allocated. Therefore, an additional procedure must be employed to estimate the remaining cost not allocated. According to the MC method, the cost allocated to each water use is shown in Eq. 5.

$$\mathrm{mc}_j = \frac{\partial f^N}{\partial q_j} \times q_j + \left\{ f^N - \left[\sum_{j=1}^{N} \frac{\partial f^N}{\partial q_j} \times \sum_{j=1}^{N} q_j \right] \right\} \times \frac{q_j}{\sum_{j=1}^{N} q_j} \quad (5)$$

where mc_j amount of money allocated to user j ($), $\frac{\partial f^N}{\partial q_j}$ marginal cost of water supplied to user j, N total number of users.

Separable costs remaining benefits method (SCRB)

In the SCRB method, the individual separable cost is the lower limit for the total separable costs allocated to different water users, and the least cost of the best substitutable program is the upper limit of allocated cost. The difference between the two limits is the benefit created by the water resource project, and is calculated as follows; if there are number of users with common allocation of the cost allocation of a certain water resource facility, then the separable cost of user is derived using Eq. 6. After deducting separable cost, the remaining amount is the common cost allocation. If $\min_c^{\{j\}}$ is the least cost of the best substitutable program when the water resource facility is constructed by user j, then the remaining benefit of user j is derived using Eq. 7. Therefore, the final cost allocation for user j is derived using Eq. 8 (Young 1985). Equation 8 calculates the non-separable costs that should be proportionally allocated to every water user according to the remaining benefit.

$$m_j = f^N - f^{N-\{j\}} \quad (6)$$

$$b_j = \min c^{\{j\}} - m_j \quad (7)$$

$$\mathrm{SCRB}_j = m_j + \frac{b_j}{\sum_{i=1}^{N} b_j} \left[f^N - \sum_{j=1}^{N} m_j \right] \quad (8)$$

where m_j separable cost of water user j ($), f^N total construction cost ($), $f^{N-\{j\}}$ total construction cost excluding j ($).

Results and discussion

Case study of the Chi-Chi Weir

The Chi-Chi Weir is located midstream in the Chou-Shui River, Chi-Chi Township, Nantou County (Fig. 1).

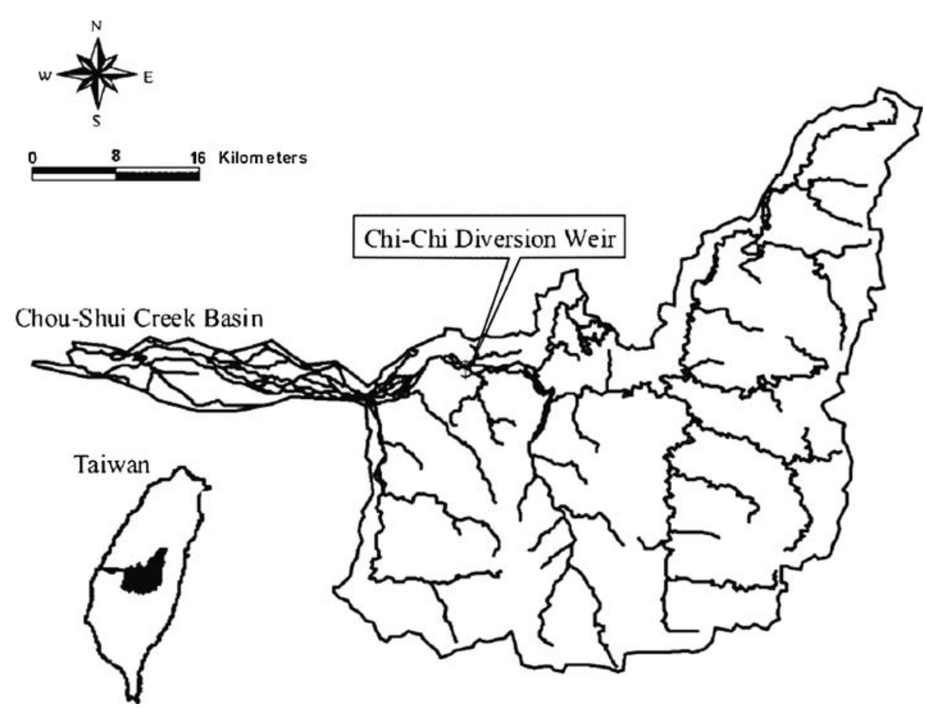

Fig. 1 Location of the Chi-Chi diversion Weir within the Chou-Shui Creek Basin, Taiwan (Shiau and Wu 2004)

The weir was originally planned and constructed by the provincial government under the Chi-Chi Common Water Diversion Scheme. The goals of this scheme were to improve existing irrigation facilities along the Choshui River, stabilize the water supply to reduce extraction of groundwater for agricultural purposes, and solve the crisis of strata subsidence in the Yunlin and Changhua areas. The primary objective was to provide a stable water supply to the off-shore industrial park in Yunlin County. The Choshui River, which originates in the Central Mountain Range, covers an area of 3,155 km^2 and has an annual surface water runoff of roughly 5 billion m^3. It is the largest river in Taiwan. An alluvial plain is on either side of the riverbank. The river flows through Nantou, Changhua, and Yunlin counties, and is considered some of the best farmland in Taiwan. The Chi-Chi Weir supplies 1.77×10^9 m^3 of water for agricultural uses, 7.3×10^7 m^3 for household usage and 15.8×10^7 m^3 for the industrial sector (Water Resource Agency 2006).

To provide water for agricultural, industrial and household use, connecting channels and a pipeline dedicated for industrial water supply are on the south and north banks of the river. The south connecting channel is 38 km long; total construction cost was NT$ 5 billion. The north connecting channel is toughly 51 km long. A hydropower plant was constructed near the Mingjen. The industrial pipeline is 42 km long; total construction cost was NT$ 5.4 billion. In addition, NT$ 1.25 billion was used to purchase the land for the Chi-Chi Common Water Diversion Scheme; total scheme investment was NT$ 23.8 billion. Annual operating and maintenance cost is roughly NT$ 2.08 billion (Water Resource Agency 2006). According to the report from Water Resource Agency in 2006, the separable cost means the total scheme investment can allocate to different water users as agriculture and industrial sector, and the non-separable cost equals total investment subtract separable cost. The results show as follows.

(1) Agriculture: NT$ 4.425 billion
(2) Industrial sector: NT$ 5.54 billion
(3) Non-separable cost: NT$ 23.8 billion − (1) − (2) = NT$ 13.84 billion

With an interest rate of 6% for 50 years, the annual cost is as follows.

(1) Agriculture: NT$ 4.425 billion × 0.06344 = NT$280.72 million
(2) Industrial sector: NT$ 5.54 billion × 0.06344 = NT$351.46 million
(3) Un-separable cost: NT$13.835 billion × 0.06344 = NT$877.69 million
(4) Combined total cost: (1) + (2) + (3) = NT$1509.87 million

Cost allocation based on the quantity-based method

The quantity-based method is the simplest cost-allocation scheme. The quantity-based method applies the average cost method, and is applicable to single-purpose public construction projects. However, when allocating the cost of multi-purpose water resource facilities, the main purpose of the construction project, and the factors associated with the benefit ratio for different water-use parties must be considered. The original purposes of the Chi-Chi Weir were first to provide a stable water supply to the offshore science park in Yunling County and the public. The secondary objective was to provide a stable water supply for agricultural irrigation and thereby reduce the extraction of underground water and prevent strata subsidence.

Therefore, when applying the quantity-based method, cost allocation is based the actual amount of water received by different water users. In addition, one must consider the priority of users of the original construction, and account for separable cost when calculating total cost, as specified in Eq. 2. According to the first method of quantity-based method, Table 1 presents the cost allocated to each sector as follows (1) agricultural sector, NT$1329.06 million; (2) public sector, NT$54.81 million; (3) industrial sector, NT$ 118.73 billion; and (4) new irrigated areas: NT$7.26 million. Therefore, the percentages of total cost allocated to agriculture, the public sector, industry, and new irrigated areas are 88.02, 3.63, 7.86, 0.49%, respectively.

Separable cost means the total scheme investment can allocate to different water users. According to data from Water Resource Agency for Chi-Chi Weir, Table 2 shows the separable cost for agriculture and industrial sector are NT$280.72 million and NT$351.46 million, respectively. According to the method 2 of quantity-based method, Table 2 shows the cost allocations for each sector as follows:

Table 1 The proportional of total cost of the Chi-Chi Weir allocated to different uses via the quantity-based method (method 1)

Item	Agriculture	Public	Industry	New irrigated area	Total
Annual water supply (10^7 m^3)	177	7.3	15.8	0.967	201.07
Allocated cost (10^6 NT$)	1,329.06	54.81	118.73	7.26	1,509.87
Proportion of allocated cost (%)	88.02	3.63	7.86	0.49	100

Table 2 The proportional of total cost of the Chi-Chi Weir allocated to different purposes using the quantity-based method (method 2)

Item	Agriculture	Public	Industry	New irrigated area	Total
Annual water supply (10^7 m^3)	177	7.3	15.8	0.967	201.07
Separable cost (10^6 NT$)	280.72	0	351.46	0	632.18
Allocated cost (10^6 NT$)	1,053.34	31.87	420.47	4.22	1,509.87
Proportion of allocated cost (%)	69.76	2.11	27.85	0.28	100

(1) agricultural sector, NT$1053.34 million; (2) public sector, NT$31.87 million; (3) industrial sector, NT$420.47 million; and (4) new irrigated areas, NT$4.221 million. Therefore, the percentages of total cost allocated to agriculture, the public sector, industry, and new irrigated areas are 69.76, 2.11, 27.85, and 0.28% respectively.

Cost allocation based on MC method

From Eqs. 3 and 4, the difference between MC and average cost is $\frac{\partial AC^*}{\partial q_j} \cdot \sum_{j=1}^{N} q_j$; therefore, the change in unit average cost created by the participation of a certain beneficiary purpose in the project multiple total water supply, results in total average cost.

Marginal cost is the increase in cost resulting from the production of an extra increment of output. Equation 3 and data from Water Resource Agency for Chi-Chi Weir were implemented to calculate the marginal cost for agriculture, the public, industry and new irrigated areas are 0.81, 0.75, 2.97, and 0.75, respectively (Table 3). The cost allocations for each sector are as follows: (1) agricultural sector, NT$1033.49 million; (2) public sector, NT$37.94 million; (3) industrial sector, NT$ 433.42 million; and (4) new irrigated areas, NT$5.024 million. Therefore, the percentages of total cost allocated to agriculture, the public sector, industry and new irrigated areas are 68.44, 2.51, 28.71, and 0.34%, respectively.

Cost allocations based on the separable cost remaining benefit method

In application of the SCRB method, Table 4 shows the separable cost allocated to water users.

According to report from Water Resource Agency in 2006, the separable cost allocated to different water users are as follows: (1) agricultural sector, NT$ 280.72 million;

Table 3 The proportional cost of the Chi-Chi Weir allocated to different users using the MC method

Item	Agriculture	Public	Industry	New irrigated area	Total
Annual water supply (10^7 m^3)	177	7.3	15.8	0.967	201.07
Marginal cost (MC)	0.815	0.751	2.974	0.751	
MC × Q (10^7 m^3)	1,442,73	54.81	469.96	7.26	1,974.77
Cost difference allocation (10^6 NT$)	−409.24	−16.88	−36.54	−2.24	−464.89
Allocated cost (10^6 NT$)	1,033.49	37.94	433.42	5.02	1,509.87
Proportion of allocated cost (%)	68.44	2.51	28.71	0.34	100

Table 4 The proportional costs allocated to different users of the Chi-Chi Weir using the SCRB method

Item	Agriculture	Public	Industry	Hydropower	New irrigated area	Total
Benefit (B) (10^6 NT$)	61.56	406.46	880.45	87.79	53.84	1,490.1
Substitutable cost (C) (10^6 NT$)	399.51	470.12	1,018.33	0	0	1,887.96
Reasonable cost min (B & C) (10^6 NT$)	61.56	406.46	880.45	87.79	53.84	1,490.1
Separable cost (SC) (10^6 NT$)	280.72	0	351.46	0	0	632.18
Remaining benefit (10^6 NT$)	−219.17	406.46	528.99	87.79	53.84	1,077.09
Proportional remain benefit (%)	0	37.7	49.1	8.2	5.0	100
Total construction cost (10^6 NT$)	–	–	–	–	–	1,509.87
Common cost (10^6 NT$)	–	–	–	–	–	906.24
Common cost allocation (10^6 NT$)	0	341.99	445.08	73.87	45.30	906.24
Allocation cost of different purpose (10^6 NT$)	280.72	341.99	796.54	73.87	45.30	1,509.87
Total proportional allocation (%)	18.2	22.2	51.8	4.8	2.9	100

(2) industrial sector, NT$351.46 million; and, public sector, NT$0. The benefits created by the water resource facility for different water users *j* are as follows: (1) agricultural sector, NT$61.56 million; (2) industrial sector, NT$880.45 million; (3) public sector, NT$406.46 million; (4) hydropower, NT$87.79 million; and (5) new irrigated areas, NT$53.84 million. The substitutable cost is the cost water user j must pay when receiving the same amount of water individually. The different water users must allocate the cost as follows: (1) agricultural sector, NT$399.51 million; (2) industrial sector, NT$1018.13 million; and (3) public sector, NT$470.12 million. Therefore, total cost derived by Eq. 8 is NT$906.24 million.

According to the proportion of remaining benefit, the costs allocated to different water users via the SCRB method are as follows: (1) agricultural sector, NT$280.72 million; (2) public sector, NT$341.99 million; (3) industrial sector, NT$ 445.08 million; (4) hydropower, NT$73.87 million; and (5) new irrigated areas, NT$45.3 million. Therefore, the percentages of total cost allocated to agriculture, the public sector, industry, hydropower and new irrigated areas are 18.2, 22.2, 51.8, 4.8 and 2.9%, respectively.

Conclusions

The Chi-Chi Weir is a multi-purpose water resource. At the initial stage of the project, its main objective was efficient allocation of water to maximize social welfare. This study explored the computational results generated by applying the cost allocation under an economic theory of efficient allocation. Some studies have overlooked the equity principle. Using the Chi-Chi Weir as a case study, three cost-allocation methods were derived. For reasonable cost allocations, this study applied the (1) quantity-based method (2) marginal cost method, and (3) SCRB method.

Tables 1 and 2 show two methods from the quantity-based method for estimating the proportional of total cost of the Chi-Chi Weir allocated to different purposes. For the quantity-based method 1, the total proportional allocations to agriculture, the public sector, industry and new irrigated areas are 88.02, 3.63, 7.86, and 0.49%, respectively. Method 2 is a modified version of the quantity-based method. First, the separable cost must be deducted from total construction cost, the remaining common cost should then be allocated to different parties according to the amount of water received. Via this method, the proportions of total allocations to agriculture, the public sector, industry and new irrigated areas are 69.76, 2.11, 27.85, and 0.28%, respectively.

This study used the MC method to estimate the marginal cost (MC) of each beneficiary party (Table 3), in which the MCs allocated to agriculture, the public sector, industry and new irrigated areas are $0.81, $0.75, $2.97, and $0.75, respectively; the MC for the industrial sector, $2.97, is highest, roughly 3–4 times that of other parties. Table 3 shows the proportional allocations to agriculture, the public sector, industry and new irrigated areas, which are 68.44, 2.51, 28.71, and 0.34%, respectively.

This study applied the SCRB method to allocate the cost in proportion to purposes. According to the cost allocations based on SCRB method, the proportions of total cost allocated to agriculture, the public sector, industry, hydropower plant, and new irrigated areas are 18.2, 22.2, 51.8, 4.8, and 2.9%, respectively.

The quantity-based method was used to calculate the average cost; this average cost was multiplied by the cost allocated to beneficiary parties based on the amount of water received. This is the cost allocated to beneficiary parties. This method is suitable for cost allocations of single-purpose water resource facilities. Using the first quantity-based method, 88.02% of construction cost is allocated to the agricultural sector; however, this is an unfair allocation because the agricultural sector has had water rights for many years. Therefore, the quantity-based methods are not applicable to multi-purpose water resource projects.

The results from MC method are very close to those obtained by method 2 of the quantity-based method. The difference between these two schemes is that in the second scheme, a difference in unit cost allocated to different water users exists. For the first scheme, the unit cost for different water users is the same.

In addition to the three water users, hydropower plants were considered in the SCRB method. Because hydropower plants have an additional construction benefit, the actual benefit of water consumption based on the different purposes and the financial benefits created by this project for different purposes. This study used the SCRB method and took the difference between separable cost and the smallest substitutable cost. Finally, this difference was used as the basis for allocating common cost.

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