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Input allocative efficiencies for operation and maintenance of rural piped water supply systems in highland areas of Vietnam

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Highlights
- Analysed rural piped water supply systems in highland areas of Vietnam.
- Studied technical, economic, allocative efficiencies by data envelopment analysis.
- Indicated level of efficient scores and optimal O&M input norms.
- Identified basics for policy implications of rural water supply management.

Abstract: Strengthening the functioning of existing rural piped water supply systems is a critical strategy for ensuring household water security, particularly in water-scarce contexts. Improving operation and maintenance (O&M) of the systems is an important area of focus, commonly plagued by poor reliability and functionality over time. From an economic perspective, there is an opportunity to optimise O&M input efficiencies as a foundation for improved management. This paper presented challenges and opportunities to optimise O&M input efficiencies based on an analysis of water supply systems in Vietnam's highland areas characterised by mountainous terrain and water scarcity. The analysis focused on state-based agencies for O&M given their mandate for restoring the inefficient systems and identified input norms for guidance on how to optimise O&M activities. We applied an input-oriented data envelopment analysis (DEA) model under constant returns to scale assumption to estimate technical, economic and allocative efficiencies. The results identified efficiency levels of 90%, 30% and 33% respectively. The study suggests a 10% reduction in general input amounts and identified efficient input target values reveal potential reduction rates for technical labour (12%), electricity (12%), as well as the technical and economic norms of technical labour (0.86 person-day·(100 m^3)$^{-1}$ water sold) and electricity (0.53 kWh·m^{-3} water sold). The policy implications for O&M state-based agencies include the adoption of input-based contracting mechanisms, while the government is encouraged to approve water tariffs and provide compensation based on input items to promote water service supply as a public good in water-scarce and challenging areas.

Keywords: data envelopment analysis, input norms, rural water supply, technical and cost efficiency, water scarcity

INTRODUCTION

In the rural water supply sector, challenges of water scarcity were compounded by a degradation of water quality and quantity, lack of appropriate infrastructure and low capacity of the operation and maintenance (O&M) management institution (Bhandari and Grant, 2007; Pereira, Cordery and Iacovides, 2009; White, 2014; Bond *et al.*, 2019; FAO, 2021). These challenges are evident in highland areas of Vietnam, constraining the ability of rural piped water supply systems (RPWS) to deliver reliable water to households. In high mountainous areas, studies have pointed to a serious reduction in the availability of groundwater (Nguyen, Ha and Nguyen, 2020) due to over-exploitation and less monitoring and high water-losses operational process of water extraction systems (2030WRG, 2017).

The functioning of RPWSs is critical for household water security in highland areas, given that piped systems are the sole standard service delivery modality, supplying water to 37% of households. Approximately 1,194 RPWSs have been constructed over the past 20 years, with 49.9% now operating at a sufficient level of sustainability to provide water in line with required standards. The remaining 51.1% are reported to be operating at "less than medium" levels or not operational, and can only provide hygienic water (Luong, 2023). Notably, RPWSs in highland regions experience substantial water loss rates, reaching an estimated 29.2%, with the highest recorded level in Gia Lai Province at 43.8%. Weak O&M management institutions have been identified as a primary cause of this challenge (World Bank, 2019). Challenges faced by RPWSs threaten Vietnam's ability to achieve national targets on rural water supply strategy towards 2030 and vision 2045 (targets of 65 and 100% of rural people respectively accessing standard water) and hence progress towards achieving Vietnam's commitments under Sustainable Development Goal 6 (Decision, 2021; United Nations, no date). To address the challenges, there was a need to strengthen rural water supply institutions to optimise RPWS's performance with a view to minimising the water losses caused by O&M management issues.

While RPWS challenges are evident, in practice, O&M management modes and performance of RPWSs in highland areas were diverse. Several studies underscored the effective operation of RPWSs managed by provincial centres of rural water supply and sanitation (PCERWASS), attributed to their technical expertise (Doan, Dinh and Dang, 2013; Toan, Hanh and Thu, 2023). Other models also performed well in O&M management due to abundant water source availability or a base of water users with the ability to pay. The less sustainable and inefficient RPWSs were typically managed under community-based management (CM) or commune people committee (CPC). These models suffered from inadequate asset maintenance, leading to deterioration and degradation within 2–3 years post-construction (Giné and Pérez-Foguet, 2008; Decision, 2021; Machado, Oliveira and Matos, 2022). To address challenges, the government has proposed appropriate O&M management models for highland areas, recommending PCERWASS management with supportive policies regarding maintenance costs and appropriate tariffs to cover those costs, especially water price compensation based on O&M input items. To develop these policies, there was a need for significant scientific evidence about O&M input allocative efficiency and cost norms (Decision, 2021; Kết luận, 2022).

Existing literature addressed several aspects of RPWS performance in Vietnam, exploring technical and economic indicators estimated by real and designed capacity rates, service times or sustainability of equipment and structures (Doan, Dinh and Dang, 2013). In the literature, sustainability was defined by integrated factors such as technique, environment, institution, management, society and finance. (Giné and Pérez-Foguet, 2008; Quynh and Hung, 2021; Machado, Oliveira and Matos, 2022; Toan, Hanh and Thu, 2023). A more narrow framing was evident in material addressing the general performance of water supply systems, which mainly used mathematical methods such as ordered logit regression and Likert's scale. For example, Sauer (2005) used a symmetric generalised McFadden function, a parametric method to estimate the allocative inefficiency of the large RPWSs managed by 47 firms in Germany, identifying key input variables as labour, energy and chemicals. The input allocative efficiency was analysed according to two RPWS groups – those with capacity above and below 250,000 m^3 with results suggesting a general allocative efficiency of 93.1 and 100% respectively (Sauer, 2005). A change of 20.5% of chemical inputs was recommended for better O&M management of the under 250,000 m^3 systems (Sauer, 2005). In another study, the stochastic frontier analysis also was used to evaluate cost efficiencies (*CE*) in water service supply for 18 urban water centres in India through six types of O&M input and output arrangements. The results identified substantial inefficiency and opportunity to cut on average 24.5% of current O&M input costs (Vishwakarma *et al.*, 2016). Qualitative research in South Africa has also emphasised the recommendation of financial incentives based on criteria of water-saving awareness and O&M labour capacity (Onyenankeya, Onyenankeya and Osunkunle, 2021). A study of private firm performance based on 26 RPWSs used a multi-step estimation procedure, finding technical efficiency (*TE*) of 88.24% (more efficient than public models), though also noting that state-based agencies were represented in both most and least efficient systems (Bhattacharyya *et al.*, 1995). The explanations for these results were differences in regulations on responsibility, administrative structures and operational modes (Bhattacharyya *et al.*, 1995).

In the context of water resources management, data envelopment analysis (DEA) has proven valuable for assessing O&M input efficiency across various domains (Coelli *et al.*, 2005; Dinh *et al.*, 2022a, Dinh *et al.*, 2022b; Dinh *et al.*, 2023). For the domestic water supply sector, DEA has been employed to estimate the water supply service efficiency of urban companies in the United Kingdom ($n = 32$), employing inputs of operational cost and two outputs of connection number and service area (Thanassoulis, 2000). DEA with a range-adjusted measure has also been used to assess the efficiency of water systems of 108 cities in Japan with five inputs being employees, operational cost (without depreciation), equipment, population, and pipe length, and two outputs being real connections and revenues (Aida *et al.*, 1998). DEA models have also been employed to assess efficiency in 33 Palestinian municipal water supply systems, identifying water losses as a primary inefficiency factor irrespective of municipality size. The inputs included four variables (water losses, water and energy, maintenance, and salary) and the output was a total revenue variable (Alsharif *et al.*, 2008). In India, a DEA output-orientation model tested the *TE* of 20 urban water utilities under constant returns to scale (CRS) and variable returns to scale (VRS) assumptions. With three outputs being water volume, hours of supply, and water quality, and two inputs being O&M expenditures and capital cost, the finding *TE* opportunities were 0.62 and 0.78 respectively, and 0.62 and 0.94 respectively, when the variable of water supply hours was adjusted (Kulshrestha, 2005). Another study used a VRS input-oriented model to assess 182 pumping and gravity-fed RPWSs according to four performance dimension models, finding efficiency scores but with large ranges within model types (Gill and Nema, 2016). However, due to the study's focus on only one or two inputs (capital and O&M costs/person), the result could not suggest the policy options for input allocation. Similarly, research conducted by Kulshrestha (2005) on urban water supply utilities used 1–2 inputs (number of staff and electricity use) finding *TE* opportunities of 14.3% for staff size and 15.1% for electricity expenditure. These studies attest to DEA's applicability for water supply utilities performance assessment.

Beyond the specific studies noted here, the application of DEA input-oriented models under CRS and VRS assumptions for analysing *TE*, *CE* and allocative efficiency (*AE*) has not been extensively explored within the rural water service supply sector. There was a particular opportunity to explore O&M inputs and real connections as the input and output variables. This study contributed novel analysis and evidence from the highland areas of Vietnam where water scarcity and management challenges hindered RPWS performance. First, we presented the DEA approach, then detailed findings related to technical and cost efficiency, and input allocative efficiency for O&M. We then discussed the potential for O&M input efficiency norms related to labour, electricity per water volume sold and real connections for benchmarking purposes and setting up O&M policy options.

MATERIALS AND METHODS

DATA ENVELOPMENT ANALYSIS

Data envelopment analysis (DEA) is a non-parametric method, developed by Farrel in 1957 according to the theory of efficient frontier which was set by input and output data of the best-observed decision-making units (DMUs) (Farrell, 1957). DEA has developed and there are now two approaches to assess productive efficiency: (1) input-oriented models (adjusting inputs for its optimal scales without change of output scales), and (2) output-oriented models (adjusting outputs for its optimal scales without change of input scales) under constant returns to scale (CRS) and variable returns to scale (VRS) assumptions (Coelli *et al.*, 2005; Ton and Nguyen, 2020).

The objectives of this study were to quantify technical and economic efficiencies as a basis for selecting the best DMUs in the management of operation and maintenance (O&M) input resources to provide water service for rural people in highland areas. In addition, the allocative efficiency (*AE*) and associated efficient input targets (*EIT*) of optimal DMUs were also estimated in order to indicate the technical and economic norms for each input variable per water amounts or real connections. Thus, a DEA input-oriented model under CRS assumption was used because these rural piped water supply (RPWS)/DMUs were considered as real optimal scales (Banker *et al.*, 1989). Lastly, the efficient indicators of RPWSs managed by state-based agencies in the highland region of Vietnam estimated under CRS assumption were technical efficiency (*TE*) – TE_{CRS}, cost efficiency (*CE*) – CE_{CRS}, allocative efficiency (*AE*) – AE_{CRS} and efficient input targets (*EIT*) – EIT_{CRS}. The general DEA models are described below.

The general model for estimating *TE* under CRS assumption:

$$\min_{\theta,\ \lambda_j} \theta \tag{1}$$

Subject to: $Y\lambda \geq y, \theta x_j \geq X\lambda, \lambda \geq 0.$

The general model for estimating minimum cost efficiencies (*CE*) under CRS assumption:

$$\min_{\lambda,\ x_j^*} w_j^T x_j^* \tag{2}$$

Subject to: $-y_j + Y\lambda \geq 0,\ x_j^* - X\lambda \geq 0, \lambda \geq 0$

In which, the meanings of the parameters in Equations (1) and (2) are: θ = technical efficiency indicator; y_j = output vectors of RPWS of the *j*-th DMU, x_j = input vectors of RPWS of the *j*-th DMU, $w_j^T x_j^*$ = minimum cost estimated from cost-efficient models, $w_j^T x_j$ = observed cost of *j*-th DMU, w_j = price vectors of input variables of *j*-th DMU, x_j^* = quantity vectors of input variables of *j*-th DMU at the time of minimum cost and calculated by a linear equation, λ = weight vectors of input and output variables, *j* = DMU using input levels (*j* = 1, 2, 3, …, *n*), *n* = the number of DMUs, *T* = technology factors.

To estimate θ indicators, the linear program in Equation (1) was processed *n* times for each DMU. The values of θ were from 0 to 1. If θ values of a DMU were 1, that DMU was considered as efficient and located on the efficient frontier. In case the θ indicator demonstrates a value lower than 1, the DMU was considered to operate inefficiently. Such a result suggested that the inefficient DMU should cut input levels with an amount of $(1 - \theta)\cdot 100\%$. The λ parameter was calculated on the basis of the linear correlation between *j*-th DMUs that have comparable conditions. The *T*-technologies added to these models were defined as the skills, management mechanisms, and staff knowledge of DMUs which were flexibly applied during the O&M decision-making for each RPWS.

CE of *j*-th DMU was estimated by rate of minimum cost and observed cost of DMUs as below formula:

$$CE_j = \frac{w_j^T x_j^*}{w_j^T x_j} \tag{3}$$

The value of *CE* was from 0 to 1. The DMU was considered to achieve optimal cost efficiency if *CE* was 1. This result indicates that when the prices of inputs were added, these DMUs used input variables at optimal levels. DMUs were considered inefficient if their values of *CE* were lower than 1.

AE of *j*-th DMU was estimated by the rate of *CE* and *TE* as below formula:

$$AE_j = \frac{CE}{TE} \tag{4}$$

The value of *AE* also ranged from 0 to 1. If the *AE* score was 1, the DMU was considered to have allocative efficiency, which means the unit allocates used inputs at the optimal scale. An AE score of less than 1 indicated a DMU with inefficient distribution of inputs.

DATA AND VARIABLES

As a representative sample of the 322 sustainable RPWSs built in all five provinces of the highland region, 24 of the 48 RPWSs operating sustainably in Dak Lak Province were chosen for this study. The sustainable RPWSs were identified based on their primary operational characteristics, which included good financial status, O&M productivity, customer willingness to utilise clean water, and O&M management organisations. These preliminary criteria will guarantee the importance throughout the data processing and evaluation. Particularly, the selected RPWSs were managed by 24 sub-stations under the authority of the provincial centres of rural water supply and sanitation (PCERWASS). These RPWSs had representative technical characteristics in terms of groundwater sources, water treatment technologies, rural water users, O&M input-based contracting mechanisms and management models. The position of sub-stations as decision-making units (DMUs) in the wider institutional set-up is shown in Figure 1.

Primary input data was collected through semi-structured interviews and available forms with DMU managers asking about O&M input categories in water price structures regulated by the government. Data related to the amount and price units of each O&M input variable such as technical labour, chemicals, electricity, minor reparation, overhead cost, and depreciation cost. The output data focused on a number of real connections. Secondary data were also gathered from both PCERWASS and relative departments of the Dak Lak Province, and addressed gaps when primary data was not available.

The input variables were organised according to O&M items relevant to the water price structures of RPWSs. DMUs were defined according to the service area and real connections of an RPWS. All input variable data were the direct inputs used by sub-stations in input-based contracting mechanisms assigned by the PCERWASS. Therefore, they did not include indirect costs incurred in the operation of professional departments and the directorate board. The rate of depreciation of inputs was determined by asset items such as pump, pipe and concrete components as regulated by design standards of connections. The six input variables were assigned codes as follows: X1 – technical labour, X2 – chemicals, X3 – electricity, X4 – minor maintenance, X5 – overhead cost and X6 – depreciation cost. The output variable of real connections was assigned the code Y. The data used for *TE* were the number of input variables such as X1: the amount of man-day of technical labour directly used to operate the headworks, monitor water treatments and delivery, collect water tariff, and maintain the system; X2: the amount of chloramine used for daily water treatments; X3: the number of kWh electricity used to run pumping systems and equipment for the production of clean water; X4: total maintenance cost which was converted into man-days based on technician wages; X5: total overhead cost, which was converted into m^3 of production water by averaging the overhead cost according to produced water and water loss; X6: total depreciation cost, which was converted into a number of designed connection by averaging all cost of depreciation by the projected number of connections made during the building phase. The converted data were to match with requirement of DEA's quantity input data. Similarly, for *CE* steps, the prices of input variables were added in the DEA program including X1 – daily wage, X2 – price of chloramine, X3 – electric tariff, X4 – man-day wage of technician, X5 – average of overhead cost by a m^3 water generated, and X6 – average of depreciation cost by a constructed connection. Data was based on a three-year average of actual costs from 2019 to 2021.

A sampling of DMUs was based on a formula developed by Banker *et al.* (1989), and previous applications of the technique testing its significance (Husain, Abdullah and Kuman, 2000; Paço and Pérez, 2013). The minimum number of DMUs was determined to be more than three times the total number of input and output variables (number of DMUs ≥ 3x (number of input variables + number of output variables)). For this study, there were six input variables and one output variable, so the minimum number of DMUs was 21. The final sample included 24 DMUs. The analysis was undertaken using DEA Solver.

RESULTS AND DISCUSSION

OPERATION AND MAINTENANCE MANAGEMENT STATUS OF THE RURAL PIPED WATER SUPPLY SYSTEMS IN HIGHLAND AREAS

Almost all of the communes in the rural mountainous areas had their own rural piped water supply systems (RPWSs) constructed by government funds, but there were very few RPWSs in water-scarce or remote mountainous areas. RPWS construction

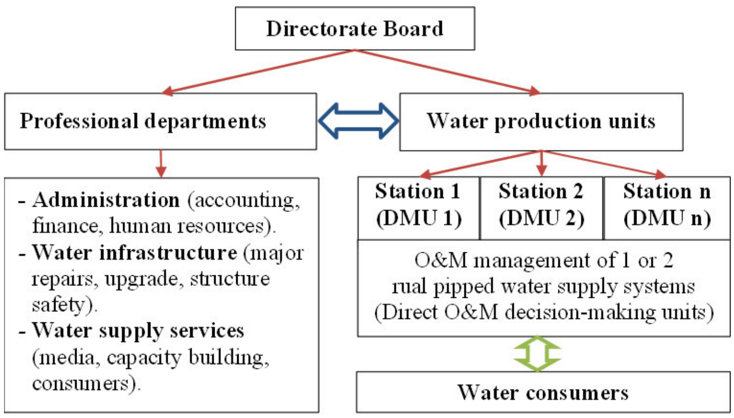

Fig. 1. Organisational chart of provincial centres of rural water supply and sanitation (PCERWASS) and decision-making units (DMUs); O&M = operation and maintenance; source: own study

decisions were mainly based on social and political targets, with economic efficiency considered as a minor criterion. As such, operation and maintenance (O&M) performance depended on the capacity of the management entity. RPWSs managed by commune people committee (CPC) or community-based management (CM) models performed poorly, while those managed by provincial centres of rural water supply and sanitation (PCERWASS) performed well due to their relatively stronger technical and economic administration. It was estimated that about 88.4% of RPWSs were managed by CM and CPC, 0.5% by the private sector and 11.1% by PCERWASS (Luong, 2023). O&M of RPWSs under PCERWASS management tended to position water services as a public good, eligible for partial government subsidisation. However, in practice, performance levels of RPWSs under the PCERWASS were diverse, with cases illustrating both the best-performing and worst-performing examples (Bhattacharyya *et al.*, 1995; Doan, Dinh and Dang, 2013; Decision, 2021). Given this assessment of O&M performance, this study applied statistical analysis to more deeply explore allocative efficiency across technical and economic dimensions.

RPWSs in the highland areas were widely distributed, spanning a range of 30–90 km in distance and located in remote areas where connection density was very dispersed (PCERWASS, 2022). The areas were characterised by low water tariff payment ability and poor awareness about clean water services (PCERWASS, 2022). The supply capacity of these RPWSs was small, typically less than 50 $m^3 \cdot d^{-1}$ distributed for multiple separate households or household groups. Government directives compelled the transfer of both O&M and asset management rights of inefficient RPWSs managed by CPC or CM to PCERWASSs. This process resulted in some management improvements, but there were still challenges in how to administer O&M input resources allocation for the PCERWASS sub-stations operating under input-based contracting mechanisms (Fig. 1). Thus, allocative efficiency as well as norms of O&M input resources was a high priority concern to improve decision-making.

With an overall objective of moving towards financial self-sufficiency, and requested to take on management of inefficient RPWSs, PCERWASSs had to apply a suitable input-based contracting approach for sub-stations. The approach sought efficient internal administration while also establishing norms relating to O&M input resource allocation. Each sub-station was assigned to manage 1–2 RPWSs, and tasked with minimising O&M input use and sharing financial risks among systems (Melita *et al.*, 2020). In this research, sub-stations were called decision-making units (DMU), operating under input-based contracting mechanisms. The DMU leaders were responsible for arranging all O&M activities and allocating input resources on an efficient basis to maintain infrastructure and meet the needs of water users.

GENERAL PERFORMANCE OF SELECTED RURAL PIPED WATER SUPPLY SYSTEMS

While O&M management of RPWSs was monitored by the same PCERWASS, the efficiency of DMU performance was diverse. Some DMUs achieved financial viability, while others bore losses despite reasonable management performance and application of the same water tariff. As specified in Table 1, the average water tariff was USD0.23·m^{-3} with a standard deviation of 0.01. However, the tariff was set up by the provincial government and was lower than the annual tariff suggested by PCERWASS which covered the full O&M cost. The other reasons for poorer performance also were that while some RPWSs had high rates of real connections, monthly water consumption was lower than designed levels resulting in low revenue and an inability to recover O&M costs. They were points for guaranteeing that RPWSs could operate efficiently and sustainably. In order to guarantee efficient water service business, the PCERWASS applied a cross-subsidy mechanism among their sub-stations because many DMUs achieved high benefits and some others got losses. Specifically, the benefit per RPWS ranged very large, from USD(−6,563.59) to 24,630.05 per year when it has not yet deducted more depreciation cost (Tab. 1).

Analysis of data from the 24 RPWSs included in the study found that many RPWSs operated above their own designed capacity. Table 1 shows a high average O&M performance rate of the number of real and designed connections being 88.89% (with a range from 60.29 to 135.19%), illustrating productive operation in cases with an average water demand per person per day of 69.21 dm^3. This water demand was higher than the national

Table 1. General operation and maintenance (O&M) performance of the selected rural piped water supply systems (RPWSs)

Criterion	Unit	Average	Range	Standard deviation
a	connection	792	135–1,589	418.64*
b		669	152–1,248	328.17*
a/*b*	%	88.89	60.29–135.19	21.25*
Water consumption per connection	$m^3 \cdot mo^{-1}$	8.72	2.26–17.23	4.03*
Water consumption per person of a real connection	$dm^3 \cdot person^{-1} \cdot d^{-1}$	69.21	17.98–136.74	32.01*
Water tariff	$USD \cdot m^{-3}$	0.23	0.23–0.28	0.01*
Water sold per RPWS	$m^3 \cdot y^{-1}$	62,007.45	14,156.55	170,101.84*
Benefit per RPWS (including depreciation cost)	$USD \cdot y^{-1}$	2,556.60	−6,563.59 to 24,630.05	6,675.96*
Benefit per real connection (including depreciation cost)		3.82	−12.17 to 23.34	8.52*
Benefit per RPWS (not including depreciation cost)		−11,012.71	−64,300.18 to 17,249.69	15,759.21*
Benefit per real connection (not including depreciation cost)		−16.45	−93.81 to 20.14	23.25*

Explanations: *a* = designed capacity, *b* = real capacity, *a*/*b* = O&M production, * = significant level at P = 0.05, e = 95%.
Source: own study.

designed standards of 60 $dm^3 \cdot person^{-1} \cdot d^{-1}$ regulated for new RPWS construction. However, the range was large, with a minimum demand of only 17.98 $dm^3 \cdot person^{-1} \cdot d^{-1}$. Further, efficiency was low when assessed according to the average economic benefit criterion. Specifically, when considering benefits inclusive of asset depreciation costs, the figure was very low at USD2,556.6 per system per year and USD3.82 per connection per year. They lost an average annual of USD11,012 per system per year and USD16.45 per connection per year if the benefits were continuously deducted more asset depreciation costs (as shown in Tab. 1). These findings indicated a need for in-depth assessment by indicators of technical efficiency (*TE*), cost efficiency (*CE*), and allocative efficiency (*AE*) by data envelopment analysis (DEA) method to find the levels of technical and economic efficiency in O&M input utilisation of the DMUs, the results of which were presented in the following sections.

TECHNICAL AND ECONOMIC EFFICIENCIES OF THE RPWSS

Estimation of technical efficiency under constant returns to scale assumption

A two-step process was used by the DEA program to evaluate an RPWS's operational efficiency based on production optimal frontiers: (i) the first step, known as technical efficiency, is the recognition of an RPWS's operational performance when the quantity of O&M inputs used to compare with the outputs is well-managed; (ii) the second step, known as economic efficiency, is the addition of more O&M inputs' price to reveal the optimal cost levels. Either rating from 0% to 100% or scores from 0 to 1 being the results of the DEA process could be used to rank the efficiency levels. In the study, the DEA input-oriented model under constant returns to scale (CRS) assumption found an average technical O&M management efficiency of 90.21% (range from 54.85 to 100%) for the 24 DMUs operating RPWSs in highland areas. This finding suggested an opportunity for inefficient DMUs to reduce O&M inputs by an average of 9.79% to achieve optimal *TE* as the efficient DMUs. The highest identified opportunity for reduction was 45.15%.

Approximately two-thirds (67%) of RPWSs achieved the average *TE* score of 0.9 (16/24 DMUs), as shown in Figure 2. Half of the DMUs obtained the optimal level with *TE* score of 1 and *TE* rate = 100% (12 DMUs) and the remaining half were at efficient levels from 0.5 to 0.9 *TE* scores, which corresponded to *TE* rates of 50.00% to 99.99%. As a result, 12 DMUs would not need to reduce any O&M inputs and could become appropriate benchmarks for analysis of the other 12 DMUs, including assessing their input norms. Also, their input norms could be set as benchmarking indicators for inefficient DMU collation and application. Potential reduction levels ranging from 1 to 20%, 21 to 40% and 41 to 60% were identified for 6, 5 and 1 DMUs respectively (Tab. 2). Approximately 75% of DMUs had *TE* scores higher than 0.8, signifying opportunity to cut current O&M inputs by a maximum of 20% (Fig. 2).

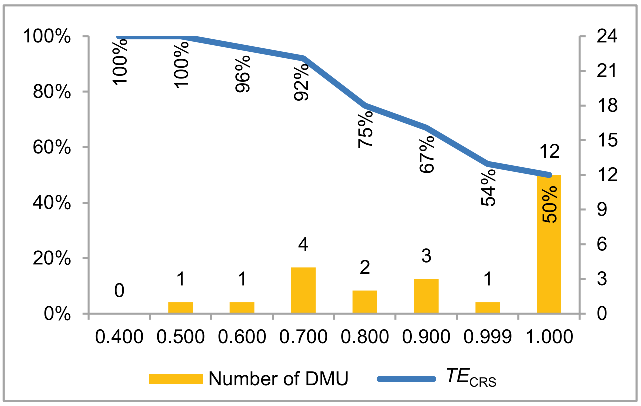

Fig. 2. Number of decision-making units (DMUs) and their exceeding cumulative percentage according to technical efficiency constant returns to scale (TE_{CRS}) scores; source: own study

Table 2. Estimation of technical efficiency (*TE*) and cost efficiency (*CE*) in operation and maintenance (O&M) input management of decision-making units (DMUs)

Specification		*TE* number of DMU	*TE* rate (%)	*CE* number of DMU	*CE* rate (%)
Percentiles (%)	≤20	0	–	7	29.17
	(20–40]	0	–	14	58.33
	(40–60]	1	4.17	0	–
	(60–80]	5	20.83	2	8.33
	(80–99]	6	25.00	0	–
	100	12	50.00	1	4.17
	total	24	100	24	100
Mean		–	90.21	–	30.38
Range		–	54.85–100.00	–	12.71–100.00
Standard deviation		–	13.75*	–	19.60*

Explanations: * = significant level at $P = 0.05$, $e = 95\%$.
Source: own study.

Estimation of cost efficiency under constant returns to scale assumption

A significant contributing factor to the subpar O&M performance of RPWSs in highland areas stemmed from the fact that, over the past two decades, economic objectives were not accorded primary importance in the development of new water supply systems. Consequently, when the O&M of these systems was socialised and transferred to the PCERWASS, cost efficiency was considered of primary importance. PCERWASSs – as new managers of existing poorly performing systems – had to reform their own O&M strategies to prioritise economic efficiency while also considering social and political dimensions.

Table 2 presents the results of the CE_{CRS} analysis, which assessed average CE_{CRS} with reference to O&M input price and technology factors. Findings demonstrated an average CE_{CRS} of 30.38% with a wide range of 12.71 to 100%. This finding signified that DMUs would need to reduce their current input quantities by approximately 70% to optimise the utilisation of O&M inputs. Notably, only a third of DMUs achieved CE_{CRS} scores higher than 0.3 (Fig. 3). Only one DMU achieved optimal economic efficiency with a CE_{CRS} score equal to 1. About 58% of DMUs had CE_{CRS} scores between 20–40%, and 29.17% of DMUs scored lower than 20% (Tab. 2).

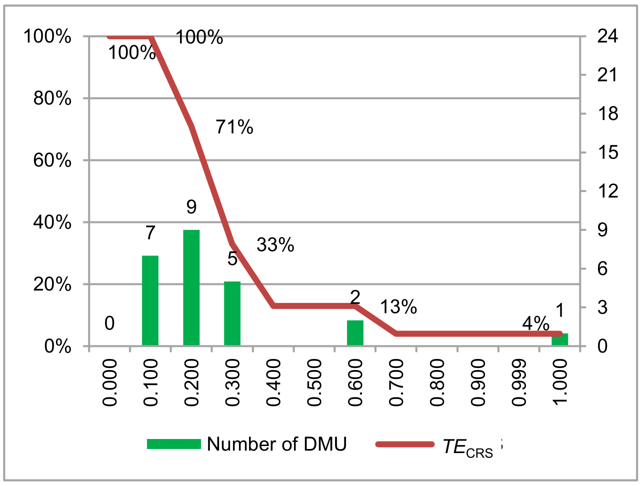

Fig. 3. Number of decision-making units (DMUs) and their exceeding cumulative percentage according to cost efficiency constant returns to scale (CE_{CRS}) scores; source: own study

ALLOCATIVE EFFICIENCY OF OPERATION AND MAINTENANCE INPUT RESOURCES

Estimation of allocative efficiency scores according to constant returns to scale assumption

As noted in above section, RPWSs included in the study were geographically dispersed and managed by sub-stations through input-based contracting. PCERWASS monitoring of these systems focused on output-based indicators including functionality of infrastructure and number of real connections. The PCERWASS provided support for complicated technical issues. Sub-stations were responsible for proactively arranging O&M inputs.

Table 3 presents percentiles and average of AE_{CRS}. Only one DMU achieved the optimal input allocative efficiency of 100% (AE_{CRS} score is 1). This high-performing DMU was the relatively new Dang Kang RPWS, constructed in 2018 and operating since 2019. Dang Kang RPWS was assessed as having a performance rating of 91% and real capacity of 1092 connections, representing above average figures on both counts within the sample of 24 DMUs. AE_{CRS} scores were grouped into six percentile bands, with 62.5% of DMUs (n = 15) achieving AE_{CRS} in the 20–40% range. Two DMUs were placed in each of the 40–60% and 60–80% percentile bands, achieving higher than average O&M performance scores of 88.89% (as previously presented in Table 1).

Options of efficient input target for improving input utilisation and technical-economic norms

DEA analysis revealed a detailed efficient input target (*EIT*) value for each DMU, calculated by eliminating inputs considered inefficient, thus aligning the inefficient DMUs with the O&M input efficiency benchmark. This approach allowed analysis of potential rates of reduction between real and target values for each input variable. By discarding input slacks as an inefficient portion of inputs, the inefficient DMUs were pushed to lie on the O&M input efficiency frontier as equal to the efficient DMUs. The results provided insights into adjusting O&M inputs for optimal levels, which was critical evidence to inform policy directions.

Table 4 presented identified potential reduction rates for each input variable, with findings suggesting reduction rates for chemicals, electricity and minor repairs of 22.96, 25.75 and 31.54% respectively. Potential reduction rates for input variables of technical labour and depreciation variables were low, at 11.51 and 11.65% respectively. It meant that the inefficient DMUs could consider and select suitable measures to improve O&M input efficiency for each variable.

Findings could support DMUs in making strategic choices about where to focus efficiency-enhancing efforts, particularly when guidance was provided about optimal technical and economic norms for input variables as a foundation for input-based contracting. On the basis of *EIT*s identified through DEA, the study results in Table 5 suggested norms for O&M input management of RPWSs which had designed and real capacity lower than 1589 and 1248 connections, respectively. The optimal technical labour norm was found to be an average of 0.86 man-days per 100 m^3 of water sold, and the optimal electricity norm was 0.53 kWh per m^3 of water sold. Both were higher than the norm established by the Ministry of Construction (Quyết định,

Table 3. Estimation of allocative efficiency (*AE*) in operation and maintenance (O&M) input management of decision-making units (DMUs)

AE		Number of DMU	Rate (%)
Percentiles (%)	≤20	4	16.67
	(20–40]	15	62.50
	(40–60]	2	8.33
	(60–80]	2	8.33
	(80–99]	0	–
	100	1	4.17
	total	24	100
Mean			33.23
Range			12.71–100.00
Standard deviation			18.90*

Explanations: * = significant level at P = 0.05, e = 95%.
Source: own study.

Table 4. Estimation of efficient operation and maintenance (O&M) input targets of rural piped water supply systems (RPWSs)

Input variables	Unit	Real inputs	*EIT*	Reduction rate (%)
X1 – technical labour	man-day	490.75	434.26	11.51
X2 – chemicals (chloramine)	kg	215.54	166.05	22.96
X3 – electricity	kWh	43,743.91	32,477.79	25.75
X4 – minor maintenance	USD	1,075.36	736.18	31.54
X5 – overhead cost	USD	332.61	271.04	18.51
X6 – depreciation cost	USD	13,569.31	11,989.10	11.65

Source: own study.

2014) for urban water supply systems being 0.43 man-days and 0.57 kWh per m^3 of water sold. The suggested higher norms for rural water supply systems were considered suitable because of the particular challenges associated with rural service delivery given the remoteness and geographic distances covered. Findings from this study could inform policy regarding how to establish input-based contracts and set appropriate rural water tariffs.

Table 5. Technical economics norm of operation and maintenance (O&M) input variables

Input variables	Units	Input norms	Ranges	Standard deviation
X1 – technical labour	man-day per connection	434.26	0.48–0.93	0.003*
	man-day·100 m^{-3} water sold	0.86	0.27–2.14	0.50*
X2 – chemicals (chloramine)	g·m^{-3} water sold	2.87	0.68–10.87	2.729*
X3 – electricity	kWh·m^{-3} water sold	0.53	0.01–1.48	0.390*
X4 – minor maintenance	USD·100 m^{-3} water sold	1.41	0.56–5.82	1.04*
X5 – overhead cost	USD·100 m^{-3} water sold	46.29	17.67–95.20	0.208*
X6 – depreciation cost	USD per real connection	18.47	3.06–48.86	13.07*

Explanations: * = significant level at P = 0.05, e = 95%.
Source: own study.

CONCLUSIONS

With a view to advancing both the technical and economic efficiency of decision-making units responsible for rural piped-water service delivery, this study applied a non-parametric DEA method under constant returns to scale assumption. The study evaluated the technical efficiency (TE_{CRS}), cost efficiency (CE_{CRS}) and allocative efficiency (AE_{CRS}) of operation and maintenance (O&M) input management of 24 decision-making units operating under provincial centres of rural water supply and sanitation (PCERWASS) oversight in highland areas of Vietnam. Some conclusions and recommendations are stated below.

1) The analysis found TE_{CRS} of 90%, CE_{CRS} of 30% and AE_{CRS} of 33%. Findings suggested opportunities for inefficient decision-making units (DMUs) to reduce O&M inputs in technical and economic domains, with the best-performing DMUs by cutting 10 and 70%, respectively. Results also revealed that out of the 24 DMUs, 12 achieved the optimal TE_{CRS} score of 1, while only one DMU achieved an optimal CE_{CRS} score of 1. Findings underscored the significance of proper input allocation, which took into account input prices, and technology factors (including management mechanisms, skills, and knowledge of water management), to achieve optimal efficiency.
2) Efficient input target (EIT) values were calculated to identify the optimal input data for estimating the reduction rates of each input variable. Two key O&M inputs – technical labour and electricity – were indicated each having potential reductions of 12%. This finding suggests an opportunity for sharing of input information across DMUs, such that those with optimal efficiencies could inform others.
3) The study also proposed technical and economic norms for O&M input items including a technical labour norm of 0.86 man-days per 100 m^3 of water sold and an electricity use norm of 0.53 kWh·m^{-3} of water sold. These findings can inform PCERWASS processes for establishing input-based contracts and water tariffs that support effective O&M for RPWSs in remote areas. Additionally, the government could use findings to propose subsidy policy options that ensure affordability and reflect the status of rural water supply as a public service, paying particular attention to the unique challenges of service delivery during the process of rural water service supply socialisation in highland areas.

The study used the DEA to demonstrate levels of technical, cost and allocative efficiency as well as benchmarking and technical cost norms for policy implications in RPWS management. It has, however, only examined research samples of 24 RPWSs run by state-based organisations in the highland region using the DEA's constant returns to scale assumption. In order to give more meaningful data for the policy discussions, the following research must broaden the study sample to include other RPWSs managed by alternative models, such as commune people committees, volunteer-based community management or private firms, and apply variable returns to scale assumptions.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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