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Productivity Dynamics Of Water User Associations: A DEA-Malmquist Analysis In The Context Of Indian Irrigation

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Abstract:
This study introduces an integrated framework for evaluating and forecasting the productivity of Water User Associations in the Rohini canal system of Uttar Pradesh, India, by combining DEA, the MPI, and machine learning techniques. The analysis covers five canals from 2018 to 2020, revealing significant variations in WUA performance. Notably, the RMC canal experienced a 17% decline in productivity, while others demonstrated improvement. OPEX emerged as the most influential factor affecting efficiency. The MPI enables decomposition of productivity into efficiency change and technological progress, offering insights into temporal and spatial disparities. For instance, Chauka WUA achieved notable gains through reduced inputs and increased outputs, whereas RMC's decline was attributed to stagnant output despite lower inputs. Findings highlight the essential role of WUAs in improving irrigation efficiency and productivity, especially in resource-limited settings. This study bridges theoretical evaluation with practical policy recommendations, supporting the optimization of irrigation systems and advancing sustainable agricultural water management in India.
Keywords: *Data Envelopment Analysis, Water User Association (WUA), Malmquist productivity Index (MPI), Productivities, reforms, efficiency*

INTRODUCTION

The rapid growth of the global population has significantly increased the demand for both food and water, highlighting the vital role of irrigated land in enhancing agricultural productivity and ensuring global food security. However, this growing demand comes against the backdrop of a looming global water crisis. Unregulated and unplanned exploitation of water resources have led to worsening environmental and social conditions, intensifying the urgency of the issue. In India, agriculture remains a cornerstone of future economic and social development. Contributing 15.4% to the country's Gross Domestic Product (GDP), the agricultural sector plays a crucial role in the national economy (Thenkabail et al., 2011). Building on the achievements of the Green Revolution, India has become a leading producer of wheat and rice. Yet, in the face of increasing climate variability, there is a critical need to adopt sustainable agricultural practices. Central to this shift is the implementation of efficient water management strategies to maintain productivity while preserving natural resources. Sustainable agriculture in India must prioritize the responsible use of water and soil to ensure long-term viability.

Water scarcity is becoming an increasingly serious concern, compounded by persistent inefficiencies in water use. Globally, it is estimated that addressing water losses in the irrigation sector could meet up to 50% of the additional water demand projected by 2050 (Phadnis and Kulshreshtha, 2010). Participatory irrigation management—where farmers are directly involved in the oversight and operation of irrigation systems—offers a promising solution. Such an approach not only reduces water waste and encourages reuse but also fosters a culture of conservation and environmental responsibility. Empowering farmers through active participation creates a sense of ownership and strengthens their engagement with government support programs, promoting collaborative water governance. Nonetheless, several obstacles hinder effective water resource management. These include inconsistent and uncoordinated water use, limited stakeholder involvement, inadequate knowledge of efficient irrigation practices, poor inter-agency coordination, and a lack of mechanisms for resolving conflicts (C.W.C., 2013). To overcome these challenges, institutions such as Irrigation Departments and Central Agricultural Development Authorities (CADAs) have established WUAs. These associations, composed of local farmers, play a vital role in managing water resources, maintaining irrigation infrastructure, minimizing waste, and mediating conflicts. By actively involving farmers in the management process, WUAs enhance the sustainability, efficiency, equity, and overall quality of irrigation services. Experiences from other countries, such as Turkey, also highlight the consequences of ineffective irrigation strategy implementation. These lessons underscore the importance of turning policy recommendations into practical actions to promote sustainable water management on a broader scale (Bastakoti & Shivakoti, 2012). In this context, the present study introduces a novel application of advanced productivity assessment techniques within the framework of a Water Resource Project in Uttar Pradesh, India. Specifically, the study integrates DEA with the MPI to conduct a dynamic evaluation of performance. While DEA is used to assess the relative efficiency of WUAs operating along various canal minors (Chun, 2014), the Malmquist Index allows for the measurement of productivity changes over time by decomposing them into efficiency change (catch-up effect) and technological change (frontier-shift effect). This dual-method approach enables the identification of temporal and spatial disparities in WUA performance across different years and regions. Understanding these variations is critical for diagnosing systemic inefficiencies that may limit the agricultural potential of the region. The findings highlight the need for targeted interventions to enhance productivity, particularly in underperforming WUAs. Addressing these inefficiencies requires a multi-faceted strategy, including the provision of high-quality agricultural inputs such as high-yielding seed varieties, fertilizers, pesticides, and improved irrigation technologies. Without the timely and sufficient supply of these critical resources, efforts to enhance agricultural productivity and ensure sustainable resource management may be significantly compromised.

MATERIALS AND METHODS

Area of Study

Lalitpur district is situated in the south-western region of the Uttar Pradesh state (Fig 1), encompassing a total area of 5098 square kilometres. Geographically, it extends between 24°11' to 25°13' north latitude and 78°11' to 79°00' east longitude. Comprising 754 villages, the district has a population of 1,221,592 individuals according to the 2011 census data. The Rohini canal system, a notable feature of the region, comprises the Rohini Dam, an earthen structure located on the Rohini river, along with five associated canals.

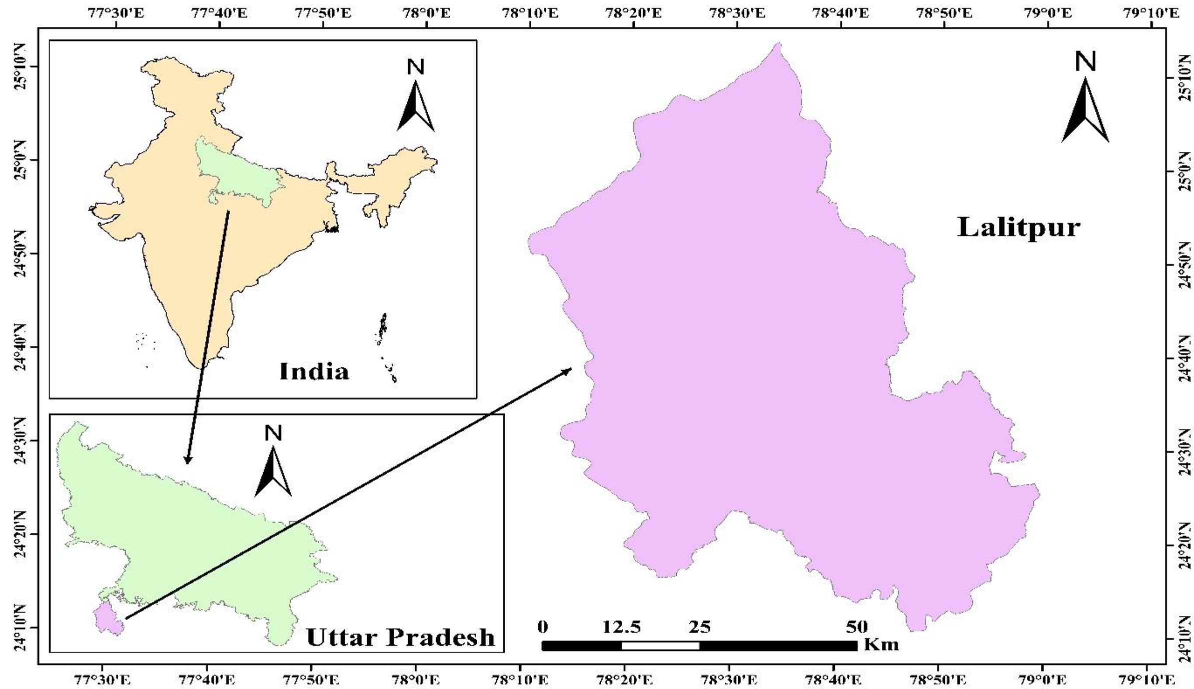

Figure 1 Lalitpur map

Methodology Applied

The Malmquist Index is a vital analytical tool for evaluating the productivity performance of WUAs. Assessing productivity is a fundamental step toward achieving long-term sustainability in the sector. In this study, the MI is used to measure productivity changes over two consecutive time periods, labeled "t" and "t+1." Named after economist Sten Malmquist, the index is a bilateral method designed to compare production technologies or sectoral performance when panel data across time is available. First introduced by (Caves et al., 1982), the Malmquist Productivity Index is grounded in the production function framework and allows for the decomposition of productivity changes into efficiency and technological components. In this paper, the construction of the Malmquist index is rooted in DEA, a non-parametric method employed for assessing the efficiencies of WUAs within the Rohini Canal System. Notably, DEA offers the advantage of not necessitating the specification of any functional form, thereby circumventing potential biases associated with assuming an incorrect functional form. Utilizing DEA-based analysis, a comparative evaluation of the performances of Water User Associations within the Rohini Canal System for the periods of 2018-19 and 2019-20 was conducted.

Model Formulation

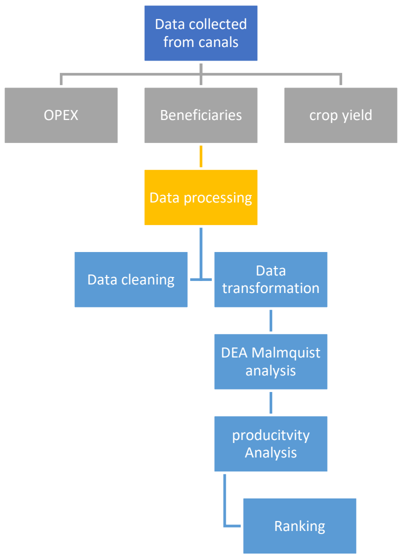

Figure 2 Model Formulation

The DEA model utilized in this study comprises one input and two outputs, aimed at evaluating the time-variant efficiency of the Rohini Canal System across five minors: Chapprauni, Chauka, Gadhauli, Tisgana, and RMC. As shown in Fig 2, this model serves as a framework for assessing the operational performance of the canal system. In the context of Malmquist index calculation within DEA analysis, the objective was twofold: to minimize inputs while maintaining a fixed output service for the Input-Oriented Models, and to maximize output services while keeping inputs constant for the Output-Oriented Models. The selection of indicators was contingent upon data availability. It is noteworthy that the complexity of the envelopment model increases with the number of zones and decreases with the number of inputs and outputs. To address this constraint, the number of zones should ideally exceed three times the total number of input and output variables. Given the availability of data for five minors, the model inputs and outputs were constrained to a maximum of five. Consequently, two Input-Oriented Models were devised to minimize OPEX (Model A) and the level of Manpower (Model B). Conversely, four Output-Oriented Models were formulated, where Passengers and Freight carried served as two outputs, while the extent of service coverage represented by Route Length and the number of stations formed the remaining two outputs. The MPI is particularly valuable for its ability to break down overall productivity change into its underlying components, allowing for a more detailed and insightful analysis, as noted by Avenzora (2008). This analytical strength is built upon the foundational work of Caves et al. (1982), who developed the first-generation MPI models. According to Bjurek (1996), these models are categorized into two main variants: the Malmquist Input Quantity Index and the Malmquist Output Quantity Index, The Input Quantity Index specifically examines changes in the input utilization of a production unit between two time periods, t and t+1, relative to the technological frontiers at both time points (k = t and k = t+1). This enables a focused analysis of how input efficiency evolves over time, independent of output variations, where:

$$MIk\ (yk, xt\ , xt+1\ ) = \frac{EkI\ (yk,xt)}{Ek\ I\ (yk,xt+1)},\ k = t,\ t+1 \qquad (1)$$

Conversely, the Malmquist Output Quantity Index solely measures changes in output quantity produced by a production unit between periods t and t+1, relative to technological references at both t and t+1 (k = t and k = t+1).

$$MOk\ (yt\ , yt+1, xk\ ) = \frac{Ek\ O\ (yt+1,xk)}{Ek\ O\ (yt\ ,xk)} =,\ k = t,\ t+1 \qquad (2)$$

Building on earlier productivity measurement frameworks, Bjurek (1996) introduced a refined definition of the MPI tailored for evaluating the performance of production units. This formulation assesses a unit's productivity across two time periods (t and t+1), using the technological frontiers at both points (k = t and k = t+1) as references—consistent with the structure of traditional productivity indices. The MPI is formulated as a ratio of an output index to an input index and is conceptually linked to the Tornqvist productivity index through appropriate adjustments, allowing for a more nuanced evaluation of changes in productivity:

$$MTFPk = \frac{MOk\ (yt\ ,yt+1,xk\ )}{MIk\ (yk,xt\ ,xt+1\ )} = \frac{Ek\ O\ (yt+1,xk)/Ek\ O\ (yt\ ,xk)}{Ek\ I\ (yk,xt)/Ek\ I\ (yk,xt+1)},\ k = t,\ t+1 \qquad (3)$$

The MPI, defined as the ratio of output to input indices, provides a direct measure of productivity change. An MPI value greater than 1 indicates an improvement in productivity, whereas a value less than 1 reflects a decline. A value equal to 1 denotes no change in productivity between the two periods under comparison (Marlina et al., 2018).

RESULTS AND DISCUSSIONS

The data used in the model is presented in the table 1. The input variable considered is operational expenditure (OPEX). The output variables include the number of beneficiaries and the area irrigated. Malmquist index analysis results are shown in the table 2 all the efficiencies are calculated. Periods of 2018-2019 and 2019-2020 are calculated for productivity analysis in main canal and minors of Rohini canal system.

Table 1 Data Used for Malmquist Index

DMU	Year	Input (OPEX)	Output (Beneficiaries)	Output (Area Irrigated)
Chapprauni	2017-2018	167996.9	179	305.77
Chauka	2017-2018	129297.04	215	217.70
Gadhauli	2017-2018	130568.9	92	133.35
Tisgana	2017-2018	162354.16	262	589.42
RMC	2017-2018	205344.91	250	582.07
Chapprauni	2018-2019	101420.35	241	314.66
Chauka	2018-2019	58508.24	235	231.25
Gadhauli	2018-2019	54982.46	114	133.317
Tisgana	2018-2019	87641.24	260	489.80
RMC	2018-2019	165237.57	330	583.14

Table 2 Malmquist index summary

Canal	Effch	Techch	Pech	Sech	Tfpch
Chapprauni	0.92	1.61	0.92	1.00	1.49
Chauka	1.13	0.40	1.13	1.00	1.59
Gadhauli	1.00	1.14	1.00	1.00	1.41
Tisgana	1.25	0.99	1.31	0.95	1.23
Mean	**1.04**	**1.18**	**1.06**	**0.98**	**1.22**

In the case of the Chauka minor, the Total Factor Productivity Change (TFPCH) registers at 59%, reflecting a notable increase compared to other minors. This surge can be attributed to a substantial enhancement in technical efficiency change by 13%, coupled with a corresponding increase in pure efficiency change by an additional 13%, while scale efficiency remains constant. Conversely, the productivity of the RMC minor experiences a decline of 17%, primarily stemming from a decrease in both technical efficiency changes and pure efficiency change. Upon comparing the inputs (Opex) of canals for the periods 2018-2019 and 2019-2020, it is observed that the Opex cost across all canals diminishes by more than 39%. However, the Opex cost reduction for the RMC minor stands at only 19.53%, despite experiencing an increase in outputs (beneficiaries and area irrigated) during the 2019-2020 period. This disparity in cost reduction contributes to the comparatively lower rank of the RMC minor among all canals and subsequently diminishes its productivity. Conversely, in the case of the Tisgana minor, although both outputs (beneficiaries and area irrigated) decrease, contrasting with the upward trend observed in the RMC minor, the reduction in input (Opex) costs positions Tisgana as the fourth-ranked canal, as depicted in the table 3.

Table 3 Difference in Data collected for consecutive years

Canal	Difference in Opex	Difference in Beneficiaries	Difference in Area Irrigated	Percentage Difference of opex (%)
Chapprauni	66,576	62	8.89	39.62
Chauka	70,789	20	13.55	54.74
Gadhauli	75,586	22	-0.03	57.8
Tisgana	74,712	-2	-99.62	46
RMC	40,107	80	1.07	19.53

1.1. Malmquist Index for Annual Means and Firm Means

The analysis for the annual means indicated for the year 2018-2019. The total factor productivity change with 1.22 or (1.22-1=0.22*100) 22% from the previous year (2017-2018). Henceforth, for the year 2014-2015, a growth in the output variables by 22% contributed by the technical and technological change of 4% (1.04-1=0.04*100) and 18% (1.18-1=0.18*100) on an average.

Table 4 Comparison of productivity index and ranking

CANAL	TFP	RANK
Chapprauni	1.48	2
Chauka	1.58	1
Gadhauli	1.14	3
Tisgana	1.23	4
RMC	0.83	5

3.2. Malmquist Productivity Index

The table 4 presents the TFP values and rankings of the various minors, highlighting those that demonstrate optimal input utilization. Among the Decision-Making Units, Chauka emerges as the top performer, exhibiting the highest productivity index. This is evidenced by an approximate 50% reduction in OPEX, coupled with a significant increase in both output indicators—beneficiaries and irrigated area. In contrast, RMC displays a decline in productivity of 17%, calculated as 1 - 0.830 = 0.17, despite a reduction in input. This decline is attributed to stagnation in one of the output variables and only a marginal increase in the number of beneficiaries. Furthermore, while Chauka demonstrates a scale efficiency score of 1.00—indicating optimal scale operation—RMC shows a negative scale efficiency, reflecting inefficiencies in resource utilization and scale of operation.

CONCLUSION

This study aims to evaluate and compare the productivity performance of WUAs by applying a DEA-based model to assess the operational efficiency of five canals within the Rohini Canal system. The proposed analytical framework serves as a critical foundational step toward initiating reforms in the irrigation sector, which is currently experiencing a decline in productivity. The analysis reveals that OPEX is the most significant determinant of WUA productivity. Addressing this efficiency gap through targeted capacity-building initiatives—such as awareness programs and training—can lead to substantial improvements. Moreover, the findings suggest that strategic interventions and policy-level reforms can enhance irrigation service delivery without necessitating significant increases in expenditure. This has important implications for policymakers and irrigation administrators operating under fiscal constraints, particularly in the context of developing economies such as India. Achieving such outcomes, however, requires detailed micro-level investigations across various irrigation zones and the formulation of context-specific management models to improve operational efficiency and service delivery. The present study endeavours to compare the productivity performance of WUAs by employing a DEA-based model to evaluate the efficiency of five canals within the Rohini Canal system. This modelling approach establishes a foundational analytical framework that can serve as an initial step toward implementing reforms in the irrigation sector, which is currently facing a decline in productivity. The analysis identifies OPEX as the most critical factor influencing WUA productivity. Targeted interventions, such as awareness programs and capacity-building initiatives, have the potential to reduce efficiency gaps.

Furthermore, strategic policy reforms and management interventions may lead to improved service delivery with minimal additional financial inputs—an insight particularly relevant for policymakers and administrators operating under the fiscal constraints typical of developing countries such as India. Achieving these improvements, however, requires detailed micro-level assessments across various irrigation zones and the development of context-specific management models aimed at enhancing service delivery efficiency. Several government initiatives have been implemented to improve water management in the irrigation sector. Based on field observations and model-based analyses, this study proposes a series of policy reforms to enhance operational efficiency and sustainability. Key recommendations include promoting farmer and family training programs to improve water governance and ensure equitable distribution, especially for tail-end users; reducing operating expenditures through regular canal maintenance led by WUAs, with farmer participation to lower staffing costs; improving water management practices to minimize wastage and mitigate waterlogging; introducing reasonable water tariffs to incentivize efficient usage; and enforcing strict penalties for canal-related violations to reduce recurring maintenance costs. Improving irrigation productivity should be a strategic priority, and studies like the present one are crucial for informing policy directions and fostering long-term sectoral reforms.

FUTURE SCOPE

There remains considerable scope for assessing the performance of WUAs at a micro-level—specifically at the distributary (kulaba) or minor canal level, as well as across the entire canal system. It is imperative to identify and document best management practices, which can subsequently be replicated to enhance the overall productivity of irrigation services. Furthermore, there is a need to develop and apply alternative methodological approaches beyond the Malmquist Index for productivity analysis, in order to facilitate cross-validation of results and minimize potential model-specific biases.

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