Inter basin water transfer for sustainable agricultural production systems – A case study of pattiseema lift irrigation scheme of Andhra Pradesh, India

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Abstract: Sustainability of agricultural production system in Krishna delta, which is at lower Krishna river basin (94% of utilizable flow), has been under threat post 2000 owing to basin closure, with available surface water fully utilized for human consumption. The Government of Andhra Pradesh contemplated for interlinking of Godavari river which has surplus water to the Krishna river by transferring 2265 Mm^3 to alleviate the water scarcity and to stabilize command area under Krishna delta (0.514 M ha) through Pattiseema Lift Irrigation Scheme (PLIS). PLIS was constructed during 2015. An attempt has been made to study the impact of the Pattiseema Lift Irrigation Schemet on the sustainability of agricultural production systems in the Krishna delta region and accrued benefits, cost economics of the project and associated Greenhouse gas emissions owing to power generated in utilizing to lift the water in the Project. The impact of PLIS on sustainability of agricultural production systems in Krishna delta has been studied. To carry out situation analysis of pre and post construction of the PLIS on stabilization of the command area of Krishna delta, the water demand and supply status, yield data were analysed. The study suggested that the quantity of water transferred through PLIS were 1591.86, 2996.09, 274.65, 1217.55 and 1177.00 Mm^3 that forms 43.92%, 67.41%, 63.33%, 23.90% and 22.77% of the total water utilization through canal releases during the years 2016-2017, 2017-2018, 2018-2019, 2019-2020 and 2020-2021, respectively with a net production advantage of 59.12, 258.08, 251.02, 93.36 and 93.36 million USD, respectively for the above crop years. Energy intensity per hectare of irrigated area was estimated at 459.81 kWh ha^{-1} and energy productivity and water productivity on production advantage was estimated as 3.63 kg kWh^{-1} and 345.52 kg ha^{-1} M^{-1} m^{-3}. Benefit cost ratio of the project was estimated as 1.90.

Key words: Pattiseema Lift Irrigation Scheme, Inter basin water transfer, CRIWAR, Greenhouse gas emissions, energy productivity, water productivity, Energy intensity per hectare of irrigated area

Citation: Vennela, G., K. Y. Reddy, S. Vishnuvardhan, D. Khalko, and K. Kanakadurga. 2025. Inter basin water transfer for sustainable agricultural production systems – A case study of pattiseema lift irrigation scheme of Andhra Pradesh, India. Agricultural Engineering International: CIGR Journal, 27(3): 1-16.

1 Introduction

India's water crisis is a constant phenomenon due to changing weather patterns and repeated droughts and India is forced to face the challenge of ensuring access to adequate water resources for livelihood and agriculture, for food security, for the ever-expanding population and for the economy. Climate change is now beginning to exacerbate water resources vulnerability with the diminishing river flows and depletion of groundwater reserves triggering wider socio-economic impacts. India will face a serious water scarcity problem in the future, particularly the

Received date: 2023-09-27 **Accepted date:** 2025-05-20

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middle and north-west region of India, while there is surplus water in the eastern part and in some parts of southern India (Singh et al., 2013). Although India has 16 per cent of the world's population, the country possesses only four per cent of the world's freshwater resources. As the economy of the country is currently witnessing rapid growth, management of freshwater resources becomes more important. In a report submitted by Central Water Commission (CWC) during June 2019, reassessment of water availability in India using remote sensing techniques was carried out and the basin-wise average annual flow in Indian rivers was estimated to be 1999.2 km^3. The utilizable annual surface water of the country is estimated as 690 km^3, which is 37% of the available water in India (National Commission on Integrated Water Resources Development, 1999). Basin wise average annual flow, utilizable flow and live storage of Godavari and Krishna rivers is shown in Table 1.

Table 1 Basin wise average flow and utilizable water (km^3 $year^{-1}$) (Anonymous, 2021)

River basin	Average annual flow	Utilizable flow	Live storage
Godavari	117.74	76.30	45.14
Krishna	89.04	58.00	54.80

At present, people of the water scarce region of India are mostly depending on the underground water and rainfall. India has become the world's largest extractor of groundwater, accounting for 25 per cent of the total, according to the most recent Central Ground Water Board data (Anonymous, 2019) due to declining water table. Three-quarters of India's rural families lack access to piped, drinkable water and rely on unsafe sources. Therefore, the concept of supplying water to the scarce region by the construction of reservoirs to store flood waters and interlinking all the river systems of India was conceived through the National River Linking Project (NRLP) in1982, with 14 probable links of the Himalayan river component and 16 probable links of the peninsular river component (Amarasinghe and Sharma, 2008). One probable link of peninsular river components is the Polavaram project, aimed at transferring 2265 Mm^3 of water from the Godavari basin to the Krishna basin stabilizing the command area of Krishna delta.

The Krishna River Basin in South India crosses the semi-arid Deccan Plateau from west to east. Since the 1850s, the Krishna Basin has seen an increasing mobilization of its water resources. As per the Tribunal award, 5128 Mm^3 of water has been allocated for the Krishna Delta Project, i.e., Prakasam Barrage at Vijayawada (Table 2). However, as per reallocation, the share of Krishna Delta is 4282 Mm^3. There has been substantial development in the irrigation sector in the Krishna basin region during last decade of 2000 without any concern for availability of water resources in the Krishna river. This progressively led to closure of the basin (zero or minimal discharge to the ocean): by 2001-2004, with available surface water resources were almost used for human consumption. Further, this situation led to reduction in surface water base flows due to increasing groundwater abstraction. Even though, basin closure is clearly evident, the southern states that share the Krishna waters showed keen interest to develop their agriculture and irrigation sectors. The downstream command areas of the Krishna Basin, *ie*., Krishna delta agricultural systems, largely depend on the actions of upstream Krishna water project users. Any hydrological changes that happen in upstream project regions, adversely affect Krishna delta system during drought years to witness both severe water deficit and a spatial redistribution of water (Venkateswarlu, 2023). It was reported that for the Lower Krishna Basin during the last fifty years there was: (i) a decrease by more than half of the surface water inflow into the lower basin (~25.8 billion cubic meters (Bm^3) a year in 1996-2000) due to water development in the upper basin; and (ii) an uncontrolled irrigation development in excess of existing formal allocation procedures in the Lower Krishna Basin itself. At the irrigation project level (notably in Nagarjuna Sagar), governmental decisions and recommendations of the World Bank have led to changes in the design and practices of protective irrigation that have resulted in increased water use. By 1996-2000, 77% of the Lower Krishna Basin net inflow was depleted and discharge to the ocean amounted to 17.9 *BCM* yr^{-1}, defining a moderately modified ecosystem (Venot et al., 2007). During the drought of 2001-2004, with depletion amounting to 98.8% of the net inflow and a lack of discharge to the ocean, a dramatic overdraft of the aquifers resulted in the shrinkage of surface irrigated agriculture. Further, the command area and the cropping intensity in the Krishna delta increased from 0.52 to 1.3 million acres and 108% to 160%, respectively, from 1955 to 2015. Cultivating during the dry season became more common as, irrigation expanded utilizing the residual moisture in the field after kharif harvest. Ground water irrigated area also increased by 14 times during the past 50 years (45% of all irrigated area in 2005, compared to 8% in1955).

Table 2 Allocation of water from Bachawat Tribunal award in 1973

Type of use			Allocation Mm3
Irrigation needs during June- November.	Kharif	Krishna Delta system	4582
		a) Krishna Eastern Delta (KED)	2580
		b) Krishna Western Delta (KWD)	2002
Irrigation needs in Rabi December -April and domestic and industrial water supply			433
Evaporation losses at Prakasam barrage			113
			5128

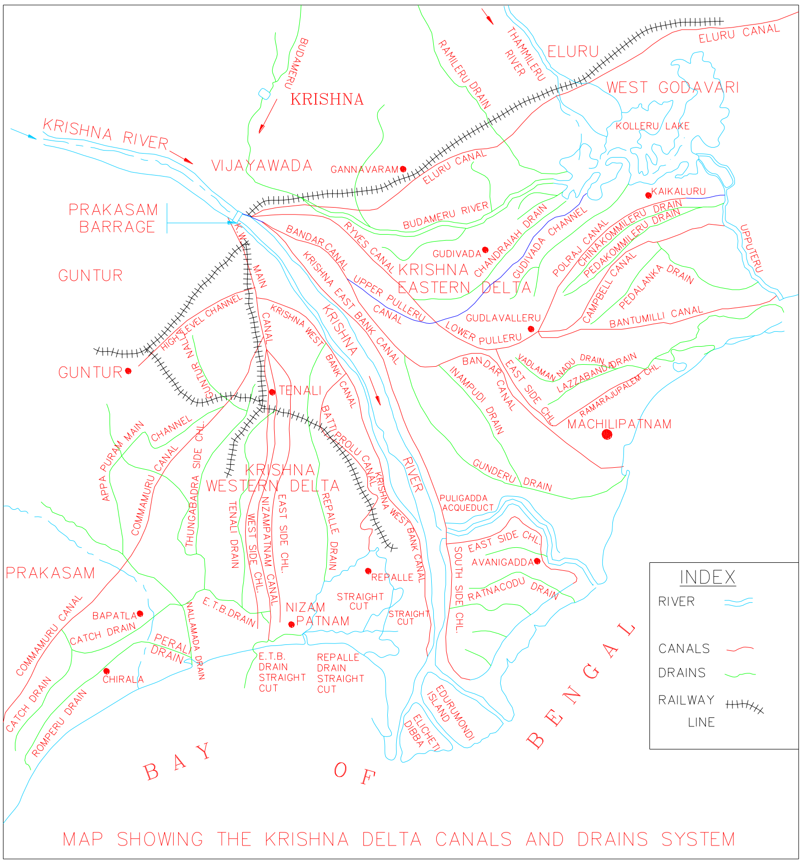

Figure 1 Index map of Krishna delta region

Post 2002, a delay in raising nurseries and transplantations by months due to lack of water in the Krishna River at the Prakasam barrage resulted in the harvest season to coincide with the cyclone season of November. Within this context, it had become imperative for the Government of Andhra Pradesh, to explore the means of alleviating the water scarcity through the interlinking of Godavari River which has surplus water to the Krishna River, which has deficit in water. Thus, the Government of Andhra Pradesh has contemplated the Polavaram Multipurpose Irrigation Project on the Godavari River in the West Godavari district of Andhra Pradesh with a design capacity of 5394 Mm^3. Further, the Government of

India has recognized the Polavaram Irrigation Project with National Project status. However, as the construction of such a huge project will take appreciable time for completion, as a temporary measure, the Government of Andhra Pradesh contemplated the Pattiseema Lift Irrigation Scheme (PLIS) and was constructed (a cost of US$ 220 millions) with the largest pump houses in Asia with 24 pumping units with a combined capacity to discharge 240 $m^3\ s^{-1}$ of water (Figure 1) (Srinivas et al., 2018). These pumps draw water from the river Godavari in Pattiseema project and discharges into the Polavaram Project Right Main Canal. The canal traverses 174 km through the districts of West Godavari and Krishna and finally linked with the Budameru Diversion Channel (BDC) that confluences with the Krishna River (Swaroop et al., 2024) (Figures 2 and 3). Vaddevolu et al. (2025) assessed the impact of PLIS on the ground water resources in West Godavari district of Andhra Pradesh. In this study, an attempt has been made to study the impact of the Pattiseema Lift Irrigation Project on the sustainability of agricultural production systems in the Krishna delta region and accrued benefits, cost economics of the project and associated Greenhouse gas (GHG) emissions owing to power generated in utilizing to lift the water in the project.

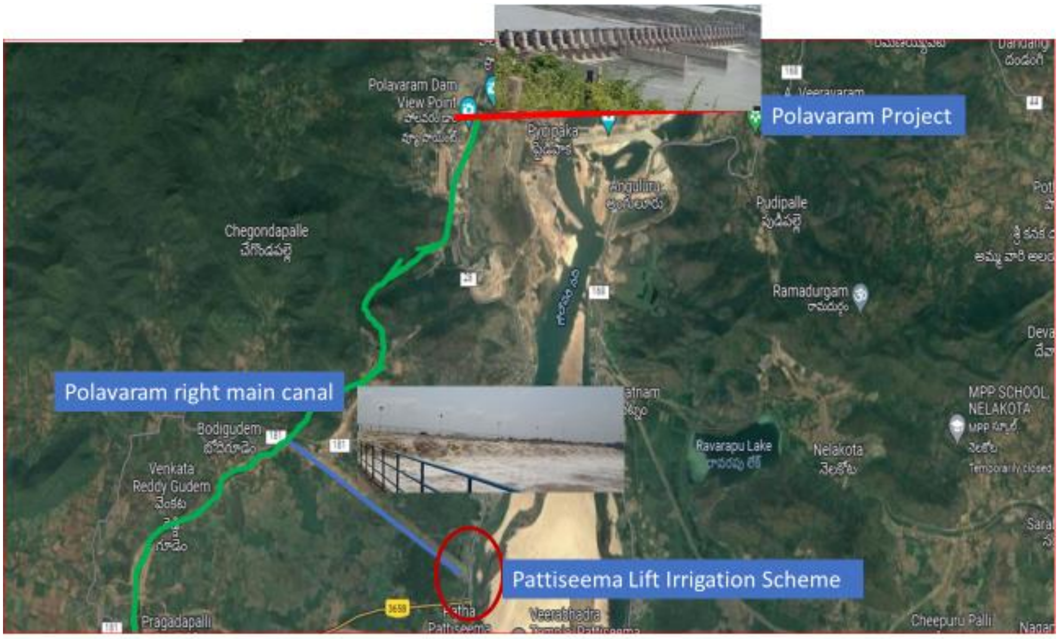

Figure 2 Location and site map of Polavaram Project and PLIS

Figure 3 Schematic layout of trans basin water transfer from Godavari river to Krishna river through PLIS

Table 3 Salient features of Pattiseema Lift Irrigation Project

Salient feature	Technical details
Total Discharge :	240 $m^3 s^{-1}$
Pump House	221 x 36 m
Diaphram Panels	189 Number, 1.20 m thick
Delivery Cisterns :	90 x 74 m
No. of Pumps :	24
Type of Motors	Synchronous motors
Discharge of each pump	10 $m^3 s^{-1}$
Head	33 m
Capacity of each pump	5300 Horse Power, H.P (3.95 MW)
Capacity of each motor	6300 H.P (4.70 MW)
Total power required	113 MW

2 Methodology

2.1 Study area

The PLIS was operational since March 2016. The scheme lies between the coordinates of 17°13'46.19"N and 81°38'43.42"E**.** It is situated in Pattiseema village of Polavaram mandal (township) in West Godavari District of Andhra Pradesh, India. The salient features of the Pattiseema Lift Irrigation Project are presented in Table 3. The entire command area (529281 ha) is part of the Krishna delta system and is located in the districts of Krishna, West Godavari, Guntur and Prakasam of Andhra Pradesh state and is divided into Krishna Eastern Delta (KED) and Krishna Western Delta (KWD). Fifty three per cent of the cropped area is sown more than once by utilizing residual moisture in the soil after kharif (June-November) harvest for raising irrigated dry (ID) crops like black gram, green gram and maize. The major crops grown in the Krishna delta command area during kharif season are paddy rice (87.04%), sugarcane (11.49%), maize (0.10%) and pulses (0.10%).

To carry out situation analysis of pre and post construction of the PLIS on stabilization of the command area of Krishna delta, the water demand and supply status was analysed. To estimate crop water requirement CRIWAR (Crop Response Irrigation Water Assessment Reports), a simulation program for calculating irrigation crop water requirement for cropped areas developed by International Land Reclamation Institute (ILRI) was used (Doorenbos and Pruitt, 1977; Bos et al., 1996). Key input for calculating crop water requirement were: precipitation, minimum and maximum temperature, maximum and average relative humidity, wind speed, sunshine hours, sowing date and harvesting date. The above data were collected for the study period (2000-2015) from the weather station at the Regional Agricultural Research Station, Lam, Guntur, India. Crop coverage and cropping pattern data was collected from the authorities of the Water Resources Department, Agriculture Department. The crop water requirement was obtained for different temporal scales, day /week/ month wise. Water requirement at Project level was computed by considering field application efficiency of 60% (Brouwer et al., 1989; Srinivasulu et al., 2003; Gupta et al., 2022). Multiple uses of water i.e., domestic use, livestock use, industrial use and aquaculture were consideration to arrive at the gross irrigation requirement (GIR).

GIR was calculated based on net irrigation requirement (NIR), inclusive of losses and multiple uses of water for different sectors, applied through irrigation. (Bokke and Shoro, 2020)

$$\text{GIR (Mm}^3\text{)} = \frac{net\ irrigation\ requirement}{Overall\ irrigation\ efficiency} \quad (1)$$

2.2 Comparison of demand and supply status in Krishna delta

The estimated GIR of crops in the study area were compared with the actual amounts of canal water released during 2000-2015 to assess the necessity of the Pattiseema Lift Irrigation Scheme. The supplies and average demands were compared by subtracting the supplies from the demands. Thereby the excess or deficient water supplies in *Mm³* and as well as percentage were calculated.

The supply status of canal releases to the Krishna delta, as well as supplementary inflows from the PLIS as part of trans-basin water transfer (TBWT) from Godavari basin to Krishna basin, was collected from the Water Resources Department, Government of Andhra Pradesh.

2.3 Energy costs and associated Greenhouse gas emissions

Further, to assess energy costs associated with TBWT and associated GHG emissions, the month wise electrical energy consumption cost was collected from the Polavaram Irrigation Project Right Main Canal Division, Kovvuru, West Godavari, and Andhra Pradesh (Zou et al., 2015).

As electrical energy used in the lift irrigation scheme has been mostly produced from coal fired thermal power stations, there will usually be emissions of carbon dioxide (CO_2), sulphur dioxides (SO_2), nitric oxides (NO), choloro fluoro carbons (CFC)s other trace gases and air borne inorganic particulates, such as fly ash and suspended particulate matter (SPM). CO_2, SO_2, and N_2O are GHGs. The amount of emission of GHGs from 1 kilo watt hour (kWh) unit of electricity generation when coal is used as a source of energy was estimated as 0.85 kg of CO_2, 0.84 kg of SO_2, and 0.00398 kg of N_2O (Mittal et al., 2012). Total GHG emissions were determined by multiplying total electrical consumption with quantity of GHG emissions per unit electricity generated (Vetter et al., 2017).

2.4 Estimation of gross value addition to agriculture

The gross value addition (GVA) to the agriculture due to supplemental irrigation from the PLIS was assessed by collecting crop yield data from the Agricultural Department, Government of Andhra Pradesh. The crop specific GVA was derived with slight modification as (Banerjee et al., 2019)

$$Crop - \text{specific GVA per hectare (M. USD)} = \frac{Crop-specific\ GVA\ of\ the\ state}{Area\ under\ that\ crop\ in\ that\ state} \quad (2)$$

Further, financial benefit-cost economic analysis of the benefits accrued from the PLI Project were also computed.

2.5 Evaluation indicators

The five indicators *viz.*, water consumption (Wc), energy consumption (Ec), energy mass productivity (Ep), water economic productivity (WEP) and energy-economic productivity (EEP) were calculated as per procedure suggested with slight modifications based on a study by El-Gafy (2017) (Table 4).

Table 4 Evaluation indicators used in water-energy-food nexus approach

Indicator	Equation	Notation
Water mass productivity (W_p) (MT/ Mm^3)	$\frac{Yc}{Wc}$	Y_c= yield (MT ha^{-1}) W_c=water consumption ($Mm^3\ ha^{-1}$)
Energy mass productivity (E_p) (MT/MW)	$\frac{Yc}{Ec}$	Y_c= yield (MT ha^{-1}) E_c = energy consumption (MW ha^{-1})
Water economic productivity (WEP) (M USD/ Mm^3)	$\frac{Nc}{Wc}$	Nc = economic production advantage (M USD) W_c=water consumption ($Mm^3\ ha^{-1}$)
Energy economic productivity (EEP) (M USD/MW)	$\frac{Nc}{Ec}$	Nc = economic production advantage (M USD) E_c= energy consumption (MW ha^{-1})

3 Results and discussions

3.1 Estimation of gross water requirement for Krishna Delta

The crop water requirements for the crops of the Krishna Delta have been computed using CRIWAR 3.0 software. All calculation procedures used in CRIWAR are based on the FAO guidelines as laid down in the publication No. 56 using Penman-Monteith method for computation of reference crop evapotranspiration (ET_o) (Allen et al., 1998).

The allocation of water to the Krishna delta has been 4282 Mm^3. However, due to changing climatic conditions net crop water requirements for the crops grown in Krishna delta using CRIWAR for various crops such as paddy rice, sugarcane, pulses and maize were computed as 0.572, 1.849, 0.259 and 0.215 m, respectively (Table 5). The gross water requirement including domestic, livestock, industrial use and aquaculture has been estimated as 6266 Mm^3. This fact clearly establishes that demand for water in

Krishna delta was more than its allocation. The comparison of actual canal releases and average water demand is shown in Table 6. It was observed that there was a deficit in inflow of water for 12 years out of 16 years during 2000-2001 to 2015-2016, with the highest deficit of 81% during 2015-2016 and average deficit of 32% during the reported period.

Table 5 Gross irrigation requirement in Krishna Delta region

Name of the crop /multiple uses of water	Registered ayacut* (ha)	Crop wise registered ayacut (ha)		Net irrigation tequirement (m)	Net irrigation requirement (Mm^3)
		KED	KWD		
Paddy	460911	229595	231316	0.572	2636.41
Sugarcane	6685	6685	0	1.849	123.60
Maize	538	538	0	0.215	1.15
Pulses	538	538	0	0.259	1.39
Aquaculture	60835	60835		1.000	608.35
Domestic water	Computed @ 55 lpcd(liter per capita per day)*https://pib.gov.in/PressReleasePage.aspx?PRID=1604871*				110.00
Water to livestock	Computed @ 25 lpcd for big headed livestock, @5 lpcd medium headed and @0.3 lpcd for small headed livestock** (Renwick et al., 2007)				94.32
Water to industries	184.41 Mm^3 has been allocated to industries in Krishna delta system				184.41
	Total (Mm^3)				3759.64
	GIR considering application efficiency @60%				6266

Note: *An 'ayacut' refers to all the lands which are entitled to irrigation under an irrigation scheme; **Accounting for water consumption for animals according to their category

Table 6 Comparison of average demand and canal releases in Krishna delta

Year	Canal releases (Kharif +Rabi) (*Mm³*)			Average kharif demand (*Mm³*)	Excess or deficient water supplies (*Mm³*)	% Excess or deficient water
	KED	KWD	Total (KDS)	KDS	KDS	KDS (%)
2000-01	3865.802	2485.644	6351.446	6266	85.45	1.36
2001-02	3219.614	2037.107	5256.721	6266	-1009.28	-16.11
2002-03	1895.806	1549.209	3445.015	6266	-2820.98	-45.02
2003-04	1360.053	1119.078	2479.131	6266	-3786.87	-60.44
2004-05	2130.835	1848.234	3979.069	6266	-2286.93	-36.50
2005-06	3220.747	2184.071	5404.817	6266	-861.18	-13.74
2006-07	3947.354	2909.263	6856.617	6266	590.62	9.43
2007-08	3894.119	2321.407	6215.526	6266	-50.47	-0.81
2008-09	3728.466	2698.303	6426.769	6266	160.77	2.57
2009-10	3884.774	2749.273	6634.047	6266	368.05	5.87
2010-11	2514.244	1593.383	4107.627	6266	-2158.37	-34.45
2011-12	3197.244	2657.527	5854.771	6266	-411.23	-6.56
2012-13	1317.578	984.5733	2302.151	6266	-3963.85	-63.26
2013-14	3754.234	2109.314	5863.549	6266	-402.45	-6.42
2014-15	3099.834	2232.209	5332.043	6266	-933.96	-14.91
2015-16	715.281	471.757	1187.038	6266	-5078.96	-81.06

Note: *Kharif – Crops cultivated during June- November; Rabi – Crops cultivated during December- April

3.2 Trans basin water transfer from Godavari river to Krishna river

The Lower Krishna Basin is one of the first regions to be adversely affected by any of upstream activities affecting hydrological changes causing a spatial redistribution or re-appropriation of water during times of drought. During the years, 2015-2021, the Krishna delta suffered due to non-uniform distribution of rainfall. The Krishna barrage, which is the diversion structure, has a capacity of 84.95 *Mm³*. Water inflows to the barrage over and above its capacity are let into the sea. Water inflows to the

Prakasam barrage are obtained from upstream projects such as the Nagarjunasagar project (NSP), the Pulichintala project and from the Keesara rivulet. Godavari water diverted from the Pattiseema Lift Irrigation Project is discharged into the Budameru drain which in turn enters into the Prakasam barrage, 14 km of upstream of the barrage. Various inflows to the barrage, water releases from the barrage through the canal system, outflow through barrage crest, and command area irrigated during the years 2009-2010 to 2020-2021 are presented in Table 7. The percent of water transferred from the Pattiseema Project to the total water utilization through canal releases worked out to be 43.92%, 67.41%, 63.33%, 23.90% and 22.77% during the years 2016-2017, 2017-2018, 2018-2019, 2019-2020 and 2020-2021, respectively. During the years 2016-2019, flood water inflow to the barrage was mainly from the runoff water due to flash floods from the local catchment area downstream of the Pulichintala Project. As the Prakasam barrage is a diversion structure with a capacity of 84.94 Mm^3, over and above the capacity, water is let into the Bay of Bengal. It became inevitable to supply water from the Godavari river basin to the Krishna basin to protect standing crop from water stress to avoid drought situation in the Krishna delta command area. A survey at field level conducted by the Department of Agriculture Personnel indicated that without supplemental irrigation from the diverted water, crop yields would have declined by 20%-40%.

Table 7 Water releases from Pattiseema Lift Irrigation Project and percent of water release to the total water utilized

Year	Releases from Pattiseema head works to barrage (Mm^3)	Inflows to the Prakasam barrage (Mm3)			Total water utilisation through canal releases (Mm^3)	Surplus flow to sea over crest of barrage* (Mm^3)	Percent of total water utilized supplied by PLIS
		NSP/PP Dam/ Wazinepalli	Keesara /Others	Total Inflows to the barrage			
2009-10	0	19051.39	2124.06	21175.45	6634.11	14541.35	-
2010-11	0	9554.44	7261.33	16815.77	4107.66	12708.10	-
2011-12	0	9863.66	2692.66	12556.32	5854.54	6701.78	-
2012-13	0	1551.21	3257.02	4808.23	2302.17	2506.05	-
2013-14	0	10086.52	7419.90	17506.42	5863.60	11642.82	-
2014-15	0	6759.27	627.79	7387.06	5332.37	2054.68	-
2015-16	0	797.97	938.99	1991.53	1187.05	804.49	-
2016-17	1591.87	4162.88	979.20	6514.61	3622.31	2892.30	43.92
2017-18	2996.09	1711.76	786.93	5052.60	4444.35	608.25	67.41
2018-19	2744.65	1898.65	1775.48	5978.85	4330.80	1648.05	63.33
2019-20	1217.55	2679.07	1656.26	5091.11	5091.11	0.00	23.90
2020-21	1177.00	1272.85	2957.71	5167.29	5167.29	0.00	22.77

Note:*Capacity of the Prakasam barrage, a diversion structure, is 84.95 Mm^3

Liu et al. (2013) assessed the environmental Impacts of China's South-North Water Transfer Project and reported that largest transbasin water transfer diverting Yangtze River water to arid north (Beijing), there by supplying water to 600 million people and boosted agriculture/industry. It was also reported that the project incurred high costs (~$80 billion), and huge displacement, and downstream ecosystem collapse. Srinivasan (2015) reported that the Periyar-Vaigai Inter-Basin Transfer enabled Enabled irrigation in drought-prone Madurai region and supports nearly 200,000 hectares. Karimov et al. (2021) reported that a number of lift irrigation schemes have been operational through transboundary water transfer on Amudarya river in Central Asia produced significant water (24%) and energy savings (19%), as well as reduced saline flows and emissions of GHG s.

3.3 GVA of the agricultural production due to trans-basin water transfer

In order to quantify the additional benefit accrued to the agricultural production due to trans basin water transfer, efforts were made to compute GVA, duly considering the scenario of net production advantage achieved due to provision of supplemental irrigation from the water transferred from the Godavari River basin. While computing GVA of net production advantage, production data of paddy rice crop alone was considered and computed, as water was supplemented during kharif season only. Area and production status of various crops of the Krishna delta system during kharif (June-November) and rabi (December-April) seasons for the years 2016-2017, 2017-2018, 2018-2019, 2019-2020 and 2020-2021 were depicted in Table 8. Net production advantage due to PLIS was assessed by making scenario analysis of possible reduction in paddy production in case of no supplementation of water from PLIS. As per field conditions based on interviews with the stakeholders, a net loss in production that would have occurred if no TBWT from Godavari River taken place was assumed as 20%, 50%, 45%, 15% and 15% for the years 2016-2017, 2017-2018, 2018-2019, 2019-2020 and 2020-2021, respectively. Depending upon the minimum support price (MSP), declared by the Government for that particular year, the **GVA** was computed by multiplying net gain in production with the minimum support price (MSP) and was estimated as 5.90, 25.80, 25.10, 9.33 and 9.33 million US$, respectively, for the above-mentioned crop years, thus, a total of 754.97 million US$ benefit was accrued. Cropping intensities of 216%, 185.10%, 164.75%, 167.07% and 167.10%, respectively, were achieved during 2016-2017, 2017-2018, 2018-2019, 2019-2020 and 2020-2021, by utilizing comprehensive surface (canal+drain), ground water resources effectively to raise irrigated dry crops like pulses and maize.

China's South-North Water Transfer Project added $14 billion/year to agricultural GVA in recipient provinces by enabling double-cropping on 12 million hectares (Wang et al., 2021). In Australia's Murray-Darling Basin, water trading following inter basin transfers increased agricultural GVA by AUD 3.6 billion year^{-1} through improved water productivity (Connor and Kaczan, 2013).

3.4 Energy costs and indicators associated with trans basin water transfer from the Godavari River

Trans-basin water transfer (TBWT) projects are energy-intensive due to large-scale pumping requirements, often leading to significant economic and environmental trade-offs. Research highlights that energy consumption is a critical factor in assessing the feasibility and sustainability of such projects. The quantity of water pumped from the Godavari River, energy consumption for pumping and maintenance and associated energy costs were presented for different years 2016 to 2020 in Table 9 and Figure 4. It was noted that an amount of 162.20, 300.58, 271.88, 122.20, 118.02 GWh energy was consumed to lift 1594.87, 2996.09, 2744.65, 1217.55 and 1177 Mm^3 of water during the years 2016, 2017, 2018, 2019 and 2020, respectively. Thus, during 2016-2020, 974.72 GWh of energy was used to lift 9727.16 Mm^3 of water by incurring a pumping cost of 71.69 million US$. The average cost for lifting one Mm^3 of water during 2016 to 2020 was found to be 7369.83 US$. Figure 5 suggested that cost per unit volume (Mm^3) of water lifted was in the range of 7039.14 to 7241.53 US$ with an average of 7369.83 US$. Due to repair and maintenance of motors, cost per unit Mm^3 water lifted was recorded as 9184.29 US$ during 2020.

Average energy intensity per hectare of irrigated area was estimated as 459.81 kWh/ha and energy productivity and water productivity on production advantage due to inter-basin water transfer was estimated as 3.63 kg kWh^{-1} and 345.52 kg ha^{-1}·Mm^{-3}, respectively. Energy mass productivity and energy economic productivity for PLIS was computed for the years 2016-2020. Energy mass productivity first decreased and then showed an increasing trend from the years 2017-2020. Possible reasons for the initial decrease could be the higher amount of energy used in lifting water and the maintenance cost during 2017-2018. Similarly, energy economic productivity was estimated as 3.04, 2.36, 3.17, 6.81 and 6.19

(million US\$ ha^{-1})/(MWh ha^{-1}) during the years 2016, 2017, 2018, 2019 and 2020, respectively (Figure 6).

Table 8 Estimation of gross value addition on net production advantage due to inter basin water transfer

Crop	Kharif Area (ha)	Kharif Production (MT)	Rabi Area (ha)	Rabi Production (MT)	Kharif Production scenario in case of no inflows from PLIS (MT)	Net production advantage due to PLIS (MT)	Minimum Support Price/MT (USD)	GVA (Million USD)	Cropping Intensity (%)
2016-2017									
Paddy	364768	1468252.07	45088	219948.71	1174601.65	293650.41	201.33	59.12	216.0
Pulses	2325	1939.18	262686	133056.98					
Maize	225	1029.84	37623	313294.77					
Sugarcane	10053	974372.96							
Total	377371	2445594.05	345037						
Remarks: 43.92% of the water utilized in the delta was supplemented by PLIS. Supplemental irrigation provided during critical stages. If water through PLIS would not be supplemented, it was assumed that yield would have reduced by 20%. Cropping intensity was estimated as 216% due to utilization of field residual moisture after harvest and supplemented through ground and surface water. Summer crop was raised as third crop									
2017-2018									
Paddy	384454	2434800.11	28750	204768.45	1217400.06	1217400.06	212.00	258.08	185.10
Pulses	752	734.14	224126	251771.17					
Maize	207	1229.90	41393	107218.41					
Sugarcane	9742	905862.12							
Total	395155	3342626.27	336282						
Remarks:67.41% of the water utilized in the delta was supplemented by PLIS. Loss in crop yield without supplementation was assumed as 50%. Cropping intensity was estimated as 185.10%									
2018-2019									
Paddy	394745	2363708.44	39282	255615.42	1300039.64	1063668.80	236.00(236.00)	251.02	164.75
Pulses	447	539.79	155992	191320.23					
Maize	227	826.23	11884	83630.08					
Sugarcane	12983	1289888.42							
Total	408402	3654962.88	264423						
Remarks:63.33% of the water utilized in the delta was supplemented by PLIS. Loss in crop yield without supplementation was assumed as 45%. Cropping intensity was estimated as 164.75%									
2019-2020									
Paddy	397357	2544155.25	73810	538806.60	2162531.96	381623.29	244.66	93.36	167.07
Pulses	486	664.91	135849	189148.20					
Maize	123	767.16	14315	100512.42					
Sugarcane	8916	852707.98							
Total	406882	3398295.30	272893						
Remarks:23.90% of GIR is provided by PLIS 23.90% of the water utilized in the delta was supplemented by PLIS. Loss in crop yield without supplementation was assumed as 10%. Cropping intensity was estimated as 167.07%.									
2020-2021									
	403990	2596491	73810	538806.60	2207018	389473..	244.66	93.36	167.10
			187811	241789.29					
Maize	440	2728	8198						
Sugarcane	4294	389251.1							
Remarks:22.77% of GIR is provided by PLIS 23.90% of the water utilized in the delta was supplemented by PLIS. Loss in crop yield without supplementation was assumed as 10%. Cropping intensity was estimated as 167.10%.									

Note: *Kharif (June-November); Rabi (December-April). Net benefit has been calculated on paddy production in kharif season only.

Table 9 Details of pumped water, energy consumption and associated cost

Month	2016			2017			2018		
	Energy consumed (kWh)	Water pumped (Mm^3)	Energy costs (M USD)*	Energy consumed (kWh)	Water pumped (*Mm^3*)	Energy costs (M USD)*	Energy consumed (kWh)	Water pumped (*Mm^3*)	Energy costs (M USD)*
June	463620	-	0.03	16903000	134.72	1.20	16084000	153.05	1.14
July	16759360	167.55	1.19	51663000	546.58	3.67	53347000	522.08	3.79
Aug	20482200	188.42	1.46	61642000	617.18	4.38	37215000	365.52	2.64
Sept	27451140	265.05	1.95	61210000	607.77	4.35	60581000	603.79	4.31
Oct	37752000	359.63	2.68	64069000	631.23	4.55	57871000	609.79	4.11
Nov	54263000	538.02	3.86	44294000	458.61	3.15	44751000	473.96	3.18
Dec	5154000	73.20	0.37			0	1390000	16.46	7.41
O &M	346000		0.02	799000		4.26	644000		0.05
Total	162207700	1591.87	11.53	300580000	2996.09	21.36	271883000	2744.65	19.32

Month	2019			2020			Total (2016-2020)		
	Energy consumed (kWh)	Water pumped (Mm^3)	Energy costs (MUSD)*	Energy consumed (kWh)	Water pumped (Mm^3)	Energy cost (M USD)**	Energy consumed (kWh)	Water pumped (Mm^3)	Energy costs (M USD)**
June	609000	5.52	0.04	16115000	151.68	1.48	50174620	444.98	3.89
July	48169000	471.88	3.42	27658000	278.99	2.53	197596360	1987.08	14.60
Aug	31013000	326.77	2.20	19625000	202.34	1.8	169977200	1700.23	12.48
Sept	8621000	89.72	0.61	16005000	165.91	1.47	173868140	1732.24	12.69
Oct	2043000	19.27	0.15	8065000	53.37	0.74	169800000	1673.29	12.23
Nov	28241000	289.11	2.01	29915000	324.72	2.74	201464000	2084.43	14.94
Dec	2019000	15.30	0.14		0	0	8563000	104.95	7.92
O &M	1312000		0.09	645000		0.06	3746000	0.00	4.48
Total	122027000	1217.55	8.67	118028000	1177.00	10.81	974725700	9727.16	71.69

Note: * 0.071 USD kWh-1. ** 0.091 USD kWh-1. O&M, Operation and Maintenance.

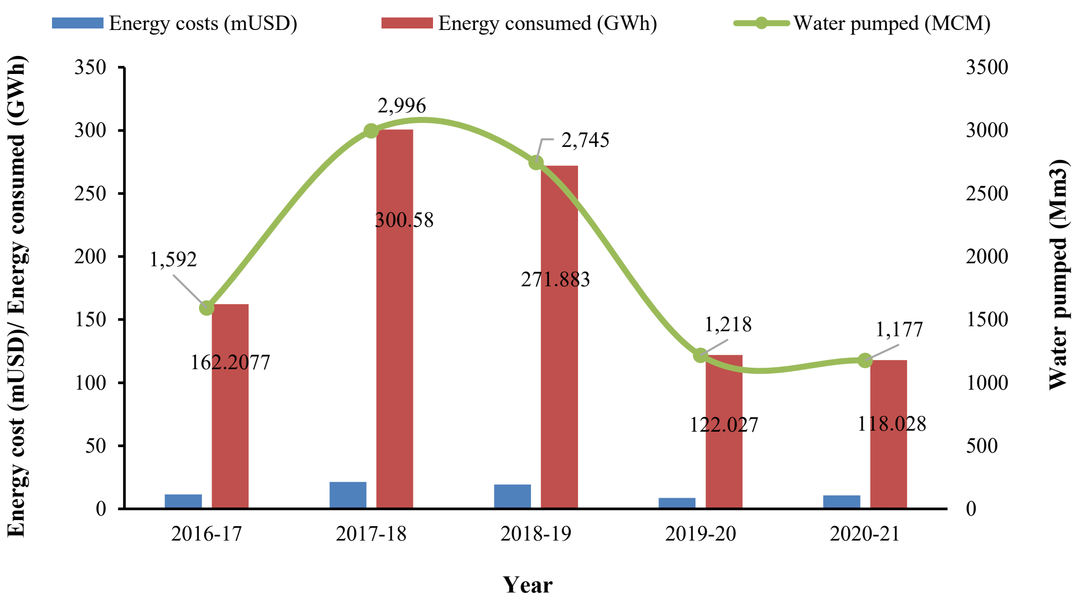

Figure 4 Year wise energy consumed, associated energy costs and water pumped from PLIS

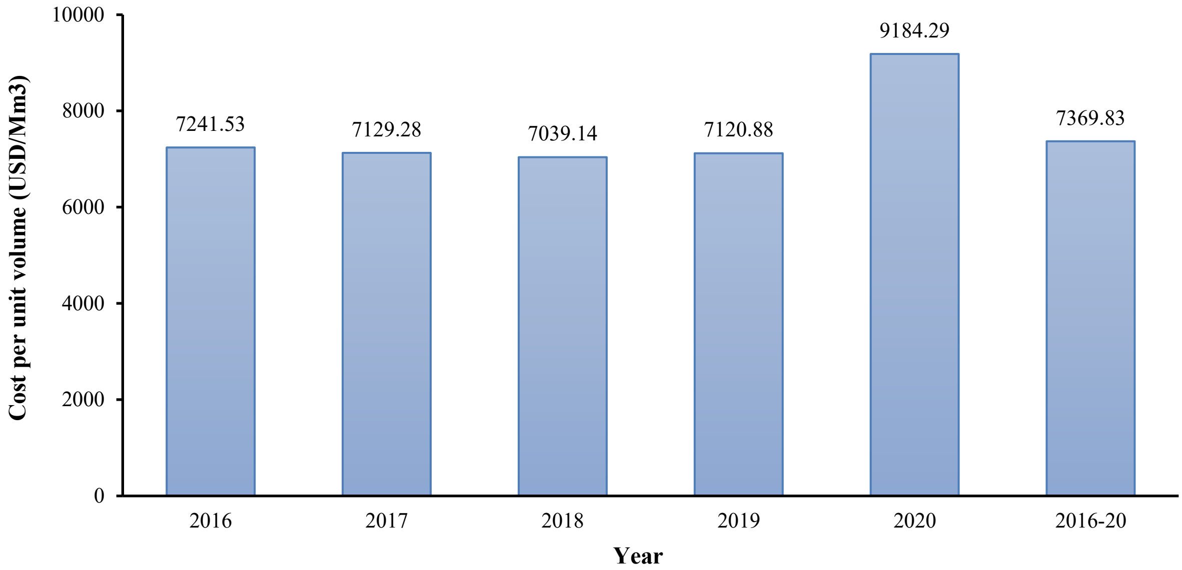

Figure 5 Associated energy cost for lifting one Mm^3 of water during different years of operation

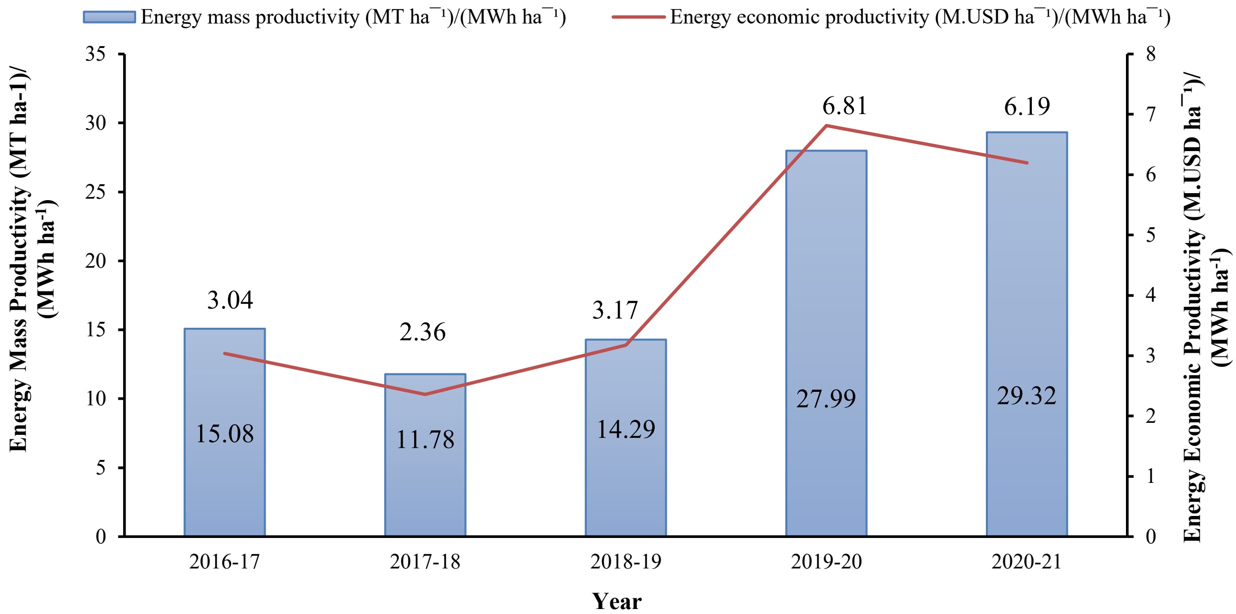

Figure 6 Computed energy mass productivity and energy economic productivity due to trans basin water transfer during different years

TBWT projects exhibit significant variations in energy intensity, with recent global benchmarks indicating a median consumption of 0.65 kWh m^{-3} according to Padowski and Gorelick's Water Resources Research study in 2023. Gravity-driven systems like Peru's Olmos Project demonstrate superior efficiency at 0.15-0.3 kWh m^{-3}, while pump-intensive operations such as Egypt's Toshka Project require substantially more energy at 1.1-1.8 kWh m^{-3}. In arid regions, Middle Eastern projects like the UAE's Taweelah system combine desalination with water transfer for a staggering 3.2 kWh m^{-3} energy footprint, plus 0.4 kWh m^{-3} for summer cooling requirements (Al-Mulla et al., 2023). Emerging research suggested that the hybrid solar-hydro systems could reduce TBWT emissions by 55-75% by 2040 (International Energy Agency (IEA), 2023), while Global Water Intelligence (2023) notes that post-2010 projects already show 18% lower energy intensity through advanced pumping technologies.

3.5 Greenhouse gas (GHG) emissions

The climate change and energy policy in India has been showing mild concern for the environmental effects of energy production using thermal energy produced by coal. Coal, being the abundant energy source available in India, will continue to play the major role in future power generation. As the government policy is based on coal-based power generation, essentially, carbon dioxide emissions will take place as long as coal is used for power generation. GHGs emitted from the electricity generated from thermal power is shown in Table 10. The year 2017-18 utilized highest electrical energy to lift water and accordingly total GHG emissions was estimated as 509176.51 MT. CO_2 equivalent of GHG emissions was computed and it was estimated as 1.92 thousand metric tons of Carbon dioxide equivalent (TMTCDE). Though, PLIS ensure sustainability of agricultural production, CO_2 mitigation strategies like improving efficiency of thermal power plants, clean coal technologies like the use of pulverized coal, disposal of CO_2 in to biosphere sinks through afforestation, carbon sequestration and storage in aquifers offer great potential to absorb released GHG gases.

Table 10 Greenhouse gas emissions from PLIS during 2016-2020

Year	Electrical Energy (kWh)	Greenhouse gas emissions (MT)			
		*CO_2	**SO_2	N_2O	Total
2016-17	162207700	137876.55	136254.47	645.59	274776.60
2017-18	300580000	255493.00	252487.20	1196.31	509176.51
2018-19	271883000	231100.55	228381.72	1082.09	460564.36
2019-20	122027000	103722.95	102502.68	485.67	206711.30
2020-21	101913000	86626.05	85606.92	405.61	172638.58
Total	958610700	814819.10	805232.99	3815.27	1623867.35
CO_2 eq	-	814819.10	-	1136950.46	1951769.46

Note: *CO_2 equivalent factors for GHG gases: CO_2 -1; N_2O – 298 (IPCC, 2007); **SO_2 is not a direct greenhouse gas as it does not absorb and trap infrared radiation

Globally, large-scale LI projects face similar challenges. China's South-North Water Transfer Project, one of the world's largest, requires 50 billion kWh of pumping energy annually, contributing 40 million tonnes of CO_2 - about 8% of China's agricultural emissions (Chen et al., 2019). The conversion of drylands to irrigated paddies has also doubled methane emissions. In California, the State Water Project consumes 8,500 GWh yearly, emitting 3.5 million tonnes of CO_2, though a shift toward renewables has reduced emissions by 30% since 2010 (Gleick and Cooley, 2021). Further, Karimov et al. (2021) estimated the productivity of water and energy resources and associated impacts namely return flow from the Karshi Main Canal lift irrigation system and carbon dioxide emissions. The estimates showed that the demand for irrigation water is 3600 Mm^3 yr^{-1} and the energy demand for lifting water into the system is 2052 GWh yr^{-1}. The power plant burns 382 Mm^3 yr^{-1} of natural gas to generate electricity, resulting in 789 thousand tons of carbon dioxide emissions per year.

4 Conclusions

In this study, detailed crop water requirement for the Krishna delta was computed using the CRIWAR 3.0 simulation programme. Multiple uses of water with sectoral water requirement was computed using secondary data. Here secondary data means statistics on population, livestock population, industrial allocation of water, were collected from the concerned Govt. Departments which were primarily collected by the Government agencies as part of census.

The GIR in the Krishna delta was computed to be 6266 Mm^3. However, water allocation was about 4282 Mm^3 which clearly depicts allocation of water has been deficient and does not fully meet water demand in the region. Irrigation development upstream has further aggravated the situation challenging the sustainability of agricultural production to meet growing population in the densely populated coastal region of Andhra Pradesh. To maintain sustainability of agricultural production systems, it has become inevitable to explore alternate means using the water rich Godavari basin to supply the water scarce Krishna basin. To reap immediate benefit by facing challenges posed by water scarcity in Krishna basin, the PLIS, as a part of Polavaram Irrigation Project, was contemplated. The study suggested that seasonal pressure on water demand for various sectors could be effectively addressed by water resources management in the region through inter basin water transfer from Godavari River by a lift irrigation system. The agricultural production sustainability in the Krishna delta region was ensured through water transfer. Without the water transfer, production in the Krishna delta would have plummeted by 10%-40%, severely impacting agriculture and livelihoods. The study highlights key energy and productivity metrics in irrigated agriculture under inter-basin water transfer. The average energy intensity was 459.81 kWh ha^{-1}**,** while energy and water productivity stood at 3.63 kg kWh^{-1} and 345.52 kg $ha^{-1} \cdot Mm^{-3}$, respectively. Analysis of energy mass productivity (2016-2020) revealed an initial decline (likely due to high energy use in water lifting and maintenance in 2017-2018) followed by a recovery. Energy economic productivity fluctuated, peaking in 2019 (6.81 (million US\$ ha^{-1})/(MWh ha^{-1})) before a slight dip in 2020 (6.19**)**. These findings underscore the dynamic relationship between energy inputs and agricultural outputs, emphasizing the need for optimized water and energy management in irrigation systems. Economical analysis suggested that benefit cost ratio of the project was 1.90, showing that the project has been economically viable (Table 11). However, care must be taken that the transfer does not result in increased water deficits during Rabi and summer months in the Lower Godavari Delta, which is being supplied with water through the Arthur Cotton Barrage at Dowleswaram, India. The water transfers should not lead water deficits being transferred from one basin to another. However, careful integrated planning and analysis is necessary to ensure that the proposed high investment schemes are able to operate as planned and can deliver the expected long-term benefits. Further, there has been environmental concern that needs immediate attention as PLIS is operated by electrical energy generated by thermal power which that has potential to emit GHGs. CO_2 equivalent of GHG emissions was computed and it was estimated at 1.92 thousand metric tons of Carbon dioxide equivalent (TMTCDE).

Table 11 Computation of Benefit-Cost, B/C ratio of PLIS

Description	Amount
Capital expenditure (USD \$)	221.33
Life	10 years
Interest rate	7%
Depreciation	10 years
Capital recovery factor	0.142
Annual costs for 5 years of operation	
Depreciation (M USD \$)	110.67
Annual payment (M USD \$)	157.56
Housing cost@1% (M USD \$)	11.07
Insurance@1% (M USD \$)	11.07
Taxes @ 1% (M USD \$)	11.07
Total annual cost (M USD \$)	301.43
Operating costs for 5 years of operation	
Operating cost for 5 years (M USD \$)	18.70
Man power (M USD \$)	12.80
Repairs and maintenance@6% (M USD \$)	66.40
Total operating cost (MUSD \$)	97.90
Total cost (MUSD \$)	399.33
Total benefit (MUSD \$)	760.60
B/C ratio	1.90

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgements

This study is part of the student post graduate project. The authors are highly grateful to Staff of Water Resource Department, Department of Agriculture, Government of Andhra Pradesh for providing necessary data.

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