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RESEARCH ARTICLE

Application of Geospatial Techniques and the MCDM Method to Optimize Interlinking of Rivers in India

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Abstract

Access to freshwater is one of the most critical challenges in drought-prone regions of India due to climate change and population growth. However, societal costs due to people displacement are often ignored while evaluating interlinking of rivers (ILR) projects though people displacement is one of the most significant impacts of ILR projects in densely populated countries. Therefore, the authors expand the scope of Integrated Water Resources Management (IWRM) by incorporating land use and land cover as key criteria in the Multi-Criteria Decision-Making (MCDM) method. The project alternatives for the proposed Almatti-Pennar (A-P) ILR project developed in this study were evaluated by applying geospatial techniques and the MCDM method before consulting expert stakeholders to finalize the optimal configuration of this project. The optimal A-P ILR configuration will utilize the existing reservoirs and canal systems and reduce the length of the proposed 587 km long link canal by 200 km. This will expedite the ILR project by reducing project-related deforestation, people displacement, and cost. This integrated approach using geospatial techniques and the MCDM method can be applied to ILR projects to achieve Sustainable Development Goal (SDG) 2 (zero hunger) and SDG target 6.1 (safe and affordable drinking water) by reducing water stress.

Keywords ILR projects · Integrated water resources management (IWRM) · People displacement · Sustainable development goals · Water stress

Introduction

The 2030 Agenda for Sustainable Development includes 17 Sustainable Development Goals or SDGs (United Nations, 2015). Of the 17 SDGs, Goal 6 (SDG 6) is to "*ensure availability and sustainable management of water and sanitation for all.*" Water scarcity has become a severe problem worldwide due to population growth and increasing water demand and can be quantified using various indices based on human and ecological water needs (Best, 2019; Brown & Matlock, 2011; Purvis & Dinar, 2020). Recognizing the seriousness of this issue, water security has been emphasized as a priority in Sustainable Development Goal 6 (UNEP, 2021). However, water resources are unevenly distributed across time and space, causing floods and drought (Gupta & van der Zaag, 2008). For example, in India, devastating floods impact one part of the nation almost every year, while at the same time, drought strikes another part of the country, impacting agriculture and the economy (Khanna et al., 2007; Lakshmi et al., 2014). Interlinking of Rivers (ILR) is often used to alleviate water shortages since they also minimize the flood and drought risks as the water moves from surplus to deficit basins through engineered structures (Amarasinghe and Sharma, 2008; Davies et al., 1992).

The preamble to the SDGs states that they are integrated and indivisible since the action in one area will affect outcomes in others (United Nations, 2015). However, their implementation in the real world has focused almost entirely on single goals (Alcamo et al., 2020). Considering the interconnected nature of economic, social, and environmental dimensions of sustainable development, the only way to achieve SDG 6 is through an integrated approach (Glass & Newig, 2019; Kroll et al., 2019; Oliveira et al.,

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2019; Pradhan et al., 2017). Alcamo et al. (2020) assert that as developing countries recover from the impact of the COVID-19 pandemic, "*an integrative approach to the SDGs has the potential to be a cost-effective way for countries to advance many SDGs simultaneously.*"

Integrated Water Resources Management (IWRM) is a process that supports the "*integrated development and management of water, land, and related resources to maximize economic and social welfare equitably without threatening ecosystem sustainability by bringing stakeholders from various sectors and regions*" (UNDP, 2019; UNEP, 2022). An integrated approach will enable the community and/or country to realize the synergies between various SDGs and minimize the trade-offs between the SDGs. The need for an integrated approach to realize the SDGs is often evident in ILR projects that are delayed due to conflicts of interest related to ecological damages, displacement of people, forest land, and poor governance (Das, 2006). Several ILR projects have also been criticized for having irreversible environmental consequences such as alteration of the river morphology in the downstream areas (Howe & Easter, 2013; McCully, 1996). On the other hand, sustainability is often equated with environmental protection or long-term strategies while the social impacts of major projects on the local communities are not given due importance (Newig et al., 2007).

Recognizing India's severe water security issues, the Ministry of Jal Shakti, Government of India (GoI) has conducted water balance studies for the optimum utilization of water resources and has delineated 16 feasible ILR links under the Peninsular component (NWDA, 2005). However, on 21 May 2022, GoI cancelled the Damanganga-Par-Tapi-Narmada link project at the request of the Chief Minister of the State of Gujarat after continuous protest from tribals against this ILR project fearing displacement with all its attendant consequences (Vaktania, 2022). Therefore, it is critical to give due importance to aspects related to people displacement and Rehabilitation & Resettlement (R & R) during the design of ILR projects. Geospatial techniques can be used for this purpose along with suitable ground-truthing and must therefore be used more widely during the preparation of feasibility reports for ILR projects.

The Almatti-Pennar Interlinking of Rivers (A-P ILR) Project is one of the 16 Peninsular links proposed by the National Water Development Agency (NWDA). This link is intended to bring surplus Krishna (i.e., in partial exchange of Godavari water) to the drought-stricken command area in the Ballari and Raichur districts in Karnataka and the Ananthapuramu district in Andhra Pradesh (AP) through a 587-km gravity canal (NWDA, 2005). However, the A-P ILR Project must be reassessed since the Government of Andhra Pradesh (GoAP) has constructed Phase-2 of the Handri Niva Sujala Sravanthi (HNSS) project which overlaps the proposed A-P ILR project between Reduced Distance (RD) 386 km and RD 587 km as shown in Fig. 1.

Further, large engineering projects like ILR projects are only acceptable by society at large if they are scientifically investigated and satisfy the following criteria (Gupta & van der Zaag, 2008).

- The donor basin must have a surplus, while the recipient basin must have a deficit.
- The project must be built sustainably, considering economic, social, and environmental factors.
- When implementing such interstate projects, a good governance process should be adopted between all stakeholder states.
- The project should respect existing rights, and appropriate compensating mechanisms should be agreed upon as needed.
- Displacement of people must be avoided.

Most pre-feasibility assessments of ILR projects in India were conducted using data gathered from time-consuming and expensive ground surveys. Therefore, conventional techniques used to study ILR projects are tedious and time-consuming due to a lack of current data on the physical and hydrological characteristics of the watershed (Kumar and Reshmidevi, 2013; Lakshmi et al., 2014). The Multi-Criteria-Decision-Making (MCDM) method is the most effective technique for tackling problems with multi-objective criteria. Several MCDM procedures have been developed to aid decision-makers, including the analytical hierarchy process (AHP), multi-attribute utility theory (MAUT), and simple additive weighting (SAW) (Gebre et al., 2021).

The MCDM method combined with geospatial techniques (to extract the latest data related to all relevant parameters) is highly suitable for interdisciplinary research on ILR projects which must necessarily address multiple design criteria (hydrology, land, ecology, forest, safety, and economics) as well as several stakeholders including local communities, project-affected-persons, and civil society. However, studies using the MCDM method along with remote sensing and GIS techniques to analyze ILR projects are hardly published in India. This is the vital research gap that the present study tries to bridge.

The first key objective of the present study is to demonstrate the integration of remote sensing and GIS techniques with the Analytical Hierarchy Process (AHP)-based MCDM method to evaluate alternative alignments for ILR projects based on multiple criteria, by using the proposed A-P ILR Project as a case study. These criteria include societal concerns related to people displacement and environmental issues linked to deforestation along with

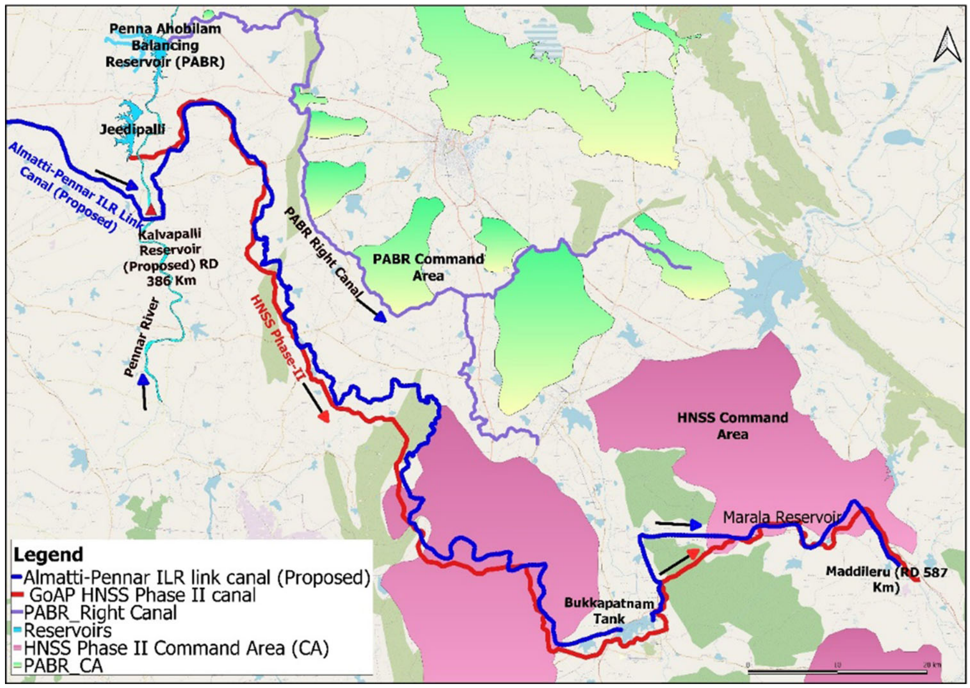


Fig. 1 Map showing the PABR and HNSS Phase-2 schemes and the A-P ILR link canal between RD 386 km and RD 587 km, and their respective command areas (GoAP, 1994b; NWDA, 2005)

geomorphological, slope and soil parameters. The second key objective of this study is to finalize the optimal configuration for the A-P ILR Project by conducting expert stakeholder consultations based on the alternative alignments developed for this ILR project by integrating remote sensing and GIS techniques with the MCDM method. The demonstration of the mixed method using both quantitative and qualitative techniques to evaluate alternative alignments for an ILR Project in this study is expected to bridge the research gap in the assessment of ILR projects based on the key criteria proposed by Gupta and van der Zaag (2008). Following this introduction, the study area is described in "Study Area" Section. "Data and methods" Section summarizes data and methods used to develop alternative configurations of the A-P ILR Project using an integrated approach to development and environment. "Results and Discussion" Section presents the results and discussions, while the conclusions of this study are summarized in "Summary and Conclusions" Section

Study Area

The study area discussed in this paper is in the Ananthapuramu district in the state of Andhra Pradesh (AP) and forms a part of the command area of the proposed A-P ILR Project as well as the existing HNSS Project as shown in Fig. 1. It is situated in the south-western part of AP between 14° 47′ 31.05″ N–14° 34′ 33.95″ N and 77° 14′ 16.19″ E–77° 21′ 50.93″ E. The study area falls under a scarce rainfall agroclimatic zone as per the India Meteorological Department's classification. Ananthapuramu district receives the second-lowest amount of rainfall in India, only next to Jaisalmer district in Rajasthan putting considerable strain on the socioeconomic conditions of the people living in this district (Anantha et al., 2021; GoAP, 2020; IMD, 2019; MoF, 2021; Reddy et al., 2008). The Long-Period-Average (LPA) rainfall recorded in the Ananthapuramu district is 536 mm. The district experienced rainfall deficits in 19 of the last 120 years compared to the LPA of 536 mm (IWRIS, 2021).

The sparse rainfall in the Ananthapuramu district is also exacerbated by inadequate water flow in the Pennar river due to the paucity of rainfall in the Upper Pennar basin (GoAP, 1994a, 2019; IMD, 2019; IWRIS, 2021). The Tungabhadra high-level canal (TBHLC) system, on the other hand, is unable to provide the planned volume of water to the Ananthapuramu district due to the siltation and breaches upstream of the TBHLC resulting in reductions in the release of water from the Tungabhadra reservoir (GoAP, 2020). Consequently, only 7.31% of the total area (19,139 km^2) of the Ananthapuramu district is irrigated while the sown area is 56.60% of the total area (GoAP, 2021b). As a result, the per capita income of this district is only 65% of that of the state of Andhra Pradesh (GoAP, 2022). As of 2019–2020, GoAP (2022) had declared 57 villages (out of a total of 534 with a total population of 167,421 persons as 'drinking water problematic villages,' while a perusal of the JJM dashboard indicates that only 76% of the rural households in Ananthapuramu district have a tap connection at present (JJM, 2022). However, GOI is implementing the Jal Jeevan Mission (JJM) to provide functional household tap connections to supply water @55 L per capita per day (lpcd) to every rural family by 2024. This will require a significant increase in surface water supplies in the coming years since the groundwater levels are already stressed in the Ananthapuramu district (CGWB, 2013).

The feasibility report prepared by NWDA (2005) for the A-P ILR project envisages the diversion of 1980 Mm^3 of water from the Almatti dam on the river Krishna through a 587-km long canal in exchange for the excess Godavari water transferred to the Krishna basin after the completion of the ongoing Polavaram project. The Polavaram project to transfer 2265 Mm^3 (80 TMC) of water from the Godavari River to the Krishna River is currently under construction and is expected to be completed in 2–3 years. On August 4, 1978, the states of A.P and Karnataka agreed that this surplus water diverted from the Godavari basin to the Krishna basin through the Polavaram project will be shared in the proportion of Maharashtra-396 Mm^3: Karnataka-595 Mm^3: A.P-1274 Mm^3. This agreement has also been recognized by the Godavari Waters Dispute Tribunal (GWDT, 1980). Based on this agreement, NWDA (2005) has designed the A-P ILR Project to supply 372 Mm^3 of water to the state of Karnataka (primarily, the drought-affected Ballari and Raichur districts) and 1342 Mm^3 of water to the Ananthapuramu district (NWDA, 2005). This is in addition to the provision of 56 Mm^3 of water for domestic and industrial uses besides making an allowance of 210 Mm^3 of water for transmission losses in both States.

The A-P ILR Project scheme appears to be the solution to the water stress in the drought-affected Ballari and Raichur districts in Karnataka and the Ananthapuramu district in A.P. since it will supply 372 Mm^3 of water to the state of Karnataka and 1342 Mm^3 of water to the A.P. after accounting for transmission losses (NWDA, 2005). NWDA (2005) has proposed a balancing reservoir with a gross storage capacity of 83 Mm^3 at Kalvapalli (@ RD 386 km) on the river Pennar (NWDA, 2005). However, the A-P link canal proposed by the NWDA (2005) may not be feasible between the Kalvapalli balancing reservoir in Ananthapuramu district (at 386 km) and the tail end of the canal (at 587 km) since GoAP has already constructed a canal from Jeedipalli to Marala (and beyond) in Phase-2 of the HNSS scheme (GoAP, 2021a). Various geospatial and ground truth points have been superimposed onto a GIS map in this research to understand the overlap between HNSS phase 2 alignment and NWDA-proposed A-P ILR alignment as shown in Fig. 1. Subsequently, a field survey was undertaken between RD 386 km and RD 587 km of the proposed A-P ILR link canal alignments along with NWDA officials to verify the overlap between the existing HNSS Phase-2 canal and the proposed NWDA alignment. This ground-truthing exercise validated the findings of the remote sensing and GIS studies.

Further, the construction of the Kalvapalli reservoir (Figure A1 in the Supplementary Information) proposed by NWDA (2005) will result in the submergence of 1323 Ha of land containing 249 houses in two villages and will displace 1333 project-affected-persons (PAPs). Since the construction of the Kalvapalli reservoir proposed by NWDA (2005) is not possible under these circumstances, alternative configurations must be developed for the A-P ILR Project that will meet the criteria listed in "Introduction" Section of this paper. These two challenges—(1) the overlap between the existing HNSS Phase-2 and the proposed A-P ILR link canal downstream of RD 386, and (2) the people displacement associated with the Kalvapalli reservoir, provided the impetus for the use of geospatial techniques in conjunction with the MCDM method to optimize the configuration of the A-P ILR link canal in Ananthapuramu district based on the criteria mentioned in Section "Introduction" of this paper.

Data and methods

The secondary data used in this study have been extracted from NWDA's Feasibility report (FR), district statistical reports, detailed project reports (DPR) of the Jeedipalli and Penna Ahobilam Balancing Reservoir (PABR), Survey of India (SOI) toposheets, and maps/drawings of the A-P ILR and HNSS projects (GoAP, 2021a; NWDA, 2005; SOI, 2021). Further, geospatial datasets were collected from the National Remote Sensing Centre (NRSC), ISRO, and other relevant agencies. The sources and details of the secondary data used in this study are summarized in Table A1 in the Supplementary Information.

Geospatial modelling coupled with the MCDM method using appropriate hydrological inputs and ground data is an effective tool for the study of various ILR projects (Chigbu & Onukaogu, 2013; Chowdary et al., 2012; Sheffield et al., 2018; Vemu & Udayabhaskar, 2010**).** The MCDM method is useful to arrive at the optimal decision in various applications such as environment, water resources management, and engineering services since it uses several criteria to manage complex problems (Gebre et al., 2021; Kulimushi et al., 2021; Mardani et al., 2015; Muluneh et al., 2022).

An MCDM-based site suitability model was constructed during this study to optimize the alignment of the segment of the proposed A-P ILR link canal falling within the Ananthapuramu district. While various methods based on MCDM are utilized to address complex problems, the fuzzy AHP method is the most efficient of all fuzzy

Table 1 The scale used for pair-wise comparisons in this study based on Saaty (1977, 2000)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two elements contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very Strong Importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate Values	When compromise is needed

techniques because it compares all criteria (pairwise) and alternatives and evaluates their weights (Mardani et al., 2015; Triantaphyllou & Mann, 1995). During the structuring of the criteria in AHP, we can understand the challenges and goals of the decision-makers as well as the available alternatives. The overall methodology can be broken down into sequential steps as shown in Figs. 2, 3.

Preparation of Thematic Layers

Several thematic layers (geomorphology, land use and landcover (LULC), slope, and soil) were generated using satellite and ground survey data. Other layers like the catchment area, drainage density, streams, flow accumulation, and flow direction, were created using the Shuttle Radar Topography Mission-Digital Elevation Model (SRTM-DEM) which was pre-processed before performing the analysis (SRTM, 2021). These thematic layers generated were calibrated and validated with data extracted from SOI toposheets and the offices of NWDA and the GoAP irrigation department. Geomorphological layers, LULC, and settlement layers were generated from LISS III and LISS-IV satellite data and validated with data extracted from SOI toposheets, Bhuvan thematic services, and field visits. The soil map of the study area was prepared from data obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS-LUP). After preparing all the thematic layers, multi-scale integration using a standard majority rule-based aggregation technique was applied to optimize the resolution of each thematic layer. The AHP method was used to establish relative weights to create a land suitability map for the canal alignment as discussed in "Analytical Hierarchy Process" Section of this paper.

Analytical Hierarchy Process

The MCDM method refers to decision-making under multiple, usually conflicting criteria. The MCDM method can be categorized into two categories: multiple attribute decision-making (MADM) and multiple objective decision-making (MODM). The development of a land suitability map using a GIS-based model incorporates the

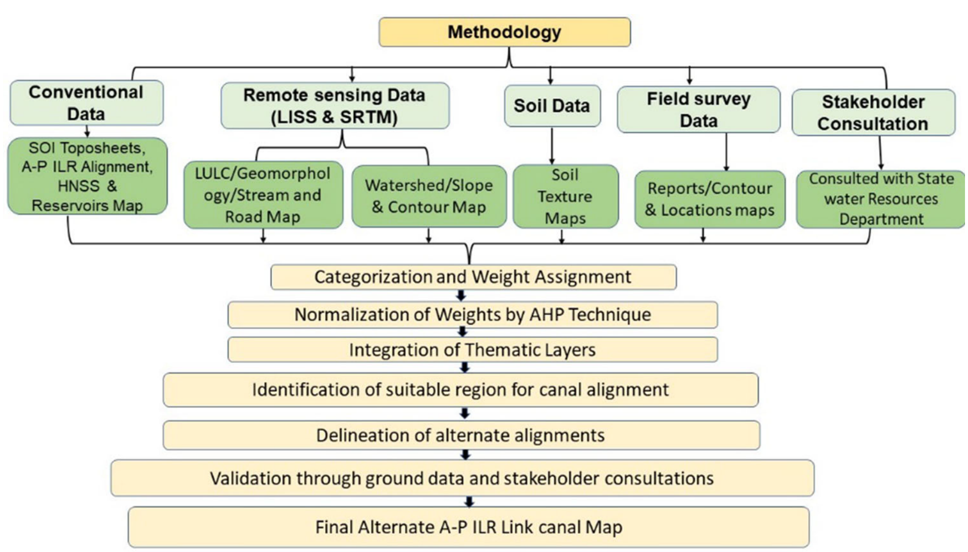
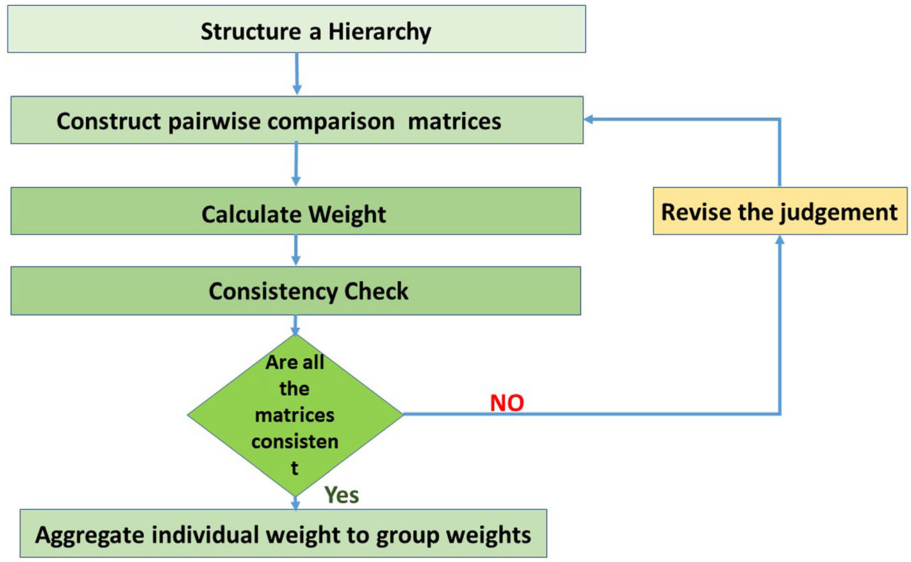


Fig. 2 Flowchart illustrating the application of geospatial techniques coupled with the MCDM method to delineate the optimal A-P ILR link canal alignment (ESRI, 2021)

Fig. 3 Flow chart illustrating the AHP method to calculate weights



MCDM method and utilizes a hierarchical structure including, land suitability classification, weight evaluation, and the development of a land suitability map (Muralitharan & Palanivel, 2015). The analytical hierarchy process (AHP) developed by Saaty (1977) is one of the most widely used MADM analytical techniques for complex decision-making issues since it can deal with both objective and subjective attributes (or criteria) of decision makers (Rao, 2007). Additionally, it provides a way to measure the consistency of preferences (Triantaphyllou, 2000). The AHP algorithm is used to determine the relative weights of available alternatives using a pairwise decision matrix. In this study, slope, LULC, geomorphology, and soil were considered the main governing factors, and suitable weights were assigned to each factor. The pairwise decision matrix was standardized to derive the relative weights for each factor using the AHP method shown in Fig. 3.

The Saaty scale used in this study has values ranging from 1 to 9 where the values 3, 5, 7, and 9 correspond to the judgements 'moderate importance', 'strong importance', 'very strong importance', and 'absolute importance'. The scale used for pair-wise comparison is given in Table 1.

Identification of Site Suitability Factors for the Proposed A-P ILR Project

Physical land characteristics such as slope, land use, geomorphology, and soil are the key relevant factors considered in this study. Topographic factors such as elevation and slope of the study region were analyzed to select the optimal canal alignment route. The site suitability factors (shown in Fig. 4) and their importance in developing a site suitability map are discussed below.

Slope

Slope is defined as the highest rate of change in value from one cell to its neighbors along a fall line (Cadell, 2002). The slope of a gravity canal is one of its major features since it also determines the canal's maximum discharge. The slope map is generated using the SRTM-DEM. The slope varies from 1 to 9 degrees in the study area. Since the proposed A-P ILR link canal is gravity-based, the slope of the natural ground should neither be too gentle nor too steep. Therefore, on a scale of 1–9, ranks were allocated to different slope classes. A moderate slope range ranging from 3 to 5 degrees was assigned a higher weightage during this study.

Land use-Land cover changes (LULC)

These are critical indicators for sustainable water resource planning and management (Daba & You, 2022). The LULC classifications for the study area were prepared using LISS-IV images using supervised classification. The land classes for the study area were categorized into five classes: fallow land, water bodies, vegetation/crop area, built-up areas (settlement), and barren land. While ILR projects have several advantages, critics have emphasized social impacts such as displacement, rehabilitation, relocation, and environmental problems which have also contributed to peoples' opposition to ILR projects in recent years (Purvis & Dinar, 2020; Sinha et al., 2020; Vaktania, 2022). Therefore, one of the key criteria used to develop the optimal alignment of the A-P ILR link canal in the

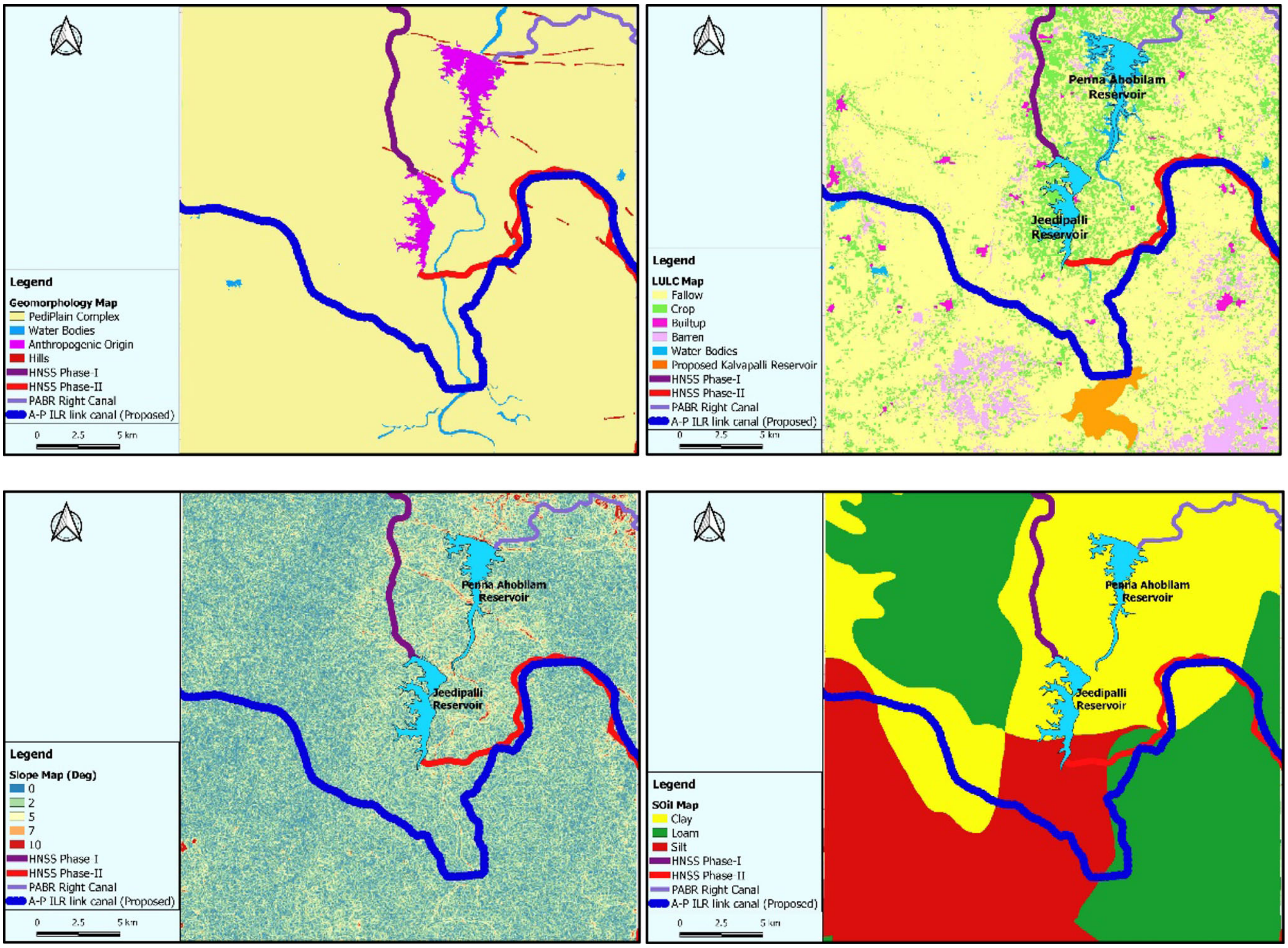


Fig. 4 Map showing different thematic layers (Geomorphology, LULC, Slope, and Soil) of the study area

Ananthapuramu district in this study was to minimize the number of people displaced by avoiding the use of built-up area as much as possible. Specifically, the built-up-area that will be affected by the submergence created by the Kalvapalli reservoir proposed by NWDA (2005) was given the lowest weightage, while fallow land and crop field areas were given the maximum weightage in the AHP-based MCDM method used in the present study.

Geomorphology

Geomorphological studies are recommended during the planning stage of all irrigation projects (FAO, 1992; MoWR, 2010). Various geomorphological features in the study area were digitized using satellite imagery and the Bhuvan geoportal and categorized into four classes, viz., the pediplain complex, anthropogenic origin, low dissected hills, and water bodies. The pediment-pediplain complex, which has a denudational origin and consists of gently sloping plains covered with weathered material is highly suitable for the construction of a canal (Bhuvan, 2022; Lakshmi et al., 2014 MoWR, 2010). Therefore, the highest weight among the geomorphological features in the study area was assigned to the pediplain followed by waterbodies.

Soil

Canals built in sandy soil will experience more seepage losses than canals constructed in clay soil because water seeps quickly through sandy soil and slowly through clay soil. Based on the soil map of the study area prepared using the NBSS and LUP data, the study area contains clay, loam, and silt soil. The slope ratio for loamy-type soil is adopted to minimize cutting and filling (MoWR, 2010). The highest weightage was given to clay soil during this study followed by silt and loam.

Implementation of the AHP-Based MCDM Method

In the present study, the AHP-based MCDM technique is applied after the preparation of all the thematic layers mentioned in "Identification of Site Suitability Factors for the Proposed A-P ILR" Project" Section The details of the calculations are shown in the supplementary information (Tables A2 to A5). The following steps were used to calculate the final weight of all the thematic layers (Muralitharan & Palanivel, 2015; Sutadian et al., 2017). Based on Saaty's scale (Table 1), a relative importance pairwise comparative matrix (*A*1 matrix) was generated as shown in Table A2. The steps in this process are summarized as follows:

Step 1 Add the values in each cell of each column of the pairwise matrix (*A*1 matrix) using Eq. (1).

$$L_j = \sum_{i,j=1}^{n} C_{ij} \tag{1}$$

Step 2 To construct a normalized pair-wise matrix (*A*2 matrix) as shown in Table A3, divide each element in the matrix by its column total, e.g., 1/1.86, 3/4.8, 3/6.3 as given in Eq. 2.

$$\mathrm{Xij} = \frac{\mathrm{Cij}}{\mathrm{Lj}} \tag{2}$$

where X_{ij} is the value in the *i*th row and *j*th column of the normalized pair-wise matrix.

Step 3 Use Eq. (3)to generate the standard weights by dividing the sum of the normalized rows of the matrix by the number of factors utilized ($N = 4$) as shown in Table A3.

$$\mathrm{Wi} = \frac{Xij}{N} \tag{3}$$

where *Wi* is the standard weight.

Step 4 Construct [A3] and [A4] matrices such that,

$$[\boldsymbol{A3}] = [A1]*[A2]$$

$$[\boldsymbol{A4}] = [A3]/[A2] \quad \text{where}, [A2] = [w_1, w_2 \ldots w_j] \tag{4}$$

The results obtained from *A*3 and *A*4 matrices are shown in Table A4.

Step 5 Consistency analysis.

The AHP method requires consistent weights derived from a pairwise comparison matrix. One of the essential features of the AHP is that it specifies and calculates the inconsistencies of decision-makers. The consistency vector (λ) is calculated by using Eq. 4. This procedure involves the multiplication of the pairwise comparison matrix values and the normalized weights of thematic layers utilizing the entries in Tables A2 and A3. The results are given in Table A4. To determine the Consistency Index (CI) in the present study, the value of $\lambda_{\max}$, which is the average of the matrix A4 is calculated as shown in Table A4. The CI which represents the consistency of a comparison matrix is the calculated using Eq. 5 as follows:

$$\mathrm{CI} = (\lambda_{\max} - N)/(N-1). \tag{5}$$

The Consistency Ratio (CR) is used to evaluate the matrix's consistency and ensure that the given weights are reliable. The Consistency Ratio (CR), computed by Eq. (6), approximates the efficiency criterion of the AHP.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{6}$$

where, RI = Random Inconsistency corresponding to the number of factors in the study (Table A5).

Stakeholder Consultations

In the present study, the MCDM-based AHP was first used to evaluate several possible routes to optimize the last-mile connectivity of the A-P ILR canal (from RD 377 km onwards) with the terminal balancing reservoirs located in the study area instead of NWDA's proposal for constructing a new Kalvapalli reservoir. These alternatives were then plotted on GIS maps and discussed with relevant experts in NWDA and expert stakeholders in the GoAP listed in Table A6 included in the Supplementary Information.

Consultation with expert stakeholders is a crucial part of this study since large water projects require the participation and input of experienced stakeholders to develop a systematic plan (Gupta & van der Zaag, 2008; Srinivas & Singh, 2018). Such stakeholder consultations will help in the evaluation of various project configurations at the feasibility stage itself thereby resulting in time and cost savings. This is in addition to the formal public consultation process mandated by Environmental Impact Assessment (EIA) process to be undertaken for all river valley projects under the EIA Notification, 2006 (MoEF, 2006). As shown in Table A6 in the Supplementary Information, the expert stakeholders consulted during this study included the relevant NWDA officials, government experts in the irrigation and water resources departments of the AP and Karnataka State Governments, as well as the authorities responsible for the major dams/reservoirs in the command area of the proposed A-P ILR Project. These experts have not only provided valuable inputs for the study but have also provided critical comments and suggestions regarding the alternative project configurations for the A-P ILR Project evaluated during this study. Their key suggestions are as follows:

- Since the capacity of the canals constructed under the HNSS Phase-2 is being enhanced under an existing project, there is no need to extend the A-P ILR Project beyond the Pennar river. The linkage of the proposed A-P ILR project to the HNSS Phase 2 scheme will enable the original command area proposed to be served by the A-P ILR Project without constructing a 200 km long canal.
- The construction of the Kalvapalli reservoir as proposed by NWDA (2005) requires the displacement of hundreds of PAPs which will have an adverse impact on the project schedule and cost besides provoking opposition to the A-P ILR Project.
- The current capacity of the PABR (147 Mm^3) is higher than that of the Kalvapalli balancing reservoir (83 Mm^3) proposed in the NWDA (2005) scheme. By connecting the A-P ILR Project to the PABR as well as the existing Jeedipalli reservoir (48 Mm^3), the construction of the Kalvapalli reservoir can be avoided.
- The proposed A-P ILR project must be connected to both PABR and Jeedipalli reservoirs so that the balancing of both ayacuts can be achieved in a reliable manner to provide water for domestic use as well as irrigation.
- The PABR designed to receive water from the Pennar and Tungabhadra rivers is also receiving water from the river Krishna through the adjacent Jeedipalli reservoir during the construction of the HNSS Phase 2 canals. The PABR is supplying drinking water to Ananthapuramu City and rural areas and the quality of the water drawn from the PABR was checked with reference to Indian Standard 10,500–2012. The data collected till date indicates that all the physiochemical parameters of the raw water from the PABR reservoir are within the acceptable limits. Therefore, the water supplied from the Krishna River to the PABR after the construction of the A-P ILR Project as proposed in this study will have no adverse impact on the water quality in PABR.

Results and Discussion

Consistency Analysis

As shown in the Supplementary Information, the Consistency index (Eq. 5) of this study is 0.033 while the Consistency ratio (Eq. 6) is 0.034. Since the value of the Consistency Ratio is less than 0.10, the weights assigned to the factors used in the present study are consistent (Rao, 2007). This proves that the AHP-based MCDM method used in this study yields valid results.

The weights and ranks assigned to Slope, LULC, Geomorphology and Soil are indicated in Table 2. Not all chosen factors or criteria are equally important for a land suitability map. We must weigh each criterion's importance in relation to the others. Since the proposed A-P ILR project envisages only a gravity canal, the slope is considered to be a crucial factor for canal alignment with the highest weight, followed by land use (to minimize people displacement) which prevails over geomorphology and soil characteristics of the study area. The AHP-based MCDM method used in the present study enables us to give due importance to social (people displacement) and environmental (forest) factors besides the technical aspects (slope and soil characteristics) of ILR project design.

Land Suitability Map Using Weighted Overlay Analysis

The weighted overlay method is the most frequently used method to integrate different thematic layers on the same evaluation scale to develop the final suitability map. In the present study, weighted overlay analysis was performed on the spatial layers to delineate the potential locations for the AP-ILR link canal (from RD 377 km onwards) in the Ananthapuramu district. A suitability value was derived by multiplying the suitability value of each raster cell by the weight of its layer and totaling the resulting values. Overlay analysis tools were used to compute the final land suitability map shown in Fig. 5 by using Eq. 7:

$$\text{Land Suitability Map} = \sum_{W=1}^{m} \sum_{j=1}^{n} (Wj * Xi) \tag{7}$$

where m and n are the total number of factors and the number of the subclass, Wj is the normalized weight of the j_{th} factor, and X_i is the normalized rank of the factor subclasses.

A land suitability map was created for this study by superimposing the essential contributing thematic layers using weighted overlay analysis (ESRI, 2022). The screenshots demonstrating the steps used to process the data in the GIS software are included in the Supplementary information. The final land suitability map (Fig. 5) contains the essential thematic layers required for the gravity-based canal alignment of the A-P ILR link canal. The higher the class, the greater the potential of the site for a canal and vice versa. As shown in Fig. 5, it is possible to develop alternatives to connect the proposed A-P ILR link canal to the existing Jeedipalli reservoir and the Pennar river (which flows into the PABR) by avoiding the 'very low' and 'low' priority areas. Therefore, different A-P ILR link configurations were digitized and analyzed and superimposed on this land suitability map.

Table 2 Final weights assigned to each class based on the AHP algorithm

Parameter	Classes	Rank	Weight	Influence (%)	Final weight assigned to each class
Slope	1	1	0.5162	51.62	51.62
	2	2			103.24
	3	5			258.10
	5	4			206.48
	> 9	3			154.86
LULC	Built-up	1	0.2382	23.82	23.82
	Fallow	5			119.10
	Vegetation/crop	3			71.46
	Proposed Reservoir	1			23.82
	Barren	4			95.28
	Waterbodies	2			47.64
Geomorphology	Waterbodies	3	0.1682	16.82	50.46
	Pediplain	5			84.10
	Hills/valley	2			33.64
	Anthropogenic	1			16.82
Soil	Clay	5	0.0769	7.69	38.45
	Loam	3			23.07
	Silt	4			30.76

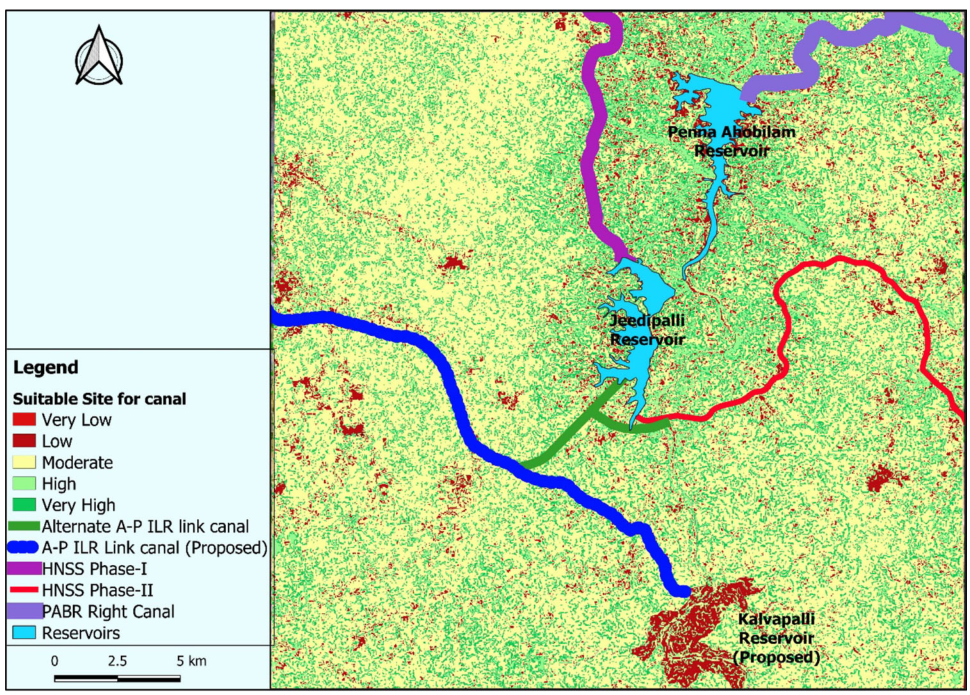
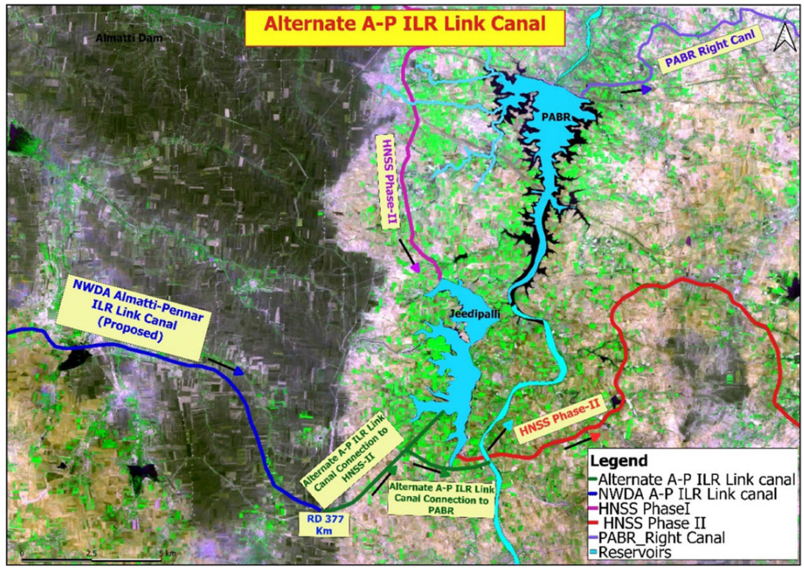
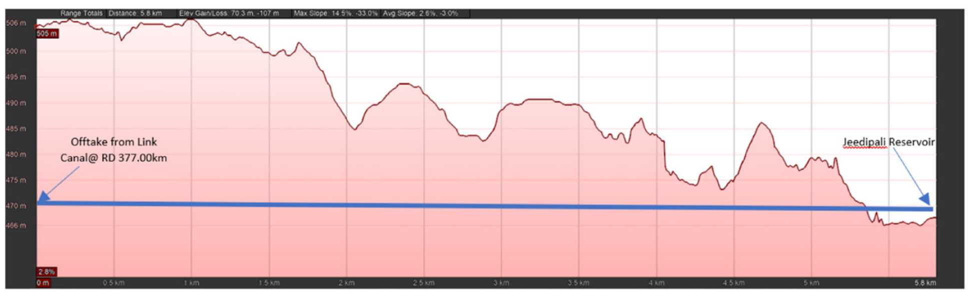


Fig. 5 Thematic layers of the study area after applying the AHP-based MCDM method

Fig. 6 **a** Map showing the optimal alignment of the link canal taking off from RD 377 km of NWDA's proposed alignment of the A-P link canal and connecting it with the PABR and Jeedipalli reservoirs. **b** Longitudinal section of the link canal connecting the A-P ILR link canal to the Jeedipalli reservoir



a. Map showing the optimal alignment of the link canal taking off from RD 377 km of NWDA's proposed alignment of the A-P link canal and connecting it with the PABR and Jeedipalli reservoirs



b Longitudinal section of the link canal connecting the A-P ILR link canal to the Jeedipalli reservoir

Alternatives Considered for the A-P ILR Link Canal Alignment

The four alternatives for the configuration of the A-P ILR link canal evaluated in the present study are shown in Fig. 6a, b, and Figures A2 to A4 in the Supplementary information. These four alternatives are summarized as follows:

Alternative 1 (Figure A2)

This is the base case in which NWDA (2005)'s proposed alignment is maintained right up to the Kalvapalli reservoir (on the river Pennar) after which the water flows to the PABR since the portion of the A-P ILR canal beyond the Kalvapalli reservoir as proposed by NWDA cannot be constructed due to the overlap with the existing HNSS Phase-2 canal (Fig. 1). This alternative requires the construction of the Kalvapalli reservoir as proposed by NWDA (2005) which will submerge an area of 1323 hectares necessitating the displacement of 1333 PAPs as explained in Section "Study Area".

Alternative 2 (Figure A3)

This alternative has a length of 6 km between the proposed A-P ILR link canal at RD 377 km and the Jeedipalli Reservoir. This alignment will connect the A-P ILR Project with the existing Jeedipalli balancing reservoir and serve the HNSS Phase 2 command area. However, this alignment cannot cater to the ayacut of the PABR scheme which is currently non-operational due to the shortfall in water supply from the TBHLC scheme as explained in "Study Area" Section

Alternative 3 (Figure A4)

This alternative has a length of 6 km between the proposed A-P ILR link canal at RD 377.8 km and a natural stream flowing into the Pennar river upstream of the PABR. While this alternative can cater to the domestic and irrigation water requirements from the PABR dam, the original command area proposed under the A-P ILR link will have to be served by the HNSS scheme only. This will perpetuate the dependence of the HNSS scheme on the pumping of water from the Krishna (Srisailam reservoir) which is possible only when surplus water is available in the Srisailam reservoir.

Alternative 4 (Fig. 6a, b)

This alternative is the optimal alignment and has been finalized based on field studies related to water supply, demand, and shortfalls in the TBHLC and HNSS command areas, duly validated with expert stakeholder consultations as explained in "Stakeholder Consultations" section. The optimum alignment developed during this study meets all key assessment criteria for ILR Projects (Gupta & van der Zaag, 2008; Sinha et al., 2020). The key advantages of the optimal alignment are explained in Sect. "Optimal Alignment of the A-P ILR Link Canal"

Optimal Alignment of the A-P ILR Link Canal

The optimal alternative for the A-P ILR link alignment developed during this study takes off from the proposed A-P ILR link canal at RD 377 km and has two branches to connect with the existing balancing reservoirs in Jeedipalli (6 km link) and PABR (4 km branch from the main link), thereby avoiding the construction of the Kalvapalli reservoir as proposed by NWDA (2005). This optimal alignment minimizes people displacement and the potential environmental impacts of the proposed A-P ILR project and satisfies the irrigation, drinking and other water needs in the command area of two existing balancing reservoirs.

Currently, the PABR and its canal systems are not able to irrigate 20,234 hectares of ayacut in six mandals in the Ananthapuramu district due to a shortfall in inflows from the TBHLC and the Pennar river (GoAP, 2020). While the maximum storage in the PABR to date is only 147 Mm^3, this storage capacity can be increased to the design capacity of 314 Mm^3 once the Government of A.P completes the strengthening of the reservoir and acquires the balance land for which actions are being taken (GoAP, 2017).

NWDA (2005) had estimated the total budget for implementing the R & R plan for the A-P ILR Project to be Rs.51 million. This cost will be much higher today due to the increase in land compensation and R & R costs post the enactment of the Land Acquisition and R & R (LARR) Act of 2013 (MLJ, 2013). For example, GoAP (2020) has estimated the cost of land acquisition for the construction of the flood flow canal to be Rs. 1.2 million per hectare compared to NWDA (2005)'s estimate of Rs.0.143 Million per hectare to acquire land needed to construct the Kalvapalli reservoir (excluding R & R costs). Therefore, the optimal configuration of the A-P ILR Project developed in this study reduces the time and cost of land acquisition besides minimizing the displacement of project-affected persons. This is critical to enhance the acceptability of the A-P ILR project among the local communities.

By adopting the optimal configuration of the A-P ILR Project developed in this study, NWDA can realize both time and cost savings by avoiding the Kalvapalli reservoir and reducing the A-P ILR canal length by 200 km. The Government of Andhra Pradesh can use water from the A-P ILR Project to balance the ayacuts of PABR as well as HNSS Phase-2 by connecting the A-P ILR link canal to the PABR reservoir and Jeedipalli reservoir. The HNSS Phase-2 schemes and PABR can then be optimally utilized to irrigate 163,700 hectares and 20,230 hectares in the command areas of the HNSS Phase-2 scheme and the PABR right canal, respectively. In addition, the A-P ILR project will enhance the crop yields of the farmers tilling 82,000 hectares of land in the command area of this project in the state of Karnataka through enroute irrigation. Further, the existing drinking water schemes to supply drinking water to Ananthapuramu town and neighboring villages from the PABR will also be able to draw on a dependable water source once the A-P ILR project is executed as per the optimal configuration proposed in this study. Finally, the connection of the A-P ILR link canal to the Jeedipalli balancing reservoir also ensures the supply of water to the HNSS Phase-2 command area through gravity instead of pumping as per the HNSS design (GoAP, 2021a). This will reduce the electrical energy required to pump water from the Jeedipalli reservoir by approximately 60 GWh per year thereby reducing the carbon footprint and costs of HNSS Phase-2.

Summary and Conclusions

Sustainable development must balance social, economic, and environmental considerations. In addition to hydrological considerations, the social, political, and ecological circumstances of ILR projects must be carefully considered right from their planning stage to mitigate the environmental and social impacts of the project in a holistic manner. In this paper, the authors describe the use of geospatial techniques and the AHP-based MCDM method to carry out an integrated assessment of a major ILR project in India coupled with the use of expert stakeholder consultations to validate the optimal configuration of the project. Specifically, the optimal configuration of the A-P ILR Project proposed in this study avoids the construction of the Kalvapalli balancing reservoir by connecting the link canal to the Jeedipalli reservoir and the currently underutilized PABR. This configuration also reduces the A-P ILR canal length by 200 km by using the existing canal systems constructed in the PABR and HNSS Phase-2 schemes. The decrease in the construction activities by implementing the A-P ILR Project as per the optimal configuration proposed in this study will reduce the construction costs of the Project as well as the costs of land acquisition and resettlement & rehabilitation of project-affected persons. This study will therefore enable the NWDA to win the support of the central and state governments for the A-P ILR Project.

The combination of geospatial techniques and the AHP-based MCDM method to carry out a transparent, integrated, and holistic assessment of ILR projects based on sound science, duly validated with expert stakeholder consultations can be used to optimize the configuration of other ILR projects to achieve SDG target 6.1 (*achieve universal and equitable access to safe and affordable drinking water for all by 2030*) as well as SDG 2 *('zero hunger')* by 2030.

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Data availability Annexure uploaded along with manuscript.

Declaration

Conflict of interest The authors report no potential conflicts of interest.

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