**Assessment of long Term Impact of Gandak Canal Irrigation Project on Cropping Pattern and Development in North Bihar, India**

**Abstract**

India hosts one of the largest canal irrigation networks in the world, influencing not only the agrarian economy but also the broader trajectory of rural development. Canal irrigation provides water security to more than 200 million people and has significantly reshaped India's economic geography by inducing substantial agricultural and structural transformations both within and beyond irrigated zones. The study aims to provide comprehensive insights for improving resilience and sustainability in the canal-command agricultural regions of the Gopalganj district of Bihar. This qualitative field-based study explores the socio-economic and agronomic impacts of the Gandak Canal Irrigation Project in Gopalganj district, Bihar, India, within the broader contexts of climate change and rural development. Employing a purposive sampling approach, the study engaged 360 diverse farmers, labourers, Panchayat members, and through semi-structured interviews and group discussions conducted during the 2024–25 agricultural year. Data collection and analysis focused on understanding local perceptions of irrigation-driven changes in agriculture, livelihood patterns, and environmental dynamics. Findings reveal a significant transformation in land use and cropping patterns since the canal's implementation. The assured availability of surface water has led to a 50% increase in paddy area and an 83.3% rise in wheat cultivation, driven by the adoption of high-yielding varieties. Vegetable farming also expanded by 260% and sugarcane by 150% facilitated by improved irrigation and demand. Fodder crop area increased by 50%, supporting livestock-based mixed farming systems. Conversely, pulses and oilseeds saw a 40% decline each, largely due to market neglect, input limitations, and displacement by more remunerative crops While the project has substantially boosted productivity and economic opportunities, it raises critical concerns regarding sustainability, ecological balance, and nutritional security. The shift toward water-intensive and input-responsive crops, combined with growing climate risks such as erratic rainfall, rising temperatures, and soil degradation, necessitates a more integrated and adaptive approach. To ensure long-term sustainability, the study recommends promoting crop diversification, integrated water and nutrient management, and institutional support for underrepresented crops like pulses and oilseeds.

Keywords: Gandak canal project, development, cropping pattern, climate resilience, irrigation network

**Introduction**

In India, the canal network provides a unique opportunity for renewable energy generation that is yet to be realised. Existing technologies for energy generation on canals include small hydropower on canal falls and, recently, canal-top solar panels. In addition, opportunities for hydrokinetic generation in irrigation canals have received limited attention (Usmani et al., 2021). India hosts one of the largest canal irrigation networks in the world, influencing not only the agrarian economy but also the broader trajectory of rural development. Canal irrigation provides water security to more than 200 million people and has significantly reshaped India's economic geography by inducing substantial agricultural and structural transformations both within and beyond irrigated zones (Asher et al., 2022). India’s canal systems, artificial waterways designed to channel surface water to farmlands, extend over 300000 km and serve approximately 130000 villages, or nearly one-fourth of all rural settlements (CWC, 2022). These networks, though now surpassed by groundwater in overall contribution, remain the second-largest source of irrigation, crucial particularly for drought-prone and water-stressed regions. Canal irrigation has been pivotal in India’s agricultural development, enabling high-yielding varieties (HYVs), multiple cropping, and overall rural water resilience. In India, low water-use efficiency (WUE) and water productivity (WP), and the widening gap between the irrigation potential created (IPC) and the irrigation potential utilised (IPU) are the major concerns in canal irrigation (Amarasinghe et al., 2021). According to the Ministry of Jal Shakti (2023), canal irrigation accounts for 17% of India’s net irrigated area, largely driven by major and medium-scale projects under schemes like the Accelerated Irrigation Benefits Program (AIBP) and Pradhan Mantri Krishi Sinchayee Yojana (PMKSY). The Indian government’s commitment to irrigation is underscored in the Union Budget 2023–24, which allocated Rs 90,000 crore to irrigation and water resources development (Ministry of Finance, 2023).

**Canal Irrigation for Agricultural Transformation and** **Economic Development in Bihar**

The project for interlinking of rivers of India may bring a permanent solution to the negative impacts of drought and water shortages in these parts. The Government of India set up a task force to consider the modalities of implementing river linking projects in India. The objective of the ILR Project is to provide national water security and alleviate poverty with a broad measure of regional and social equity. It envisages storage dams and link canals to transfer water from areas of absolute or seasonal plenty to water-stressed basins for the development of new or augmentation of existing irrigation commands and water supply, and sanitation schemes (Chitra et al., 2016; Baitha et al., 2024). The link between agricultural productivity and irrigation structural transformation is well-established in development economics. Increased productivity in irrigated zones not only raises farm output but also enhances rural incomes and triggers demographic shifts such as population growth around canal-fed regions (Asher et al., 2022). However, this growth is typically localised and does not automatically spill over to non-farm rural sectors, indicating the need for complementary interventions in health, education, and market access. The state of Bihar has undergone significant economic transformation since the mid-2000s, with agriculture playing a surprisingly strong role. 13% of Bihar's net state domestic product (NSDP) growth during 1999–2009 was attributed to agriculture, indicating a revival from its historically poor performance. This revival is closely tied to the development and rehabilitation of canal irrigation systems, particularly in the Gangetic plains and flood-prone districts. Major canal systems such as the Sone Command Area, Western Kosi Canal, and the Gandak Canal have significantly enhanced the state’s irrigation potential. As of 2022, Bihar’s major and medium irrigation schemes covered about 2.8 million hectares, directly benefiting over 60% of its agrarian population (Bihar Department of Water Resources, 2022). In the State Budget 2023–24, Rs. 6,500 crore was earmarked for irrigation projects, with an emphasis on desiltation, canal lining, and command area development (Government of Bihar, 2023). The Gandak Canal Irrigation Project is one of India’s largest inter-state irrigation initiatives, involving Bihar, Uttar Pradesh, and Nepal. Originating from the Gandak River, a transboundary tributary of the Ganga, the project comprises the Eastern and Western Gandak Canal systems and has been operational since the 1960s. In Bihar, the canal commands a total irrigation potential of around 2.14 lakh hectares, primarily covering the districts of West Champaran, East Champaran, Gopalganj, Siwan, Saran, Muzaffarpur, and Vaishali (CWC, 2022). As of 2022, more than 55% of the rural population in the Gandak canal command area relies on agriculture as their primary livelihood source. The availability of assured irrigation has enabled the adoption of HYVs, intensification of cropping (from one to two or even three crops per year), and a shift from rainfed to irrigated agriculture. The 2023–24 Bihar budget allocated Rs. 1250 crore for canal rehabilitation under PMKSY and Atal Bhujal Yojana (Government of Bihar, 2023). Climate change is increasingly influencing water availability in Himalayan-fed river systems such as the Ganges. Studies predict that climate-induced shifts in precipitation and glacial melt will alter river flow regimes, thereby affecting the timing and volume of irrigation water (Hock et al., 2019; Lutz et al., 2014). Effective adaptation strategies, such as climate-resilient cropping systems, farm ponds, and efficient water delivery mechanisms, are critical. Despite their potential, the Gandak canals face chronic challenges including sedimentation, leakage, and management inefficiencies. Digital monitoring tools and participatory water governance are increasingly being promoted to ensure equitable water distribution and sustainable use. The present study aims to critically examine the multifaceted impacts of canal irrigation, particularly the Gandak Canal Project, on rural agrarian systems, focusing on aspects such as crop productivity, cropping pattern shifts, irrigation dependency, and adaptive strategies in the face of climate risks. It explores how canal-based irrigation influences livelihood diversification, gender participation, water management, institutional support, and soil health, while also assessing farmers’ risk perceptions, environmental awareness, and the evolution of agricultural inputs, market linkages, and infrastructure. The study aims to provide comprehensive insights for improving resilience and sustainability in the canal-command agricultural regions of the Gopalganj district of Bihar.

**Materials and Methods**

The present study employed a qualitative field-based research design, focusing on understanding the local perceptions and impacts of the Gandak Canal Irrigation Project in the context of agriculture, climate change, and rural socio-economic transformation in Gopalganj district, Bihar, India. As the investigation was exploratory and aimed at capturing ground-level realities rather than producing statistically generalizable results, a non-probability purposive sampling method was adopted. Primary data was collected during the field visits conducted across multiple villages in Gopalganj district during the agricultural year 2024–25. A total of 360 respondents were engaged through informal group discussions and semi-structured interviews. These respondents included a diverse group of stakeholders comprising farmers, agricultural labourers, Panchayat representatives (Mukhias and Sarpanchas), village-level workers (VLWs), retired teachers, and other locally recognised key informants. Given the rural context, where a majority of residents are directly or indirectly involved in agriculture, this sample was considered representative of the village socio-economic fabric. The research aimed to capture participants’ perceptions of agricultural changes, impacts of the Gandak Canal irrigation system, climate variability, and their cumulative effect on food production, livelihood patterns, and rural socio-economic structures. Special attention was paid to understanding shifts in cropping practices, irrigation dependency, risk perception, and adaptation strategies. Data collection tools included manual note-taking, audio recordings. All recorded information was subsequently transcribed to create a comprehensive dataset, which was systematically analysed using thematic content analysis techniques. This qualitative approach enabled a rich, nuanced understanding of the intersection between irrigation infrastructure, environmental change, and rural development as perceived by the local communities.

**Results and Discussion**

# Table 1: Change in area under major crops in Gopalganj district (before and after the Gandak canal irrigation project)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Crop** | **Area Before Canal Project (in '000 ha)** | **Area After Canal Project (in '000 ha)** | **% Increase/****Decrease** | **Remarks** |
| Paddy (Rice) | 60 | 90 | +50.0% | Increased due to assured water supply; shift to HYV and paddy. |
| Wheat | 30 | 55 | +83.3% | Area expanded with canal irrigation during rabi. |
| Maize | 15 | 20 | +33.3% | Moderate increase due to diversification efforts. |
| Pulses | 25 | 15 | -40.0% | Declined as more land brought under cereals. |
| Oilseeds | 20 | 12 | -40.0% | Reduced due to less priority and input focus. |
| Sugarcane | 10 | 25 | +150.0% | Significant increase, driven by irrigation and industry demand. |
| Vegetables | 5 | 18 | +260.0% | Strong growth due to market access and irrigation. |
| Fodder crops | 8 | 12 | +50.0% | Slight increase, supporting dairy and livestock. |

The data presented in Table 1 reveal a significant transformation in the cropping pattern and land use in Gopalganj district following the implementation of the Gandak Canal Irrigation Project. The assured availability of surface irrigation has led to a marked increase in the area under water-intensive and high-yielding crops. Paddy, a staple crop in the region, registered a 50% increase in cultivated area, supported by the adoption of high-yielding varieties (HYVs). Wheat showed an even greater rise of 83.3%, reflecting improved rabi season irrigation and the district’s shift toward intensified double cropping. Vegetable cultivation experienced the highest expansion, with a 260% increase, primarily due to enhanced irrigation access, market demand, and short cropping cycles. Similarly, sugarcane saw a 150% rise, driven by both water availability and industrial demand from nearby sugar mills. Fodder crops increased by 50%, which supports the intensification of livestock farming, reflecting a gradual shift toward mixed farming systems. On the other hand, the area under pulses and oilseeds declined sharply by 40% each. This reduction may be attributed to the displacement effect, as more remunerative and input-responsive crops replaced traditional legumes and oil crops. Additionally, limited policy incentives, input support, and market infrastructure for pulses and oilseeds further discouraged their cultivation. While the canal project has undoubtedly boosted the region’s agricultural productivity and cropping intensity, it also raises concerns over long-term sustainability, nutritional diversity, and soil health. To address these emerging challenges, integrated nutrient and water management practices, crop diversification strategies, and support for underrepresented crops such as pulses and oilseeds are critical in maintaining a balanced and resilient agri-ecosystem (ICAR, 2022).

**Table 2: Local Perceptions and Impacts of the Gandak Canal Irrigation Project in Gopalganj, Bihar**

|  |  |  |
| --- | --- | --- |
| **Dimension** | **Local Perceptions** | **Observed Impacts** |
| **Crop Productivity** | - Availability of assured surface irrigation has enhanced the viability of cultivating water-intensive crops such as paddy, wheat, and sugarcane.- High-Yielding Varieties (HYVs) have become more viable due to dependable water availability. | - Significant increase in cropping intensity (from 1.7 to 2.3 crops annually).- Reduced incidence of crop failure during drought-prone periods. |
| **Cropping Pattern Shift** | - Transition from traditional coarse cereals to high-value crops, particularly sugarcane and vegetables.- Expansion of fruit cultivation (e.g., banana, litchi) in proximity to canal distributaries. | - Emergence of diversified cropping systems.- Decline in the area under traditional pulses and millets.- Greater market integration of cropping systems. |
| **Irrigation Dependency** | - Strong reliance on canal irrigation, especially for Rabi season cultivation.- Groundwater extraction remains a secondary or contingency option. | - Decreased use of diesel-operated pumps, leading to reduced input costs.- Spatial inequality in irrigation access in tail-end regions often leads to shortages. |
| **Risk Perception** | - Uncertainty due to periodic canal maintenance, siltation, or unannounced closures.- Perceived risk of waterlogging or flooding during high-discharge periods. | - Increased reliance on informal community water-sharing mechanisms during irrigation shortfalls.- Temporary outmigration during canal water stress events. |
| **Adaptation Strategies** | - Shift toward short-duration and climate-resilient crop varieties to cope with variability in irrigation supply.- Adoption of horticulture and floriculture as alternative income sources. | - Implementation of mixed cropping systems and organic mulching techniques.- Use of decentralised water structures such as farm ponds and contour bunding. |
| **Livelihood Diversification** | - Rising inclination among rural youth towards non-agricultural employment due to increased agricultural income stability.- Expansion in allied sectors like dairy, poultry, and aquaculture. | - Enhanced household income from agri-allied activities.- Emergence of rental markets for agricultural machinery and irrigation equipment. |
| **Water Management Practices** | - Continuation of traditional water allocation norms at the community level.- Growing awareness regarding efficient irrigation scheduling and maintenance requirements. | - Adoption of lined distributary canals and temporary field bundling in some locations.- Challenges persist in canal maintenance, particularly siltation and seepage. |
| **Environmental Perception** | - Farmers increasingly recognise signs of climate variability such as delayed monsoons and rising summer temperatures.- Concerns about waterlogging and soil degradation near canal-influenced fields. | - Incremental shift to drought-tolerant and low-input cropping systems.- Community demand for better canal desilting and infrastructural upkeep. |
| **Agricultural Input Usage** | - Need for fertilisers, and pesticides has increased with intensive farming.- Improved access to credit and input dealers due to stable irrigation. | - Higher use of chemical inputs observed.- Enhanced fertiliser efficiency due to timely irrigation. |
| **Crop Yield Stability** | - Farmers perceive higher yield consistency with canal irrigation.- Reduced anxiety about monsoon failure. | - Year-on-year reduction in yield fluctuation for paddy and wheat.- Improved food security at the household level. |
| **Gender Participation in Farming** | - Women’s role in irrigation and allied activities is increasing.- Participation in decision-making related to farming remains limited. | - Women engaged more in vegetable cultivation, dairy, and water management.- Need for targeted irrigation training for women farmers. |
| **Infrastructure Development** | - Roads, markets, and input supply chains have improved near the canal command areas.- Concerns about canal maintenance remain. | - Improved rural connectivity and marketing of perishable goods.- Canal breaches and siltation affect infrastructure efficiency. |
| **Institutional Support and Governance** | - Mixed views on government response in canal management.- Dependency on Panchayat-level coordination. | - Performance varies by distributary; institutional bottlenecks in equitable water delivery remain.- Inadequate extension services. |
| **Soil Health and Quality** | - Concerns over soil fatigue due to continuous intensive cultivation.- Waterlogging has degraded the soil in low-lying fields. | - Signs of reduced organic carbon content.- Emergence of salinity and reduced soil aeration in certain pockets. |
| **Agricultural Marketing and Value Chain** | - Farmers want better pricing mechanisms for increased output.- Need for aggregation points and cold storage. | - Improved output, but often forced to sell at low prices due to gluts.- Rise in middlemen and post-harvest losses where infrastructure is lacking. |
| **Climate Risk Awareness and Mitigation** | - Greater awareness of changing rainfall patterns and heat waves.- Need for crop insurance and risk management tools. | - Adoption of early maturing varieties and insurance schemes.- Farmers demand canal-linked climate advisories. |

Table 2 suggests that the Gandak Canal Irrigation Project has significantly influenced agricultural and socio-economic dimensions in the Gopalganj district. Crop productivity improved, with cropping intensity increasing from 1.7 to 2.3 crops per year and reduced crop failure during dry spells. A clear shift toward high-value crops like sugarcane, vegetables, and fruits has emerged, replacing traditional pulses and millets. Canal irrigation reduced dependence on diesel pumps, cutting input costs, though access remains unequal in tail-end areas. Farmers report risks from canal maintenance issues and waterlogging, leading to water-sharing practices and occasional migration. Adaptation strategies include short-duration crops, horticulture, and decentralised water management. Livelihoods have diversified into dairy, poultry, and aquaculture, improving rural income. Water management awareness is growing, though challenges like siltation persist. Environmental concerns such as delayed monsoons, soil degradation, and salinity are leading to a gradual shift toward low-input, climate-resilient crops. Input usage has increased with intensive farming, but irrigation has improved fertiliser efficiency. Yield stability has improved, especially in paddy and wheat. Women’s participation in allied sectors has increased, though decision-making roles remain limited. Infrastructure and market access have improved near canal zones, but institutional and extension support is uneven. Soil health is under pressure from overuse and waterlogging, while rising climate risk awareness has led to the adoption of early-maturing varieties and crop insurance, with growing demand for canal-linked climate advisory services

**Table 3: Climate Change Impacts and Suggested Measures in Gopalganj District, Bihar**

|  |  |  |
| --- | --- | --- |
| **Climate Factor** | **Observed/Projected Impact** | **Suggestive Measures** |
| Rainfall Variability | Increasing monsoon irregularity, occasional flooding and dry spells. | Promote rainwater harvesting, strengthen flood management, and diversify cropping systems. |
| Temperature Rise | Average temperatures are increasing, especially during rabi, heat stress on wheat. | Adopt heat-tolerant crop varieties and adjust sowing dates. |
| Groundwater Depletion | Over-extraction due to increased irrigation demand post-canal. | Promote micro-irrigation (drip/sprinkler), crop diversification, and groundwater recharge. |
| Soil Degradation | Canal waterlogging in lowlands leads to salinity in some pockets. | Improve drainage infrastructure and encourage salt-tolerant crop varieties. |
| Pest & Disease Incidence | Warmer, wetter conditions promote new pest outbreaks (e.g., fall armyworm). | Enhance pest monitoring, adopt IPM practices, and strengthen agricultural extension services. |
| Livelihood Vulnerability | Smallholders are facing risk due to the changing climate and fluctuating yields. | Promote crop insurance, alternative livelihoods, and training in climate-smart agriculture. |
| Waterlogging and Drainage | Poor drainage in canal command areas leads to crop loss in some kharif seasons. | Construct proper drainage channels and promote ridge-furrow planting in low-lying areas. |

Perusal of Table 3 indicates that Gopalganj district, while benefiting from the Gandak Canal irrigation system, is increasingly facing climate-induced challenges affecting agricultural sustainability. Rainfall variability has led to irregular monsoons and flooding, necessitating rainwater harvesting, flood management, and cropping diversification. Rising temperatures, especially in rabi, cause heat stress in crops like wheat, which can be mitigated by heat-tolerant varieties and sowing time adjustments (ICAR, 2022). Groundwater depletion from excessive irrigation calls for micro-irrigation systems and recharge measures (CGWB, 2021). Canal-induced soil degradation, especially salinity and waterlogging, requires drainage improvements and salt-tolerant crops. Increased pest outbreaks, such as fall armyworm, demand enhanced IPM practices and extension support (FAO, 2020). Smallholder livelihood vulnerability due to yield fluctuations can be addressed through crop insurance, climate-resilient practices, and diversified income sources. Lastly, poor drainage in kharif requires field drainage infrastructure and ridge-furrow planting techniques for water management.

**Conclusion**

The Gandak Canal Irrigation Project exemplifies the multifaceted role of canal irrigation in rural transformation, enhancing agricultural productivity, enabling economic diversification, and ensuring water security, fostering a substantial increase in high-yielding and water-intensive crops like paddy, wheat, sugarcane, and vegetables. However, this shift has come at the cost of traditional crops such as pulses and oilseeds, raising concerns over nutritional security and ecological balance. Concurrently, climate-related challenges—such as rainfall variability, rising temperatures, groundwater stress, and soil degradation—pose additional threats to long-term agricultural sustainability. To safeguard and sustain these irrigation-led gains, an integrated approach is essential, combining efficient water and nutrient management, climate-resilient crop planning, institutional support, and the promotion of diversified and balanced farming systems that address both productivity and resilience. However, for sustained impact, challenges such as ageing infrastructure, water distribution inequity, and climate-related risks must be addressed through integrated water resource management, institutional reforms, and adaptive practices.

**Consent**

As per international standards or university standards, respondents’ written consent has been collected and preserved by the author(s).

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1.

2.

3.

**References**

Alcamo, J., Dronin, N., Endejan, M., Golubev, G., & Kirilenko, A. (2007). A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Global Environmental Change*, 17(3–4), 429–444

Asher, S., Campion, A., Gollin, D., & Novosad, P. (2022). *The long-run development impacts of agricultural productivity gains: Evidence from irrigation canals in india*. London, UK: Centre for Economic Policy Research.

Biswas, D., & Venkatachalam, L. (2015). Farmers' Willingness to Pay for Improved Irrigation Water—A Case Study of Malaprabha Irrigation Project in Karnataka, India. *Water Economics and Policy*, *1*(01), 1450004.

Central Water Commission. (2022). Annual report 2021–22. Ministry of Jal Shakti, Government of India. Retrieved from https://cwc.gov.in

Department of Water Resources, Bihar. (2022). Status of major and medium irrigation projects in Bihar. Government of Bihar. https://wrd.bih.nic.in

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., & Best, N. 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences, 111, 3239–3244.

Eriksson, M., Xu, J., Shrestha, A. B., Vaidya, R. A., Santosh, N., & Sandström, K. (2009). *The changing Himalayas: Impact of climate change on water resources and livelihoods in the greater Himalayas*. International Centre for Integrated Mountain Development.

FAO. (2016). *Water withdrawal by sector, around 2010*. Food and Agriculture Organization of the United Nations. Accessed 23 August 2017, [http://www.fao.org/nr/Water/aquastat/tables/WorldData-Withdrawal\_eng.pdf(open in a new window)](http://www.fao.org/nr/Water/aquastat/tables/WorldData-Withdrawal_eng.pdf)

Fischer, G., Tubiello, F. N., Van Velthuizen, H., & Wiberg, D. A. (2007). Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technological Forecasting and Social Change*, 74(7), 1083–1107. [https://doi.org/10.1016/j.techfore.2006.05.021(open in a new window)](https://doi.org/10.1016/j.techfore.2006.05.021)

Fujita, K. (2014). How agriculture in Bihar lagged behind: Implications for future development. In *Inclusive growth and development in India: Challenges for underdeveloped regions and the underclass* (pp. 40-73). London: Palgrave Macmillan UK.

Government of Bihar. (2023). Bihar Budget 2023–24: Detailed demand for grants—Water resources department. Retrieved from https://finance.bih.nic.in

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, 377(1–2), 80–91. [https://doi.org/10.1016/j.jhydrol.2009.08.003(open in a new window)](https://doi.org/10.1016/j.jhydrol.2009.08.003)

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., & Steltzer, H. 2019. High mountain areas. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer, eds.).

ICAR. (2022). Vision 2050: Sustainable intensification of agriculture. Indian Council of Agricultural Research, New Delhi.

Jiang W L, Yu L S, Liu R H, Han G C, Wang H D (1993) Study on the price upper limit of water resources. China Water Wastewater 2: 58-59 (in Chinese)

Lutz, A., Immerzeel, W., Shrestha, A., & Bierkens, M. (2014). Consistent increase in High Asia’s runoff due to increasing glacier melt and precipitation. *Nature Climate Change*, 4(7), 587. [https://doi.org/10.1038/nclimate2237(open in a new window)](https://doi.org/10.1038/nclimate2237)

Ministry of Finance. (2023). Union Budget 2023–24: Budget at a glance. Government of India. Retrieved from https://www.indiabudget.gov.in

Ministry of Jal Shakti. (2023). Status of irrigation in India: Report of the Standing Committee on Water Resources. Lok Sabha Secretariat. Retrieved from https://jalshakti-dowr.gov.in

Moreno-Pérez, M. F., & Roldán-Cañas, J. (2013). Assessment of irrigation water management in the Genil-Cabra (Córdoba, Spain) irrigation district using irrigation indicators. *Agricultural Water Management*, 120, 98–106. [https://doi.org/10.1016/j.agwat.2012.06.020(open in a new window)](https://doi.org/10.1016/j.agwat.2012.06.020)

Motta R S D, Ortiz R A (2018) Costs and perceptions conditioning willingness to accept payments for ecosystem services in a Brazilian case. Ecol. Econ. 147: 333-342.

Pandey, V. P., Dhaubanjar, S., Bharati, L., & Thapa, B. R. (2019). Hydrological response of Chamelia watershed in Mahakali Basin to climate change. *Science of the Total Environment*, 650, 365–383. [https://doi.org/10.1016/j.scitotenv.2018.09.053(open in a new window)](https://doi.org/10.1016/j.scitotenv.2018.09.053)

Schultz, B., Tardieu, H., & Vidal, A. (2009). Role of water management for global food production and poverty alleviation. *Irrigation and Drainage*, 58.

Tesfaye, K., Zaidi, P., Gbegbelegbe, S., Boeber, C., Stirling, C., Stirling, C., Stirling, C., Stirling, C., & Stirling, C. (2017). Climate change impacts and potential benefits of heat-tolerant maize in South Asia. *Theoretical and Applied Climatology*, 130(3–4), 959–970. [https://doi.org/10.1007/s00704-016-1931-6(open in a new window)](https://doi.org/10.1007/s00704-016-1931-6)

Xian W, Xu Z, Deng X (2014) Agricultural irrigation water price based on full cost recovery: A case study in Ganzhou District of Zhangye Municipality. Journal of Glaciology and Geocryology, 36: 462-468 (in Chinese)

Amarasinghe, U. A., Sikka, A., Mandave, V., Panda, R. K., Gorantiwar, S., & Ambast, S. K. (2021). Improving economic water productivity to enhance resilience in canal irrigation systems: a pilot study of the Sina irrigation system in Maharashtra, India. Water Policy, 23(2), 447-465.

Usmani, S., Siddiqi, A., & Wescoat Jr, J. L. (2021). Energy generation in the canal irrigation network in India: Integrated spatial planning framework on the Upper Ganga Canal corridor. Renewable and Sustainable Energy Reviews, 152, 111692.

Chitra, R., Gupta, M., Noor, S., Singh, A., & Sarma, C. B. (2016). Geotechnical investigations for the Burhi Gandak–None–Baya–Ganga link canal project. International Journal for Research & Development in Technology, 5(2).

Baitha, R., Borah, S., & Sinha, A. (2024). Significance, Threats, Conservation, and Management of Indigenous Small Fish (ISF) of Gandak River (Bihar), India. In Perspectives and Applications of Indigenous Small Fish in India: An Introduction (pp. 385-396). Singapore: Springer Nature Singapore.