**Dynamics of Surface and Groundwater Irrigation Systems across districts of Madhya Pradesh in India: An Economic Analysis**

**ABSTRACT**

Surface and groundwater irrigation systems are essential agricultural water sources that support year-round crop production, ensure food security, and sustain farmers' livelihoods. The present study analyzed the decade wise shift in the surface and groundwater irrigation systems in the major districts of Madhya Pradesh. The top ten districts covering more than one third of the irrigated area in the state was selected for the purpose of study and the data of four major irrigation sources namely Canal, Tank, Well and Borewell were used for a period of 50 years from 1970 to 2019. The structural change in the irrigation scenario was analyzed using Markov Transition Probability Matrix. The trend, growth rate and instability was estimated to understand the dynamics of irrigation pattern. The study revealed that the area under all the four major irrigation sources had increased till the year1997, after that a sudden decline was observed till 2000, and the area under irrigation expanded slowly yet attained a good growth from 2016 to 2019. Among the surface irrigation source, Tanks showed the highest growth percentage of 6.60, annually on an average whereas Borewells showed the highest average growth percentage of 11.20, among the groundwater irrigation sources. Although Borewells and Tanks had the highest growth but they were critically lacking in reliability. Tanks and borewells showed the highest instability index of 20.52 per cent and 18.10 per cent respectively. Wells and canals were the most reliable source of irrigation with the least instability of 9.88 per cent and 10.80 per cent respectively. Transition probability matrix indicated that borewells and wells retained more than 50 per cent of its irrigated area during the study period whereas Canals could retain only 45 per cent of irrigated area in the current decade. Tanks fully transitioned to canals in the current two decades. Sources other than canals, wells, tanks and borewells transitioned to well and lost 31 per cent to borewells in the current decade. The administration must keep a check to avoid over exploitation of groundwater. At the same time the conditions of canals and wells should be improved to make it even more reliable and efficient for irrigation use.

**Keywords:** *Growth, Instability, Irrigation pattern, Markov Transition Probability Matrix,* *Structural change, Trend.*

1. **INTRODUCTION**

Structural change in irrigation refers to the long term changes in the kind and scope of irrigation, such as a reduction in surface water systems and an increase in groundwater extraction. These changes affect the irrigated area and the cropping patterns that are supported by these systems (Madhurima *et al.,* 2022). It refers to the profound shift in the key components of a system. In terms of water resource management, Structural change refers to switching from one primary irrigation source or technique to another, thereby transforming the technical, social and environmental aspect of the water use system.

Globally, irrigation is vital to agricultural productivity, with surface and groundwater as the primary water sources. Of the approximately 324 million hectares irrigated worldwide, groundwater contributes over 40% due to the increasing use of tube wells and pumps in regions like South Asia and North China (FAO, 2021; Siebert et al., 2010). However, this has led to over-extraction and aquifer depletion in many areas (Shah, 2009). Surface irrigation, once dominant, now faces issues such as water loss through evaporation and poor maintenance.

India has the world’s largest net irrigated area, over 70 million hectares (Ministry of Agriculture & Farmers Welfare, 2022). Groundwater dominates irrigation, accounting for about 64% of irrigated land, while surface sources contribute 36% (CGWB, 2020). This shift began post-Green Revolution, driven by the need for reliable irrigation. While beneficial for productivity, unregulated groundwater use has caused serious depletion, especially in northwestern states (Rodell et al., 2009). Government initiatives like Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and Atal Bhujal Yojana aim to promote water use efficiency and sustainable practices (NITI Aayog, 2019). A balanced approach using both groundwater and surface sources, supported by efficient irrigation technologies and policy reforms, is essential for long-term sustainability.

It is imperative to study the current scenario of surface and ground water as it directly impacts the hydrological cycle, farming and livelihood of majority of the population in the world. The economic developments around the globe, climate change and rising population possess a major challenge to the environment. Irrigation consumes 70 per cent of the global freshwater withdrawals, making it momentous to study its use and management (Akhtar & Rampurawala, 2024). When the groundwater is tapped excessively, irrigation practices often shift towards unsustainable use. Studying the dynamics of irrigation water helps to detect and prevent depletion crises. Devi and Nair (2018) in their study, found that, despite abundant rainfall, the groundwater reserves declined in Assam, India, underlining the importance of analysing the groundwater withdrawals. Rural livelihoods, farmers’ income and crop choices are affected by the irrigation decisions. Proper understanding of current irrigation scenarios is crucial for reducing poverty and equitable water distribution. According to Shah (2009), private groundwater irrigation increased the profit of some farmers in South Asia, but also increased the economic disparity for those without its access. Crop yields could be stabilized and food security can be ensured through modern irrigation. However, wastage of water may happen due to poor irrigation planning, threatening future planning etc. Ozdemir (2010) in a study linked the irrigation techniques to sustainable agricultural output by using remote sensing to monitor changes in surface water and groundwater in Turkish river basins. It is essential to analyze the irrigation scenario in order to provide food security, safeguard farmer livelihoods, adapt to climate change and manage resources sustainably. Considering the importance, a study was undertaken with the objectives to analyze the irrigation pattern, trend, growth and instability of surface and ground water sources in the major districts of Madhya Pradesh.

**2. METHODOLOGY**

**2.1. Study Period**: The study has been conducted for a period of 50 years from 1970 to 2019.

**2.2. Selection of Study Area:** The top 10 districts (namely Hoshangabad, Morena, Dhar, Khargone, Ujjain, Sehore, Mandsaur, Shivpuri, Tikamgarh and Vidisha) covering 35 per cent (one-third) of irrigated area in Madhya Pradesh has been purposively selected for the study.

**2.3. Selection of Data**: The study is purely based on secondary data of Irrigated area under surface irrigation sources (Canals and Tanks) and groundwater sources (Wells and Borewells). The data from the year 1970-1997 has been taken from the website of Commissioner of Land Records, Madhya Pradesh (2022) and the data for the years 1998-2019 has been taken from the official website of Ministry of Agriculture and Farmers Welfare (2023).

**2.4. Study Objective**: The study was conducted to achieve the following objectives

1. To analyze the irrigation pattern of surface and ground water sources in major districts of Madhya Pradesh
2. To determine the trend of irrigated area under surface and groundwater sources in major districts of Madhya Pradesh
3. To evaluate the growth and instability of irrigated area under surface and groundwater sources in major districts of Madhya Pradesh

**2.5. Analytical Tools and methods:**

**2.5.1. Absolute change (AC)**

The Absolute change is defined as the difference between the initial irrigated area and final irrigated area over a period of time (Vani et al., 2023). It has a unit same as that of irrigated area.

**Absolute change =**

Where,

= Average of the irrigated area in current three years (Triennium Ending (TE) 2019) of the study period (Current year)

= Average of the irrigated area in initial three years (TE 1970) of the study period (Base year).

The absolute change has been worked out to find the difference in irrigated area under various irrigation sources from the initial base year period (TE 1970) to final current year period (TE 2019).

**2.5.2 Relative change (RC)**

Relative change is a representation of Absolute change in terms of percentage which gives a broader perspective of interpretation and comparison for the researcher. It is represented as a percentage change in the current year with respect to the base year (Vani *et al.,* 2023).

Relative change in area under irrigation was estimated by using the following formula-

**Relative change = × 100**

= Average of the irrigated area in current three years (TE 2019) of the study period (Current year)

= Average of the irrigated area in initial three years (TE 1970) of the study period (Base year)

Relative change has been computed in order to find the difference in irrigated area under various sources of irrigation from initial base year period (TE 1970) to current year period (TE 2019) in terms of percentage which provides a better perspective of comparison between the two periods.

**2.5.3. Trend analysis**

The long-term pattern of increase or decrease in the irrigated area over time is termed as trend. It shows the fashion of change in pattern of any variable (irrigated area under various sources of irrigation) in a long-term time series data. The direction of change in a time series data is represented geometrically by a trend line. It usually takes the form of a linear equation called a ‘Trend equation’ which consists of a slope, an independent variable and an intercept. (Singh *et al*, 2025)

For the purpose of the study,

Trend of irrigated area have been worked out using linear trend equation (Sananse *et al*, 2009)

**Linear equation:**

Where,

Y=Dependent variable (Area under Irrigation Sources)

a = Constant

b = Regression coefficient (Slope or Rate of change)

T = Time (years)

**2.5.4. Growth rates**

**2.5.4.1. Simple Growth Rate (SGR)**

The simple growth rate calculates the average yearly increase in irrigated area (from the trend line), relative to the average area over the study period. When the growth is linear in order, the linear trend curve is preferred. Following formula is used to calculate the simple growth rate for area under irrigation. (Sananse *et al*, 2009, Singh *et al*, 2025)

**SGR = × 100**

Where,

b = Regression coefficient (Slope or Rate of change)

Y= Mean of dependent variable (Area under sources of irrigation)

**2.5.4.2. Average Annual Growth Rate (AAGR)**

The average yearly percentage increase or decrease in irrigated area by various sources of irrigation smoothened through year-to-year fluctuations is represented by AAGR. This method provides a consistent result which is more robust to outliers (Vani et al., 2023), (Singh et al., 2025).

**AAGR =**

Where,

Yt represents the area under particular source of irrigation in the current year

Y (t+1) represents the area under particular source of irrigation in the succeeding year

T represents the total number of years

‘ln’ represents natural log to the base 10

**2.5.5. Instability:** Instability is termed asthe year-on-year fluctuations in the extent of irrigated area, often caused due to variable input, climatological changes, political changes, changes in water supply. The method is proposed by Ray (1983b) and applied by Ray (1983a), (Anjum *et al*, 2018). This method of finding instability was used by (Chand and Raju, 2008) and (Singh *et al,* 2025).

**Instability =**

Where,

denotes the irrigated area in a particular year

denotes the irrigated area in the succeeding year

‘ln’ denotes natural log to the base 10

t denotes total number of years within particular period (decade)

‘Var’ denotes variance

**3.RESULT AND DISCUSSION**

Table 1 shows that Hoshangabad district covers the largest irrigated area with 4.68 per cent followed by Morena and Dhar with 3.86 per cent and 3.64 per cent respectively. Overall, the top 10 districts covered 35 per cent of total irrigated area which is more than one third of the total irrigated area of the state.

Table 1: Top 10 districts having largest irrigated area in Madhya Pradesh

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **S.N** | **District** | **Irrigated Area (ha)** | **Share of Irrigate area (%)** | **Cumulative share of irrigated area (%)** |
| 1 | **HOSHANGABAD** | 11609680 | 4.68 | 4.68 |
| 2 | **MORENA** | 9564610 | 3.86 | 8.54 |
| 3 | **DHAR** | 9030873 | 3.64 | 12.19 |
| 4 | **KHARGONE** | 8922592 | 3.60 | 15.79 |
| 5 | **UJJAIN** | 8805397 | 3.55 | 19.34 |
| 6 | **SEHORE** | 8049355 | 3.25 | 22.59 |
| 7 | **MANDSAUR** | 7960874 | 3.21 | 25.80 |
| 8 | **SHIVPURI** | 7906556 | 3.19 | 28.99 |
| 9 | **TIKAMGARH** | 7894186 | 3.19 | 32.18 |
| 10 | **VIDISHA** | 7835066 | 3.16 | 35.34 |
|  | **Sub Total** | 87579189 | 35.33 |  |
|  | Grand Total | 247818471 | 100 | - |

Table 2 revealed that borewells had the highest relative change of 16635.24 per cent in the irrigated area in the current year (TE2019) compared to the base year (TE 1970). The surface water sources (canals and tanks) had a good growth of more than 500 per cent during the study period whereas wells grew by 338 per cent from the base year.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Source of Irrigation** | **Current Year**  **(TE 2019) (ha)** | **Base Year**  **(TE 1970)**  **(ha)** | **Absolute Change**  **(ha)** | **Relative Change (%)** |
| Canal | 751330.66 | 115640 | 635690.67 | 549.72 |
| Tanks | 121394.66 | 18200.33 | 103194.33 | 566.99 |
| Wells | 1217159.33 | 277402.33 | 939757.00 | 338.77 |
| Borewells | 1537299.33 | 9186 | 1528113.33 | 16635.24 |

Table 2: Irrigation pattern of surface irrigation sources (Canals and Tanks) and groundwater irrigation sources (Wells and Borewells) in major districts of Madhya Pradesh.

(Unit in hectares)

Table 3 represents that the irrigated area under groundwater sources (borewells and wells) were increasing at a higher rate compared to surface resources when assumed a linear growth during the study period. Borewells and Wells increased at 28080 ha/year and 18134 ha/year on an average respectively whereas irrigated area under Canal and tanks grew at the rate of 10526 ha/year and 1830 ha/year only. The surface water resources had a lower increase in the irrigated area compared to those of groundwater sources.

Table 3: Value of slope (linear rate of change) of various sources of irrigation in major districts of Madhya Pradesh

|  |  |
| --- | --- |
| **Source of Irrigation** | **b-value (ha/year)** |
| Canal | 10526 |
| Tanks | 1830 |
| Wells | 18134 |
| Borewells | 28080 |

Figure 1 shows an increasing trend in both the irrigated area under surface water and groundwater resources in major districts of Madhya Pradesh. The irrigated area in all the resources grew strictly from 1970 to 1994. It took a sudden fall around the year 2000, after which the irrigated area was found to increase till 2019. This severe fall in irrigated area may be because of consecutive droughts in the year 1999 and 2000 which reduced the surface water availability causing many canals, tanks and reservoirs to operate below capacity. There was a severe fall in irrigation potential during this period as a result of drought (Planning Commission, 2002). During this period, the Comptroller and Auditor General (CAG) of India noticed the delays and cost overruns in canal infrastructure in MP (CAG, 2001). Nash (2002) stated that, in the late 1990s, El Nino caused widespread drought across the central India, including the state of Madhya Pradesh, reducing surface water flows and irrigation. In the mid-1999, the siltation, mismanagement and chronic underuse of canal systems lead to an unreliable water delivery during that period (FAO, 2010). The low agricultural prices and poor returns in the late 1990s compelled many farmers to revert to rainfed cultivation since they could not afford to invest in irrigation infrastructures including diesel pumps. Area under borewells had a steeper slope towards the current year representing a faster rate of growth in present times.

Figure 1: Trend of irrigated area under surface irrigation resources (Canals and Tanks) and underground irrigation resources (Wells and Borewells).

Table 4 depicts that borewells had the highest growth rate of 6.93 per cent, growing at the highest average rate of 11.20 per cent per year. But simultaneously, another ground water resource, wells, grew at the lowest rate of 2.46 per cent (SGR) and growing at the rate of only 3.37 per cent per year. In the surface irrigation sources, Canals had the lowest growth in area with just 2.88 per cent, growing at a lower rate of 4.37 per cent per year on an average. Tanks grew at 4.02 per cent and growing at a moderate rate of 6.60 per cent per year during the study period. Tubachi (2024) in a study showed similar findings by concluding that tubewells demonstrated the highest growth rate with an increase of 14.62 per cent, in contrast the net irrigated area under canals reduced by 6.88 per cent in Karnataka. Narayanmoorthy (2022) in a study in Andhra Pradesh state, also concluded that frequency of groundwater irrigation increased from less than 6 million hectares in 1950-51 to about 44 million hectares in 2017-18. Groundwater has become a major source of irrigation in the past few decades in Southern peninsular India (Sharma et al, 2021). A decline in canal irrigation with a rise in borewell irrigation was reported by Narayanmoorthy (2022) in his study done across different states of India, which shows that in post 1980s, share of tank and canal irrigation had declined while those of borewells and tubewells had increased.

Table 4: Growth in the area under surface and groundwater irrigation sources in major districts of Madhya Pradesh.

|  |  |  |
| --- | --- | --- |
| **Source of Irrigation** | **SGR (%)** | **AAGR (%)** |
| Canal | 2.88 | 4.37 |
| Tanks | 4.02 | 6.60 |
| Wells | 2.46 | 3.37 |
| Borewells | 6.93 | 11.20 |

Table 5 shows that irrigated area under Tanks and Borewells were found to be highly unstable with 20.52 per cent and 18.10 percent respectively in the major irrigated districts of Madhya Pradesh during the study period. Canal and wells were found to be more reliable source of irrigation as they are more stable with an instability of 10.8 per cent and 9.88 per cent respectively. While conducting study on tanks in India, (Palanisami, 2006) reported similar findings that tanks worked only in normal or excess rainfall years hence many farmers abandoned the usage of tanks for irrigation in farming. Tanks got normal supply of three years, deficit supply for five years and failed completely during two years out of a ten years period in Southern states of India. Also in a study, Naryanmoorthy (2022) pointed out that instability of borewell irrigation had increased as a result of over exploitation of groundwater in India. (Biswas & Panda, 2024) also indicated the irregularity and greater volatility in tank water availability compared to canals and wells while studying trends in different sources of irrigation in India.

Table 5: Instability in the irrigated area under various irrigation sources in major districts of Madhya Pradesh

|  |  |
| --- | --- |
| **Source of Irrigation** | **Instability (%)** |
| Canal | 10.8 |
| Tanks | 20.52 |
| Wells | 9.88 |
| Borewells | 18.1 |

Table 6 and Figure 2 shows that the area irrigated under canals increased from 44 per cent to 86 per cent in the third decade. In the last decade, canals retained only 45 per cent of area under it while losing 26 per cent of irrigated area to wells. Similar findings were found by Kumar (2018) which mentioned the rapid growth in private wells in India in the last three decades due to heavy institutional financing for wells and pumps, better electrical subsidies and massive rural electrification. (Andrade *et al.,* 2017) in a study in Northern India reported that inefficient delivery and seepage losses in canal networks pushed the farmers to depend on wells and tubewells promoting a transition towards wells and borewells from canal irrigation. Borewells retained more than 60 per cent of its irrigated area throughout the study period showing its complete dominance. In the last decade it retained 89 per cent of its irrigated area. Similar study in Rajasthan, India, it was found that electrically operated tubewells offered a resilient source of irrigation in arid area especially during droughts (Kumar *et al.,* 2022). Sharma *et al* (2021) in their study pointed out that groundwater irrigation i.e. Borewells had turned out to be the major source of irrigation in the past few decades. Dutta (2018) in a study indicated that despite availability of canals and rivers, farmers preferred borewells due to greater control and showed declining trust in collective systems. The lift and surface irrigation were replaced all across the region in Barddhaman district of West Bengal. Besides this increasing usage of ground water through borewells, precautions should be taken to check the over exploitation of groundwater. A study conducted in Jaipur district of Rajasthan revealed the problem of salinity and alkalinity in soil due to long term usage of groundwater making it unsuitable for irrigation (Sharma *et al.,* 2023).

Table 6: Probability of transition of irrigated area from canals and borewells to various other sources in top ten districts of Madhya Pradesh.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Canal** | | | | | **Borewell** | | | | |
| **Irrigation source** | **Decade 1** | **Decade 2** | **Decade 3** | **Decade 4** | **Decade 5** | **Decade 1** | **Decade 2** | **Decade 3** | **Decade 4** | **Decade 5** |
| Canal | 44 | 72 | 86 | 0 | 45 | 0 | 0 | 0 | 14 | 7 |
| Borewell | 2 | 2 | 0 | 0 | 7 | 90 | 100 | 69 | 75 | 89 |
| Well | 37 | 0 | 14 | 63 | 26 | 0 | 0 | 0 | 5 | 0 |
| Tank | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 5 | 0 |
| Others | 17 | 26 | 0 | 37 | 11 | 10 | 0 | 30 | 1 | 4 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

Figure 2: Probability of transition of irrigated area from Wells and Tanks to various other sources in top ten districts of Madhya Pradesh.

Table 7 and figure 3 shows that wells retained more than half of its irrigated area throughout the study period. This shows the constant popularity among farmers for the usage of wells for irrigation. Similar study by Kuriachen *et al* (2021) concluded that the shift towards well irrigation continues as the shares of canals and tanks declined, which indicated that wells retained and even expanded the irrigated areas. Another study conducted in Tamil Nadu by (Alexendar *et al.,* 2021) revealed that Wells, especially shallow ones were the most important source of irrigation for small and marginal farmers hence it was popular among the majority of rural farmers’ population, this shows wells continued significance despite challenges. In the last decade, wells lost 23 per cent of its irrigated area to other sources while 14 per cent to canals.

The irrigated area under tanks completely transitioned to wells and other sources in the Decade 2 and Decade 3. In the last two decades, area under tanks completely transitioned to canals. This shows that although canals lost more than half of its irrigated area in the current decade, but it took the area covered by tanks in the current two decades. Similar study by Narayanmoorthy (2021) showed that as tank irrigation fell sharply in Andra Pradesh, it was replaced by groundwater and canal irrigation.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Well | | | | | Tank | | | | |
| **Irrigation source** | **Decade 1** | **Decade 2** | **Decade 3** | **Decade 4** | **Decade 5** | **Decade 1** | **Decade 2** | **Decade 3** | **Decade 4** | **Decade 5** |
| **Canal** | 22 | 9 | 5 | 27 | 14 | 0 | 0 | 0 | 100 | 100 |
| **Borewell** | 0 | 0 | 5 | 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Well** | 78 | 84 | 79 | 56 | 63 | 12 | 100 | 0 | 0 | 0 |
| **Tank** | 0 | 5 | 3 | 2 | 0 | 88 | 0 | 0 | 0 | 0 |
| **Others** | 0 | 2 | 9 | 2 | 23 | 0 | 0 | 100 | 0 | 0 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

Table 7: Probability of transition of irrigated area from Wells and tanks to another source in top 10 districts of Madhya Pradesh.

Figure 3: Probability of transition of irrigated area from Wells and Tanks to another source in top 10 districts of Madhya Pradesh

Table 8 and figure 4 shows that area under sources other than canal, borewell, well and tank lost almost half of its area to wells in each decade during the study period. It lost 36 per cent of its area in the third decade and 31 per cent of its area to borewells in the current decade. Around 8 per cent of irrigated area under other sources transitioned to wells in the current decade. Similar findings were noted by Biswas & Panda (2024) which concluded that well irrigation had become dominant form, slowly replacing smaller irrigation systems including lift irrigation and temporary structures.

Table 8: Probability of transition of irrigated area from other sources to various other sources in top ten districts of Madhya Pradesh

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Others** | | | | |
| **Irrigation source** | **Decade 1** | **Decade 2** | **Decade 3** | **Decade 4** | **Decade 5** |
| Canal | 21 | 35 | 0 | 0 | 7 |
| Borewell | 0 | 1 | 36 | 9 | 31 |
| Well | 57 | 64 | 55 | 48 | 54 |
| Tank | 3 | 0 | 7 | 0 | 8 |
| Others | 18 | 0 | 2 | 43 | 0 |
| Total | 100 | 100 | 100 | 100 | 100 |

Figure 4: Probability of transition of irrigated area from other sources to various other sources in top ten districts of Madhya Pradesh.

1. **CONCLUSION**

The study analyzed the irrigation pattern, trend, growth and instability of surface and groundwater sources in major districts of Madhya Pradesh. It was found out that Surface irrigation sources (canal and tanks) and underground sources (borewells and wells) had a positive and increasing trend. Assuming a linear development over the research period, the irrigated area under subterranean sources (wells and borewells) grew faster than the surface sources. Borewells grew at a highest average rate of 11.20 per cent annually. However, at the same time, wells, another subterranean irrigation source, expanded at the slower rate of 2.46 per cent (SGR) and 3.37 per cent annually. Canals had the slowest expansion in irrigated area with 2.88 per cent (SGR) and 4.37 percent annually. The area under tanks grew moderately at an annual growth rate of 6.60 per cent. Although Borewells and Tanks had the highest growth, but their high instability revealed that they are less reliable compared to canal and wells. The lower instability of Canals and wells shows the higher reliability of farmers on the traditional sources of irrigation. The farmers are moving towards the underground sources specially borewells for irrigation, but the high cost of setting up, depleting underground water table and lack of awareness about the usage of borewells made it more unstable. The results of transition matrix showed that borewells and wells retained more than 50 per cent of their irrigated area during the study period. Irrigated area under tanks transitioned to canals in the current two decades. Canals started retaining its area in the initial three decades but lost 25 per cent of its area to wells in the last decade. The sources other than canals, borewells, wells and tanks lost almost half of its irrigated area to wells. This shows the popularity of well usage as a source of irrigation among farmers.

**POLICY RECOMMENDATIONS**

The irrigated area took a sudden dip during the 1999 and 2000 which caused a heavy destruction of crops and ultimately adversely affected the lifestyle of farmers. To prevent such losses, early warning systems and digital monitoring like remote sensing and GIS tools should be implemented for real-time tracking of shift in irrigated area and groundwater levels. Incentives should be provided for using multiple irrigation sources like combining wells and canals to reduce risk from source failure. The frequency of groundwater irrigation had increased in last few decades, the borewell drilling should be regulated by the use of permits and groundwater zoning. Micro-irrigation such as drip and sprinkler should be promoted. Usage of reliable sources like canals should be promoted. Investment should be done in lining of canals and de-silting of tanks to improve efficiency of water delivery and reduce losses. The study revealed a shift from reliable sources (canals and wells) to unstable but high growth sources (borewells and tanks). A balanced policy mix, improving surface irrigation, regulating groundwater and promoting integrated water management is critical for long term irrigation sustainability in Madhya Pradesh.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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