Assessment and Mitigation of Groundwater Pollution in Sikar City: A Comprehensive Review

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Abstract

Water pollution is a pressing global environmental issue with far-reaching consequences for the environment, public health, and economic development. Assessing and mitigating water pollution are critical for safeguarding environmental and public health. It involves identifying pollution sources, measuring impacts on health and the environment, and implementing reduction strategies. Sikar is one of the cities of Rajasthan facing a severe water pollution crisis, with significant contamination affecting surface and groundwater, highlighting the urgent need for sustainable water management practices. Additionally, Sikar is experiencing increasing groundwater levels due to excessive irrigation, inefficient water use, and limited recharge. This trend exacerbates water quality issues and poses risks to infrastructure and agriculture. This paper assesses the impact of current water pollution levels by measuring key water quality indicators (pH, BOD, COD, etc.) of Sikar City and comparing the indicators to national and international standards. It also addresses the issue of increasing groundwater levels due to factors such as excessive irrigation, inefficient water use, and limited recharge. The study then proposes mitigation strategies by reviewing relevant or similar case studies and research papers on water pollution in Sikar and similar regions.

1. Introduction

One of the significant global environmental concerns is water pollution, which affects ecosystems and human health at all levels worldwide. According to [17], this continues to be a significant issue. The main reasons are agricultural runoff, industrial discharges, and untreated sewage that lower water quality. It has the most severe impact on human beings who suffer from millions of waterborne diseases annually especially those in developing nations. In addition, pollution leads to the loss of biodiversity and the destruction of habitats. India’s fast urbanization, industrialization, and agriculture result in severe water pollution. According to the provisions of [3], water quality standards shall be regulated through the [4]. Despite that, scores of people suffer from various diseases caused by water pollution: dying because of waterborne diseases, contamination of drinking water sources, and depletion of aquatic resources. High levels of industrial effluents, agricultural runoff, untreated sewage, and plastic wastes disrupt civic life and compromise public health.

Nine case studies comprising research papers and government reports were studied, with situations similar to those in the current study area. These case studies detailed a step-by-step methodology and some of the many available strategies to investigate water pollution. The methodology of these case studies consisted of forming a core research team and stakeholder committee [7], followed by site selection and initial reconnaissance to obtain preliminary data [11]. The process of data collection involved detailing a sampling plan, field surveys using piezometers and water quality testing kits, and remote sensing and GIS for spatial data visualization [5][6][9][13]. The physio-chemical characterization of these water samples was done by advanced techniques, which included ion chromatography and atomic absorption spectroscopy [6] The data analysis in these papers is justified by employing quality assurance and control procedures, software like MODFLOW [6] which is used to[13]. simulate groundwater flow, and statistical analyses like PCA and HCA [13]. Health risk assessments were carried out for some pollutants like nitrates. GIS helps in mapping and visualization, essential for making detailed maps of contamination spots and areas of pollution impact [8]. There are proposals and strategies for solving water pollution in these research papers; they involve pilot projects testing effective management practices for water [5] policy recommendations [9]and economic valuation of impacts from pollution [10]. Focus group discussions [7], stakeholder consultancies [5]semi structured interviews [6] and public engagements [7], have been emphasized. It creates a documented and reported workflow whereby methodologies, findings, and recommendations are adequately captured and shared. These case studies present inclusive information regarding water pollution: sources, effects, and mitigation measures being practiced or that can take effect. The paper identifies significant contributors to water pollution due to industrial discharges, agricultural activities, untreated sewage, and community wastes. It uses data from different regions to project the severity of the situation. These parameters included groundwater levels and water-quality parameters like pH, Total Dissolved Solids, Electrical Conductivity, Total Hardness, Total Alkalinity, Dissolved Oxygen, Residual Sodium Carbonate, Sodium Absorption Ratio, Percentage Sodium, Permeability Index, Calcium Absorption Index, Sodium, Potassium, Calcium, Magnesium, and Chloride. These parameters are essential for the perception of water quality for drinking, agricultural, and industrial uses. Hence, this study endeavors to answer the following questions:

- How severe is the water pollution in Sikar City, and what are the specific contaminants of concern?
- What are the impacts of water pollution on the local ecosystem in Sikar City?
- What technological interventions and management practices can be implemented or proposed to mitigate water pollution in Sikar City?

2. Methodology

The methodology for addressing water pollution in Sikar City involves a structured approach encompassing data collection, analysis, and planning. Water levels and quality data are gathered from sources such as WRIS and WDO, and parameters like pH, TDS, DO, BOD, and various ions are assessed against WHO and CPCB standards. A literature review identifies similar case studies and effective mitigation strategies. The Analytic Hierarchy Process (AHP) is used to select criteria, perform pairwise comparisons, and rank techniques based on weight calculations. The analysis highlights critical issues, leading to the development of an implementation plan that includes top-ranked solutions, stakeholder engagement, community awareness initiatives, policy recommendations, and future sustainable water quality management measures.

3. Study Area Introduction

Sikar Municipal Council is a city and the district headquarters of Sikar District in the eastern part of Rajasthan in India, located at 27.62° N 75.15° East. It forms the largest part of the Shekhawati area of Sikar, Churu, and Jhunjhunu. Sikar is midway between Agra and Churu on the National Highway 52 in Rajasthan, India. It serves as the administrative headquarters of the Sikar district. Sikar is a historical city with many old Havelis and large houses in Mughal-era architecture. The place is located 114 km away from Jaipur, 320 km from Jodhpur, 215 km from Bikaner, and 280 km from Delhi. Sikar is facing a severe water pollution crisis. In the case of groundwaters, the extent of contamination is high in this city. Moreover, the pollution has led to the degradation of the local ecosystem in this area and has turned out to be a threat to aquatic life and biodiversity. The ground water conditions in Sikar have been considerably at alarming levels between 2013 and 2018; it is more so in the southwestern region. This depletion has a legacy effect on the city's water-scarcity problems and emphasizes the need for sustainable water management practices. There is an urgent need, on a full scale, for intervention regarding water pollution in Sikar district so that quality can be restored, public health safeguarded, and water resources sustained for overall growth.

4. Data Collection & Analysis

4.1. Groundwater Level

Sikar, a city primarily devoid of water bodies, heavily relies on groundwater for various activities. The water level data has been collected from various stations spread across the city, and the fluctuations in water level are occurring at an alarming level. The map shows the monitoring stations for groundwater levels in Sikar City. All of them are equidistance-based to cover the central and peripheral areas. Station 1 is northeast, Station 2 is southeast of it, Station 3 is east, Stations 4 and 5 are west, Stations 6 and 7 are central, Station 8 is in the south, and Station 9 is in the southwest. It will, therefore, ensure complete coverage of the urban and suburban sectors for monitoring purposes.

The ground water level of each station across the city from 2011 to 2018 has been collected from (WDO). The table is given below:

Table 1
Table shows Groundwater Level at various stations (2011–2018)

(Source: WDO)

Station	**Level (m)**							
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
RJGW_7238	61.3	62.99	65.2	67.68	70.83	73.35	75.62	78.76
RJGW_7242	-	-	82.35	84.67	85.27	86.08	88.85	90.42
RJGW_7357	60.32	58.27	58.33	58.75	58.3	60.1	60.1	60.1
RJGW_7364	55.22	57.58	60.52	60.9	61.11	64.27	65.9	67.68
RJGW_7365	73.86	75.25	75.25	79.8	85.5	83.42	85.57	85.57
RJGW_7373	61.25	62.92	65.04	65.36	66.78	69.25	71.1	72.27
RJGW_7375	55.4	56.44	57.14	57.95	60.1	58.69	59.22	59.54
RJGW_7387	-	-	75.98	78.51	80.08	81.75	83.18	85.64
RJGW_7388	-	-	60.8	77.52	79.2	80.54	79.25	75.89

Maps have been prepared to show spatially how the groundwater level has changed over the years. From 2011 to 2018, three maps were made with a gap of three years, and the groundwater level has been shown. The groundwater levels at the five monitoring stations exhibit a general trend of increasing depth over the period from 2011 to 2018. RJGW_7238 and RJGW_7373 show a consistent rise from 61.3 m and 61.25 m to 78.76 m and 72.27 m, respectively, indicating significant groundwater depletion. RJGW_7242 and RJGW_7387, with available data from 2013 onwards, also show increasing depths, suggesting a similar depletion trend. RJGW_7364 displays a steady increase from 55.22 m to 67.68 m, while RJGW_7365 rises sharply from 73.86 m to a peak of 85.57 m by 2017. RJGW_7357 shows a relatively stable depth of around 60.1 m after some fluctuations, while RJGW_7375 fluctuates slightly but generally increases from 55.4 m to 59.54 m. RJGW_7388 has the most variability, peaking at 80.54 m in 2016 before slightly declining to 75.89 m in 2018. Overall, the data reflects a notable increase in groundwater depth across most stations, indicating a trend of declining groundwater levels.

4.2 Groundwater Quality

Groundwater pollution in Sikar has reached alarming levels, particularly in the southwestern region, between 2013 and 2018. The contamination is primarily due to the infiltration of untreated sewage, industrial discharges, and domestic waste. This pollution has significantly degraded water quality, making it unsafe for consumption and other uses. The depletion of clean groundwater exacerbates the city's water scarcity issues, highlighting the urgent need for sustainable water management practices to safeguard public health and ensure the availability of clean water.

From the (WRIS portal), data on the water quality of Sikar city has been obtained for the past 14 years for the five water quality monitoring stations located across different parts of the city. The stations have data for various parameters such as Hydrogen (pH), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Total Hardness (TH), Total Acidity (TA), Dissolved Oxygen (DO), and sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{+2}), magnesium (Mg^{+2}), chloride (Cl^{-}), sulphate ($SO4^{-2}$), bicarbonate (HCO^{3-}), carbonate (CO^{3-2}), fluoride (F^{-}), nitrate (NO^{3-}) using American Public Health Association methods.

Table 2- Groundwater Quality (Sabalpura Station) (Source: WRIS portal)

Sabalpura

Parameters	TA (mg/L)	Ca (mg/L)	Cl (mg/L)	CO3 (mg/L)	EC (µS/cm) at 25°C)	F (mg/L)	Fe (mg/L)	TH (mg/L)	HCO3 (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	pH	RSC	SAR
2010	218	29	126	0	840	0.42	0.2	130	266	3.6	13.984	205	8.29	1.76	7.82
2011	159.8	52	163	0	910	0.23	0.06	160	195	1	7	140	7.75	0.02	4.83
2012	209.8	24	121	0	790	0.41	0.2	110	256	1.6	12.19	20	7.62	1.99	0.83
2014	249.51	40	85	12	780	0.2	0.01	220	280	1	29	92	8.42	0.61	2.7
2018	140.16	8	120	0	910	1.1	0.4	220	171	2	48.64	125	8.25	0	3.67
2021	Nil	68	475	0	2050	0.3	Nil	280	207	4.84	26.752	350	7.38	Nil	Nil
Standards	200(WHO)	100(WHO)	250(WHO)	-	1400(WHO)	1.5(WHO)	0.3(WHO)	500(WHO)	150(WHO)	10(WHO)	200(ICMR)	200(WHO)	6.5 - 8.5(WHO)	1.25	9

Table 3- Groundwater Quality (Nani Station)(Source: WRIS portal)

Nani

Year	TA (mg/L)	Ca (mg/L)	Cl (mg/L)	CO3 (mg/L)	EC (µS/cm) at 25°C)	F (mg/L)	Fe (mg/L)	TH (mg/L)	HCO3 (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	pH	RSC	SAR
2011	290.2	24	149	0	1120	0.86	0.05	130	354	0.3	17	201	7.96	3.2	7.67
2012	230.3	28	156	0	910	0.32	0.23	110	281	2	9.76	170	7.92	2.4	7.04
2013	218	25	161	Nil	1060	0.9	Nil	130	266	3	16.41	189	8.3	1.7	7.21
2016	Nil	12	156	0	980	1.05	0.12	80	293	1	12	216	8.21	Nil	Nil
2017	219.67	20	163	Nil	1020	0.8	0	110	268	1	14.59	194	8	Nil	Nil
2018	190	12	170	24	1060	1.3	0.28	90	183	2	14.6	200	8.32	0	9.17
2021	Nil	2	57	0	1150	8.8	Nil	15	634	1.56	2.432	280	8.2	Nil	Nil
Standards	200(WHO)	100(WHO)	250(WHO)	-	1400(WHO)	1.5(WHO)	0.3(WHO)	500(WHO)	150(WHO)	10(WHO)	200(ICMR)	200(WHO)	6.5 - 8.5(WHO)	1.25	9

Table 4- Groundwater Quality (Gokalpura Station) (Source: WRIS portal)

Gokalpura

Year	TA (mg/L)	Ca (mg/L)	Cl (mg/L)	CO3 (mg/L)	EC (µS/cm) at 25°C)	F (mg/L)	Fe (mg/L)	TH (mg/L)	HCO3 (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	pH	RSC	SAR
2010	250	32	128	0	970	0.5	0.1	150	305	3	17.06	148	8.22	2	5.25
2013	59.7	56	156	24	900	0.22	Nil	240	24	3	24	113	8.23	Nil	3.18
2014	213	72	142	0	840	0.22	0.03	300	260	1	29	65	8.28	1.72	1.64
2016	Nil	12	483	0	1950	0.48	0.31	360	268	3.8	80	335	8.15	Nil	Nil
2018	309.84	44	156	0	1160	1.5	0.34	240	378	4.7	31.66	160	8.12	0	4.49
2021	Nil	16	149	0	1300	14.2	Nil	120	183	15.6	19.456	250	7.81	Nil	Nil
Standards	200(WHO)	100(WHO)	250(WHO)	-	1400(WHO)	1.5(WHO)	0.3(WHO)	500(WHO)	150(WHO)	10(WHO)	200(ICMR)	200(WHO)	6.5 - 8.5(WHO)	1.25	9

Table 5- Groundwater Quality (Nami Tehsil) (Source: WRIS portal)

Public Tubewell Village- Nami Tehsil

Year	TA (mg/L)	Cl (mg/L)	COD (mg/L)	EC (µS/cm) at 25°C)	F (mg/L)	FC (MPN/100ml)	Calcium Hardness (mg/L)	NO3 (mg/L)	pH	TC (MPN/100ml)	TDS (mg/L)
2019	108	304	21.2	1470	0.86	3	40	1.54	7.7	3	1088
2020	Nil	Nil	Nil	1320	0.68	4	Nil	1.5	7.9	7	Nil
2021	100	176	6.56	820	0.74	3	43	2.2	7.61	4	638
Standards	200(WHO)	250(WHO)	< 20-40 mg/L	1400(WHO)	1.5(WHO)	-	-	50(WHO)	6.5 - 8.5(WHO)	-	600(WHO)

Table 6- Groundwater Quality (Nani Tehsil) (Source: WRIS portal)

Tubewell of Hariprasad Pannalal Bada Talab Village- Nani Tehsil

Year	TA (mg/L)	Cl (mg/L)	COD (mg/L)	EC (µS/cm) at 25°C)	F (mg/L)	FC (MPN/100ml)	Calcium Hardness (mg/L)	NO3 (mg/L)	pH	TC (MPN/100ml)	TDS (mg/L)
2019	96	172	19.2	890	1.16	3	33.6	1.6	8	3	634
2020	Nil	Nil	Nil	900	1.12	7	Nil	1.24	8.4	11	Nil
2021	92	188	8.61	850	0.7	9	35	1.8	8.02	14	626
Standards	200(WHO)	250(WHO)	< 20-40 mg/L	1400(WHO)	1.5(WHO)	-	-	50(WHO)	6.5 - 8.5(WHO)	-	600(WHO)

The values of various parameters of the five stations collected over ten years have been analyzed similarly by comparing them against the standards specified (WHO, CPCB) and the trend has been analyzed as to whether it is exceeds the standards. The water quality trends across the stations indicate several notable patterns. Sabalpura shows a significant worsening in 2021, with chloride, electrical conductivity, and sodium levels exceeding WHO standards, while most other parameters remain within limits or show minor fluctuations. Nani has ongoing issues with total alkalinity and bicarbonate exceeding standards, and a sharp increase in fluoride in 2021. Most other parameters remain compliant but with occasional exceedances. Gokalpura exhibits persistent exceedances in total alkalinity and bicarbonate, with significant spikes in chloride, electrical conductivity, and fluoride in 2016 and 2021. This indicates potential episodic contamination events. Public Tubewell Village-Nami Tehsil faced temporary exceedances in chloride, chemical oxygen demand (COD), electrical conductivity, and total dissolved solids (TDS) in 2019, with fecal and total coliforms indicating microbial contamination in recent years. Tubewell of Hariprasad Pannalal Bada Talab Vill-Nani Tehsil shows consistently low total alkalinity and compliance with most parameters. However, significant microbial contamination and exceedances in TDS in 2019 and 2021 suggest quality issues. Overall, trends indicate that 2021 was particularly problematic across several stations, highlighting chemical and microbial contaminants spikes that exceed WHO standards.

The map of groundwater quality monitoring stations in Sikar City shown in Fig. 5 illustrates the distribution of five stations, labeled Station 1 through Station 5, across the urban area. It can be observed that the stations are concentrated towards the west side of the city except one. Hence, to acquire water quality data in the eastern part, a research paper talking about Groundwater Chemistry in the eastern part of Sikar City has been referred to [16]. As per the research paper, the samples obtained were analyzed for the potential of Hydrogen (pH), Total Dissolved Solids (TDS), Electrical Conductivity (EC), Total Hardness (TH), Total Acidity (TA), Dissolved Oxygen (DO), and sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{+2}), magnesium (Mg^{+2}), chloride (Cl^{-}), sulphate ($SO4^{-2}$), bicarbonate (HCO^{3-}), carbonate (CO^{3-2}), fluoride (F^{-}), nitrate (NO^{3-}) using American Public Health Association methods. Some samples showed EC, TDS, nitrate, chloride, and fluoride levels exceeding WHO standards, indicating the need for treatment and caution. The graphs of these parameters are shown below in Fig. 6.

The average values of various parameters from the eastern part of the city have been analyzed by comparing against the standards as specified (WHO, CPCB) etc. The values are then reviewed for the possible effects on humans and environment due to and increase or decrease in the values and have been tabulated.

Table 7- Table shows Groundwater Quality for eastern part of Sikar city (Source: Author)

Parameter	Average	Standards	Effects on humans	Effects on environment
pH	7.55	6.5 - 8.5(WHO) 7.0 - 8.5(ICMR)	High pH can cause skin irritations, gastrointestinal issues etc.	Decreased pH can result in acidification of water bodies, harming aquatic life, and disrupting the overall ecosystem.
TDS (mg/L)	768	600(WHO)	Gastrointestinal irritation, salty or bitter taste	Affects aquatic life, leads to osmotic stress
EC (µS/cm)	1456	1400(WHO)	Indicates high levels of harmful ions	Affects aquatic ecosystems, potential pollution indicator
TH (mg/L)	333.31	500(WHO)	Scaling in plumbing, potential kidney stones	Harms aquatic species sensitive to hardness, affects soil permeability
TA (mg/L)	389.1	200(WHO)	Bitter taste, affects digestive health	Causes scaling, affects soil pH and plant growth
DO (mg/L)	6.5	>6(CPCB)	None within range	Essential for aquatic life, low levels cause fish kills
RSC (meq/L)	-0.05	<1.25 (Richard 1954)	Potential sodium hazard for soils if used for irrigation	Affects soil structure, reduces permeability, harms plant growth
SAR	4.65	<9 (Richard 1954)	High sodium levels, affects heart health	Reduces soil permeability, affects plant growth
%Na	54.83	<60 (Wilcox 1955)	Hypertension, cardiovascular diseases	Affects soil structure, harms plant growth
PI	71.18	75 (Doneen 1964)	Indicates poor water quality for irrigation	Affects soil quality, reduces crop yield
CAI	-0.89	-	Presence of sodium and potassium	Indicates potential water quality issues
Na+ (mg/L)	178.71	200(WHO)	Hypertension, cardiovascular diseases	Affects soil structure, harms plant growth
K+ (mg/L)	3.75	10(WHO)	Hyperkaliemia, affects heart and kidney function	Excessive potassium affects soil health
Ca+2 (mg/L)	79.13	100(WHO)	Scaling, potential kidney stones	Affects soil structure, reduces permeability
Mg+2 (mg/L)	33.81	200(ICMR)	Diarrhea, affects heart and kidney function	Contributes to hardness, affects soil structure
Cl- (mg/L)	215.75	250(WHO)	Corrosion, taste issues, hypertension	Toxic to plants, affects aquatic life
SO4-2 (mg/L)	61.74	200(WHO)	Laxative effect, gastrointestinal irritation	Affects soil pH, harmful to aquatic life
HCO3- (mg/L)	370.75	150(WHO)	Affects blood pH balance	Causes scaling, affects soil pH and plant growth
CO3-2 (mg/L)	27.08	-	Alkalosis, affects blood pH balance	Causes scaling, affects soil pH and plant growth
F- (mg/L)	1.19	1.5(WHO)	Dental and skeletal fluorosis	Toxic to plants, affects aquatic life
NO3- (mg/L)	34.03	50(WHO)	Methemoglobinemia, cancer risk	Eutrophication, harmful to aquatic life

5. Issue Identification

5.1. Groundwater Quality

- Sabalpura Station: The chloride concentration at Sabalpura Station in 2021 was 475 mg/L, exceeding the WHO guideline limit of 250 mg/L for drinking water. Elevated chloride levels can impart a salty taste to the water and cause gastrointestinal discomfort. Additionally, individuals with salt-sensitive hypertension may experience worsened conditions. High chloride concentrations are environmentally toxic to aquatic organisms, potentially disrupting ecosystems.
- Nani Station: The fluoride level at Nani Station in 2021 was 8.8 mg/L, far exceeding the WHO guideline of 1.5 mg/L, posing severe dental and skeletal fluorosis risks. Chloride concentration was 57 mg/L, causing potential gastrointestinal discomfort and hypertension issues. The electrical conductivity (EC) was 1150 µS/cm, indicating salinity, which can harm aquatic life and degrade soil quality if used for irrigation.
- Gokalpura Station: In 2021, Gokalpura Station reported fluoride levels of 14.2 mg/L, significantly above WHO standards, leading to severe dental and skeletal fluorosis. Chloride levels were 149 mg/L, contributing to gastrointestinal discomfort and hypertension. The EC was 1300 µS/cm, suggesting high salinity that could damage aquatic ecosystems and soil health.
- Tubewell of Hariprasad Pannalal, Bada Talab Village, Nani Tehsil: In 2021, this tubewell recorded a chloride concentration of 188 mg/L, resulting in salty taste, gastrointestinal issues, and potential hypertension. The EC was 850 µS/cm, indicating contamination that can affect aquatic life and soil quality.
- Public Tubewell, Village-Nami Tehsil: Chloride levels in 2021 were 176 mg/L, causing salty taste, gastrointestinal discomfort, and potential hypertension. The EC was 820 µS/cm, indicating possible pollution, harmful to aquatic organisms and soil quality.
- Eastern part of Sikar City: The eastern part of Sikar City reported elevated total dissolved solids (TDS) at 768 mg/L, EC at 1456 µS/cm, total alkalinity (TA) at 389.1 mg/L, and bicarbonate (HCO3) at 370.75 mg/L in 2021. These parameters can cause gastrointestinal irritation, cardiovascular effects, digestive discomfort, and potential blood pH imbalance, as well as environmental impacts like osmotic stress, reduced biodiversity in aquatic ecosystems, and soil salinization, negatively affecting agricultural productivity.

5.2. Groundwater Level

The groundwater levels at most stations, such as RJGW_7238, RJGW_7364, and RJGW_7373, show a consistent decline from 2011 to 2018, indicating significant depletion. For instance, RJGW_7238 dropped from 61.3 m in 2011 to 78.76 m in 2018. RJGW_7242 and RJGW_7365 also exhibit increased depths over time. While RJGW_7357 remains relatively stable around 60 m, RJGW_7388 shows notable fluctuations. The general trend suggests over-extraction, leading to a concerning decrease in groundwater availability across the stations.

6. Literature Review

A total of nine case studies comprising of research papers and government report were studied which had similar situations as the current area of study. These case studies have been compiled in Table 8 below:

Table 8
Table shows the compiled Case Studies

(Source: Author)

S. No	Title of study	Issues	Proposals
1	State of Groundwater in Uttar Pradesh - A Situation Analysis with Critical Overview and Sustainable Solutions.	• Significant Decline in Water Levels • Widespread Contamination • Insufficient Recharge • Inconsistent Data Management • Regulatory Inadequacies	1. Establishing an efficient data management system for vast groundwater data, for up-to-date information for decision-making. 2. Developing a robust, integrated regulatory framework to control and manage groundwater. 3. Harmonizing existing regulations, such as the U.P. Ground Water Act-2019, with other guidelines to avoid conflicts and confusion.
2	An integrated approach for an impact assessment of the tank water and groundwater quality in Coimbatore region of South India: implication from anthropogenic activities	• Degradation of tank water quality due to disposal of municipal and industrial waste. • Percolation of polluted tank water into the groundwater, impacting groundwater quality. • Impact of anthropogenic activities like irrigation, industrialization and urbanization on groundwater resources.	1. Implement proper collection, treatment, and disposal mechanisms for solid and liquid wastes to prevent contamination of surface water bodies. 2. Develop decentralized wastewater treatment systems for effective treatment of wastewater before disposal. 3. Implement artificial groundwater recharge techniques to promote the percolation of clean surface water into the aquifer. 4. Integrate the water quality data with GIS for spatial analysis and visualizing the spatio-temporal trends.
3	Adopting Integrated Urban Water Management in Indian Cities (Adopt IUWM) SOLAPUR	• High Transmission & distribution losses to the tune of 40% • Water scarcity during summers since Ujjani Dam is the only perennial source of water, but is also getting polluted • Water logging and sanitation issues in slum areas • STP for the city is not functional • Untreated sewage discharged into Shelgi Nallah which meets Sina River leading to pollution	1. Reduction of Non-Revenue Water (NRW) 2. Sewage Treatment and Reuse: Reducing the pollution of the Shelgi Nallah and Sina River by treating the sewage before discharge. 3. Implementing Sustainable Urban Drainage Systems (SUDS) to retrofit the city fabric and manage stormwater more effectively. 4. Retrofitting stone quarries around the city with infiltration trenches to enhance aquifer recharge using treated wastewater.
4	Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India	• Groundwater Contamination and Overuse Urban Infrastructure Leaks • Groundwater Recharge Complexity: The natural recharge process is complicated by the city's predominantly granitic terrain, which limits natural infiltration to only 7–8% of precipitation.	1. Regular maintenance of the existing water supply and sewage networks. 3. Implementing advanced sewage treatment technologies to prevent contamination of surface water bodies. 4. Control of Leakage Losses: Installing smart water meters and leak detection systems to monitor water loss in real-time. 5. Sustainable Groundwater Management: Promoting the use of alternative water sources, such as rainwater harvesting and treated wastewater, to reduce reliance on groundwater.
5	Constraints and solutions for groundwater development, supply and governance in urban areas in Kenya	• There is a disconnect between national water policies and their implementation at the county level. • County Integrated Development Plans (CIDPs) primarily focus on Vision 2030, with limited consideration given to other national policies such as the National Water Master Plan (NWMP) 2030. • Lack of Expertise and Capacity in Water Management	1. Propose the development of a comprehensive planning framework that integrates groundwater and surface water management holistically. 2. Enhanced Policy Translation: • Advocate for the establishment of strong coordination structures between national and county institutions • Emphasize the need for a two-way flow of information between national and county-level stakeholders.
6	Valuation of ecosystem damage induced by soil-groundwater pollution in an arid climate area: Framework, method and case study	• Human Health Loss • Ecological Restoration Cost: Costs associated with soil and groundwater remediation. Ecological restoration cost: 85.6% of the total cost. • Ecosystem Services Loss: The total ecosystem services loss was calculated to be 405,049 yuan. It is the loss in climate regulation and soil conservation services over a 5-year period	1. Establish a system for the public to supervise and report pollution events. 2. Introduce an incentive mechanism to reward informants based on the severity of the pollution. 3. Create a national unified management system to notify polluters and link it to the credit information system. 4. Form an independent nongovernmental organization to handle reports and develop economic valuation of impacts from pollution.

S. No	Title of study	Issues	Proposals
		• Emergency Disposal Cost: Emergency disposal cost: 11.2%.	
7	Investigation of implementing solar energy for groundwater desalination in arid and dry regions: A case study	• Severe Water Scarcity: Yazd province suffers from a significant shortage of drinking water due to low precipitation levels.	Solar-Powered Reverse Osmosis (PV-RO): The study concludes PV-RO is the best method for groundwater desalination in Yazd province due to its superior desalination capability, lower construction and maintenance costs, and longer lifespan compared to other methods like Multi-
8	Tackling Water Pollution and Promoting Efficient Water Use in Industries	• Lack of decentralized data generation and participatory data gathering involving all stakeholders. • Low public awareness on the state of water quality and pollution. • Poor communication with industry and other stakeholders. Inadequate capacity to carry out policy commitments, especially monitoring.	1. Continuous Water Quality Monitoring: Implement sustained water quality monitoring to generate reliable and continuous data. 2. Decentralized and Participatory Data Generation: Involve local communities and stakeholders in data collection to improve the comprehensiveness of the information gathered. 3. Increase Public Awareness: Enhance public awareness regarding water quality and pollution to foster community engagement and advocacy.
9	Spatial groundwater quality and potential health risks due to nitrate ingestion through drinking water: A case studyin Yan'an City on the Loess Plateau of northwest China	• High Nitrate Levels: Nitrate (NO3–) contamination is a significant issue, primarily stemming from the application of fertilizers in agriculture, domestic sewage, and poultry manure. • High Total Dissolved Solids (TDS): Elevated TDS levels impact the suitability of groundwater for domestic use. • Hardness and Sulphates (SO4^2–): Presence of (TH) and sulphate concentrations also affects groundwater quality, making it difficult for consumption and domestic use.	1. Enhancing Groundwater Quality Monitoring: Systematic monitoring of groundwater quality to address contamination early. 2. Integrated Water Management: Integrate management practices for groundwater, surface water, and rainwater to mitigate the concentrations of other contaminants such as total hardness (TH), total dissolved solids (TDS), and sulphate (SO42-). 3. Reducing Nitrate Concentration: Implementing measures to lower nitrate levels in drinking water.

7. Evaluation of Best Practices

7.1. Analytic Hierarchy Process (AHP)

Groundwater pollution mitigation involves complex, multifaceted decision-making processes due to the variety of factors influencing pollution and the diverse methods available for addressing it. These factors can include sources of pollution (e.g., agricultural runoff, industrial waste), geographic and hydrological conditions, technological interventions, regulatory policies, and socio-economic considerations. Hence, AHP analysis was conducted on three samples to evaluate best practices for groundwater pollution mitigation. The samples compared four primary criteria: **Agro-Pollution Control, Groundwater Technology, Water Resource Management, and Water Regulations and Policies.** AHP is particularly useful for groundwater pollution mitigation because it helps structure complex environmental problems into a hierarchy of interrelated criteria and sub-criteria. This method provides a systematic approach to compare various practices against multiple criteria, allowing decision-makers to prioritize actions based on their effectiveness in mitigating groundwater pollution.

7.2. Evaluating the samples

From the Analytical Hierarchy Process (AHP) analysis for Sample-1, the eigenvector calculations reveal that **Water Regulations and Policies** are the most prioritized strategy with a significant weighting of 39.17%, indicating their critical role in effectively addressing groundwater pollution. This strategy's high priority suggests that regulatory measures, such as setting legal limits on pollutants and enforcing compliance, are perceived as the most impactful approach. **Water Resource Management** ranks second with 27.92%, emphasizing the importance of integrated water resource planning and management to control pollution levels. Agro-Pollution Control and **Groundwater Technology** have lower priorities (16.46% each), indicating that while these strategies are recognized, they are considered less crucial and impactful than regulatory policies or broader resource management efforts. The **Agro-Pollution Control's** lower ranking may reflect the challenges in implementing and monitoring agricultural practices that prevent pollution. At the same time, despite its potential for innovation, Groundwater Technology may be limited by costs and practical application issues. **The Consistency Index (CI)** is calculated as **0.0236** using the formula (λmax-n)/(n-1), which measures the deviation from a perfectly consistent matrix. **The Consistency Ratio (CR**), the CI divided by the Random Consistency Index (RCI) for a matrix of the same size, is **0.0262**. Since the CR is below the commonly accepted threshold of 0.1, it indicates that the judgments are consistent and reliable.

Table 9
Table shows First sample

(Source: Author)

SAMPLE-1				
Parameters	Agro-Pollution Control	Groundwater Technology	Water Resource Management	Water Regulations & Policies
Agro-Pollution Control	1	1	0.5	0.5
Groundwater Technology	1	1	0.5	0.5
Water Resource Management	2	2	1	0.5
Water Regulations & Policies	2	2	2	1
Total	6	6	4	2.5

Table 10
Table shows EV calculation for first sample

(Source: Author)

SAMPLE-1	**Agro-Pollution Control**	**Groundwater Technology**	**Water Resource Management**	**Water Regulations & Policies**	**Eigen Vector**	**Percentage**	**EV**	**λmax**
Agro-Pollution Control	0.17	0.17	0.13	0.20	0.66	16.46	0.16	0.9875
Groundwater Technology	0.17	0.17	0.13	0.20	0.66	16.46	0.16	0.9875
Water Resource Management	0.33	0.33	0.25	0.20	1.12	27.92	0.28	1.1167
Water Regulations & Policies	0.33	0.33	0.50	0.40	1.57	39.17	0.39	0.9792

From the Analytical Hierarchy Process (AHP) analysis for Sample-2, the eigenvector calculations reveal that **Water Regulations & Policies** are the most prioritized strategy with a significant weighting of 38.73%, underscoring their essential role in addressing groundwater pollution. This high priority suggests that regulatory frameworks, such as imposing legal restrictions on contaminants and ensuring enforcement, are perceived as the most effective measures. **Water Resource Management** ranks second with 27.48%, highlighting the importance of comprehensive water resource planning and management in mitigating pollution levels. **Groundwater Technology** follows with a priority of 19.81%, indicating its recognized potential for addressing pollution through technological innovation, albeit possibly constrained by costs and implementation challenges. **Agro-Pollution Control** has the lowest priority at 13.97%, suggesting that despite its importance, it faces significant hurdles in practice, such as the difficulty in changing agricultural practices and monitoring compliance. The **Consistency Index (CI)** for Sample-2 is calculated as **0.0451** using the formula (λmax-n)/(n-1), measuring the deviation from a perfectly consistent matrix. The Consistency Ratio (CR), the CI divided by the Random Consistency Index (RCI) for a matrix of the same size, is **0.0501**. Since the CR is below the commonly accepted threshold of 0.1, it indicates that the judgments are consistent and reliable.

Table 11
Table shows second sample

(Source: Author)

SAMPLE-2				
Parameters	Agro-Pollution Control	Groundwater Technology	Water Resource Management	Water Regulations & Policies
Agro-Pollution Control	1	0.5	0.5	0.5
Groundwater Technology	2	1	0.5	0.5
Water Resource Management	2	2	1	0.5
Water Regulations & Policies	2	2	2	1
Total	7	5.5	4	2.5

Table 12
Table shows EV calculation for second sample

(Source: Author)

SAMPLE-2	**Agro-Pollution Control**	**Groundwater Technology**	**Water Resource Management**	**Water Regulations & Policies**	**Eigen Vector**	**Percentage**	**EV**	**λmax**
Agro-Pollution Control	0.14	0.09	0.13	0.20	0.56	13.97	0.14	0.9778
Groundwater Technology	0.29	0.18	0.13	0.20	0.79	19.81	0.20	1.0897
Water Resource Management	0.29	0.36	0.25	0.20	1.10	27.48	0.27	1.0994
Water Regulations & Policies	0.29	0.36	0.50	0.40	1.55	38.73	0.39	0.9683

From the Analytical Hierarchy Process (AHP) analysis for Sample-3, the eigenvector calculations reveal that **Water Regulations and Policies** are the most prioritized strategy with a significant weighting of 48.53%, highlighting their crucial role in addressing groundwater pollution. This high priority suggests that regulatory frameworks, such as establishing legal limits on pollutants and ensuring compliance, are considered the most effective measures. **Groundwater Technology** ranks second with a priority of 21.73%, indicating its recognized potential for tackling pollution through technological advancements, though possibly limited by implementation costs and practical challenges. **Agro-pollution control** follows with a priority of 18.96%, suggesting that while it is essential, it faces significant implementation and monitoring challenges. **Water Resource Management** has the lowest priority at 10.78%, emphasizing that integrated water resource planning and management are less impactful than regulatory policies and technological solutions. The **Consistency Index (CI)** for Sample-3 is calculated as **0.0475** using the formula (λmax-n)/(n-1), measuring the deviation from a perfectly consistent matrix. The **Consistency Ratio (CR)**, the CI divided by the Random Consistency Index (RCI) for a matrix of the same size, is **0.0528**. Since the CR is below the commonly accepted threshold of 0.1, it indicates that the judgments are consistent and reliable.

Table 13
Table shows Third sample

(Source: Author)

SAMPLE-3				
Parameters	Agro-Pollution Control	Groundwater Technology	Water Resource Management	Water Regulations & Policies
Agro-Pollution Control	1	1	2	0.333333333
Groundwater Technology	1	1	3	0.333333333
Water Resource Management	0.5	0.333333333	1	0.333333333
Water Regulations & Policies	3	3	3	1
Total	5.5	5.333333333	9	2

Table 14
Table shows EV calculation for third sample

(Source: Author)

SAMPLE-3	**Agro-Pollution Control**	**Groundwater Technology**	**Water Resource Management**	**Water Regulations & Policies**	**Eigen Vector**	**Percentage**	**EV**	**λmax**
Agro-Pollution Control	0.18	0.19	0.22	0.17	0.76	18.96	0.19	1.0425
Groundwater Technology	0.18	0.19	0.33	0.17	0.87	21.73	0.22	1.1591
Water Resource Management	0.09	0.06	0.11	0.17	0.43	10.78	0.11	0.9702
Water Regulations & Policies	0.55	0.56	0.33	0.50	1.94	48.53	0.49	0.9706

7.3. Selection of Best Practices

Based on the Analytical Hierarchy Process (AHP) analysis across three samples, Water Regulations and Policies emerge as the most prioritized strategy, with an average weightage of 42.14%. This consistently high ranking underscores the critical role of establishing legal frameworks, setting pollutant limits, and enforcing compliance as the most effective measures for managing groundwater pollution.

Table 15
Table shows selection of Best Practices

(Source: Author)

WATER					
Variable	**Sample-1**	**Sample-2**	**Sample-3**	**Average**	**Rank**
Agro-Pollution Control	16.46	13.97	18.96	16.46	4
Groundwater Technology	16.46	19.81	21.73	19.33	3
Water Resource Management	27.92	27.48	10.78	22.06	2
Water Regulations & Policies	**39.17**	**38.73**	**48.53**	**42.14**	**1**

Water Resource Management ranks second with an average weighting of 22.06%, emphasizing the importance of comprehensive planning and management of water resources to control pollution levels. This highlights the need for sustainable and integrated approaches to water management. Groundwater Technology follows in third place with an average weighting of 19.33%. This indicates the value placed on technological solutions for addressing groundwater pollution, despite potential practical and cost-related challenges that might affect their implementation. Agro-Pollution Control ranks fourth with an average weighting of 16.46%, suggesting that while agricultural practices to prevent pollution are essential, they are perceived as less impactful than regulatory policies, resource management, and technological solutions. The lower ranking may reflect the challenges in effectively changing and monitoring agricultural practices. In conclusion, the final rankings suggest that regulatory policies should be the primary focus for addressing groundwater pollution, supported by comprehensive water resource management, technological innovations, and sustainable agricultural practices.

8. Findings and Discussion

The study reveals significant insights into groundwater pollution in Sikar City; however, several limitations were encountered. Data was unavailable for all years, with some parameters missing for specific years, and data does not extend to the most recent years. These gaps hinder a comprehensive temporal analysis. Additionally, inconsistent sampling methods and the spatial variability of pollutants further challenge the accuracy of the assessment. Addressing these limitations through continuous monitoring, better data management and resource allocation is essential. Enhanced community awareness and public participation will also be critical in effectively implementing mitigation strategies.

9. Recommendations

9.1. Water Regulation and Policies

9.1.1 Incentives for Green Technology

- **Positive Incentives**: Introduce subsidy programs for green technology, in addition to the monitoring of technologies. Step up funding. Positive incentives can encourage the adoption of environmentally friendly practices and technologies.
- **Negative Incentives**: Introduce pollution taxes and implement the polluter pays principle to encourage cleaner practices. Financial penalties can act as deterrents, and full compliance can be achieved with regard to the environment.
- **Nature-Based Solutions**: Opt for natural ecosystem services, such as wetlands and riparian buffers, for effective treatment of pollutants. Nature-based solutions, like these, not only provide extra environmental benefits but also enhance water quality.
- **Environmental Rating Systems**: Design rating systems that would encourage companies to act in a regulatory-compliant manner and strive for improved sustainability performance. Ratings may be based on environmental performance, which will encourage businesses to adopt good practices.

9.1.2 Regulatory Framework

- Plan an integrative regulation that will use efficient water withdrawal control and management. Integrate the existing Acts—especially **THE RAJASTHAN WATER RESOURCES REGULATORY ACT, 2012—**with other national and regional guidelines to avoid conflicts and confusion in having them together, ensuring single governance and compliance. Further, it strongly argues for interinstitutional coordination at the national and regional levels to ensure effective policy implementation. Good communication and coordination with the stakeholders in water management have to be integrated. Create a fund for ecosystem damage compensation to be managed by a non-governmental organization. This money is to be directed to the restoration of the affected ecosystems or supporting communities affected by water pollution.

9.2. Water Resource Management

9.2.1 Rainwater Harvesting and Contamination Control

- **Rainwater Harvesting**: Implement and enforce comprehensive guidelines for rainwater harvesting, supplemented with artificial groundwater recharging. It will thus be constructed with appropriate infrastructure to capture and store the rainwater, through public awareness and advocacy of its use for various purposes to reduce overdependence on groundwater.

- **Pollution Control**: Address groundwater contamination through stringent pollution control measures. This would involve continuous monitoring of the quality of the water, identification of sources of contamination, and remediation. Preventive measures should also be emphasized to protect water sources from future pollution.

9.2.2 Climate Adaptation and Sustainable Water Use

- **Climate Adaptation**: Design and implement adaptation strategies to the effects of climate change, such as declining rainfall and alteration of weather patterns. Enhance artificial recharge methods for sustainable use of water resources to facilitate resilience against climate variability.
- **Geomorphology-Based Mapping**: Employing geomorphology-based mapping techniques is crucial for pinpointing areas with a high potential for groundwater recharge. This approach is especially vital in arid and semi-arid regions such as Sikar, where targeted recharge efforts can substantially influence water availability.

9.2.3 Waste Management and Treatment Systems Use

- **Solid and Liquid Waste Management**: Implement effective collection, treatment, and disposal mechanisms to ensure minimal surface water and groundwater source contamination. Proper waste management practices along with the latest technologies such as Advanced Leak Detection Systems to protect water quality.

9.3. Groundwater Technology

9.3.1 Advanced Scientific Methods and Water Modelling

- **Resource Estimation**: Utilization of advanced scientific methods to address variances and gaps in groundwater resource estimation. This includes validating norms such as specific yield and unit draft. The testing of these standards means that resource assessments become more accurate. Accurate assessments mean sustainable extraction rates and enlightened policymaking.
- **Advanced Modelling Tools**: Using advanced modeling tools such as MODFLOW and MT3D to simulate groundwater flow and contaminant transport. These tools help to predict the impact of various management strategies; hence, it can be beneficial in enabling decision-making.

9.4. Agro-Pollution Control

9.4.1 Sustainable Agricultural Practices

- **Sustainable Agriculture**: Encourage practices such as integrated nutrient management, precision irrigation, and organic farming to reduce the environmental impact of agriculture. These methods can help minimize runoff, reduce the use of chemical fertilizers and pesticides, and promote soil health.
- **Nitrate Reduction**: Implement specific measures to lower nitrate levels in drinking water, including regulating fertilizer use, proper sewage management, and water treatment processes. Addressing nitrate contamination is crucial for protecting public health.
- **Water-Efficient Agriculture**: Reduce groundwater extraction—this can be done by involving water-wise farming practices by promoting water-saving devices, changing cropping patterns to less water-intensive crops, and promoting the cultivation of species that require less water. Education and incentives for farmers can facilitate necessary transitions.

10. Conclusion

In conclusion, addressing water pollution in Sikar City requires a multifaceted approach involving technological solutions and active community engagement. Community awareness and public participation are crucial in ensuring the success of any water management initiative. Educating the public about the importance of water conservation and pollution prevention can foster a sense of responsibility and collective action. Local communities must actively monitor water quality and report pollution incidents, as their participation can lead to more effective and sustainable water management practices.

Moreover, adequate resource allocation and continuous monitoring are essential to maintain the progress and effectiveness of these initiatives. Investing in advanced scientific methods, modern agricultural practices, and robust waste management systems will require significant financial and technical resources. Continuous monitoring of water quality and regular assessments of groundwater resources will help identify emerging issues promptly and enable timely interventions. By integrating these efforts, we can create a resilient water management framework that mitigates pollution and ensures the long-term sustainability of water resources in Sikar City.

Declarations

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Conflict of Interests

The authors declare that they have no competing interests

Author Contribution

All authors contributed equally to the research and the development of the manuscript. Each author was involved in the conceptualization, methodology design, data collection and analysis, literature review, application of the Analytic Hierarchy Process (AHP) method, and preparation of the manuscript text, figures, and tables. All authors reviewed and approved the final manuscript.

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Figures

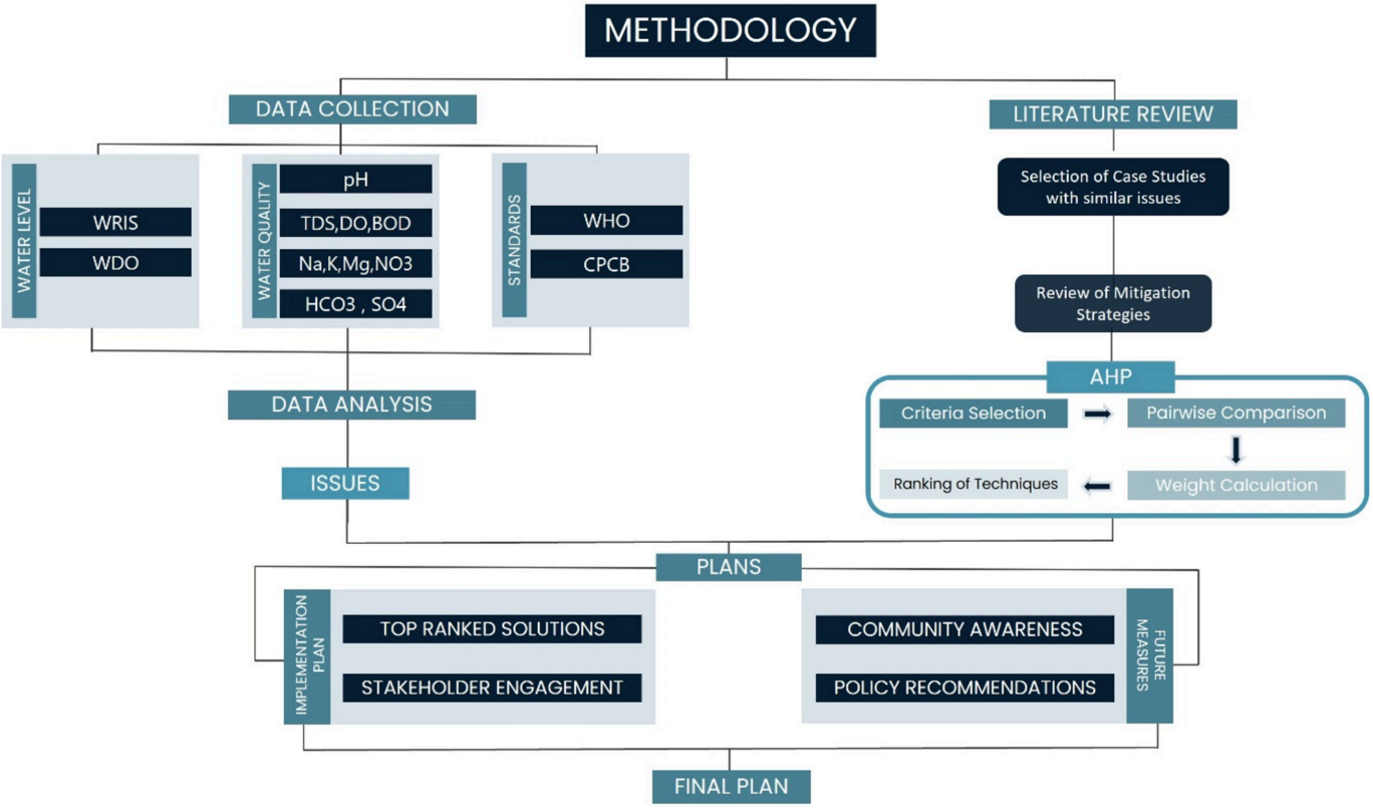


Figure 1

Methodology (Source: Author)

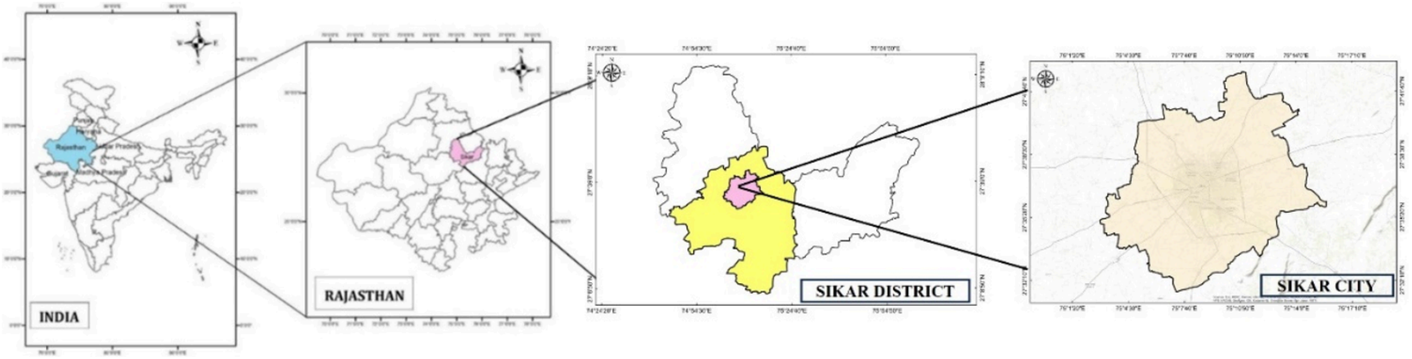


Figure 2

Key map of Sikar city (Source: Author)

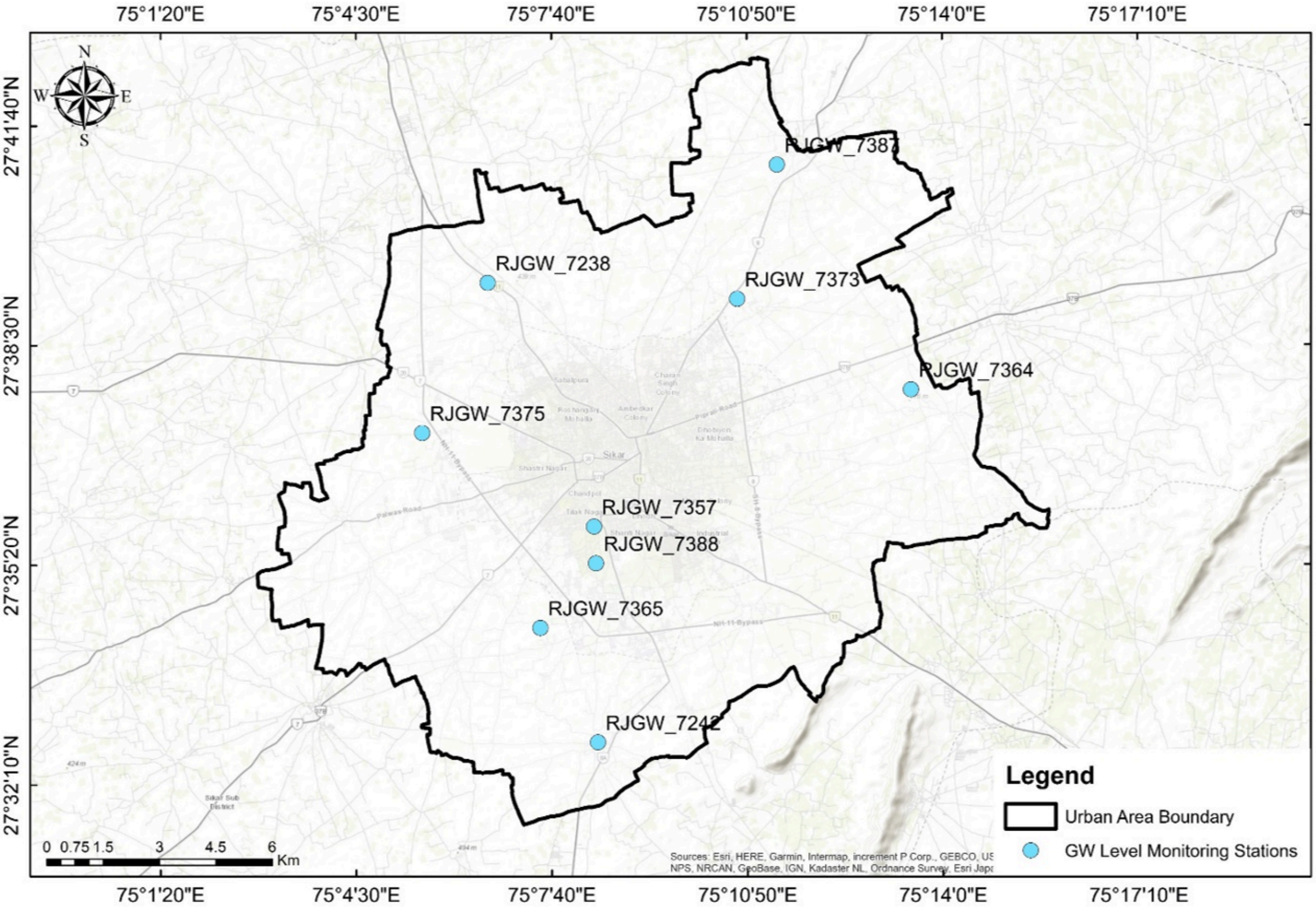
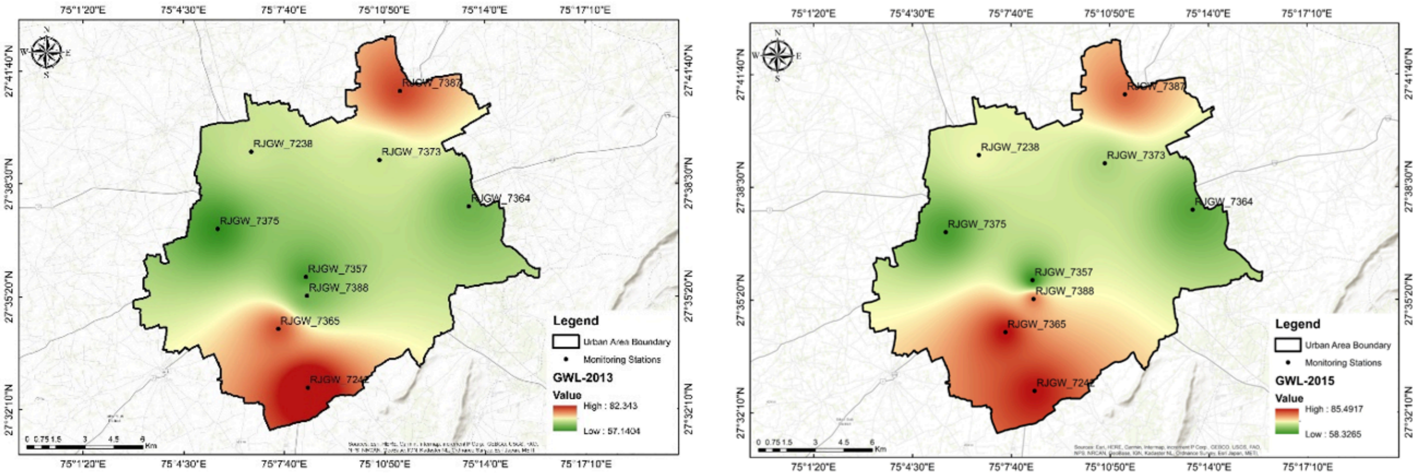
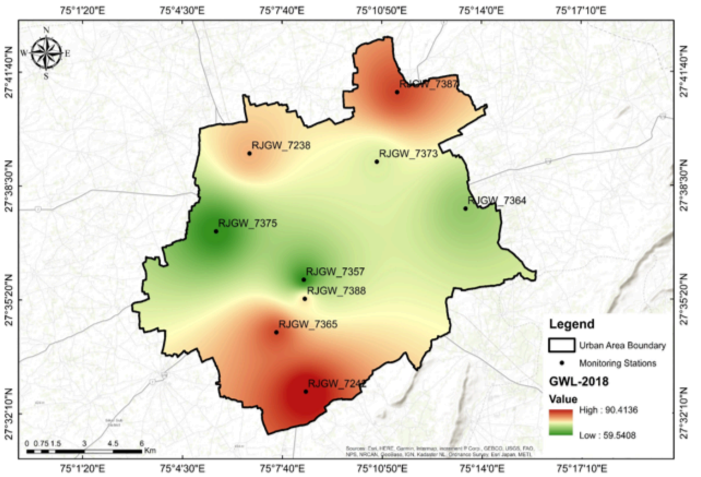


Figure 3

Map shows Groundwater Level monitoring stations of Sikar (Source: WDO)





- The maps and table show a clear trend of decreasing groundwater levels from 2011 to 2018, with most stations reporting significant increases in groundwater depth, such as RJGW_7238 increasing from 61.3 meters to 78.76 meters.
- The southern region, particularly around stations like RJGW_7365 and RJGW_7242, shows significant declines in groundwater levels, aligning with the red areas on the maps, while the central and northern regions have more stable levels.

Figure 4

Maps show the Ground Water Level in 3 years; Top Left (2013), Top Right (2015) & Bottom Left (2018) (Source: WDO)

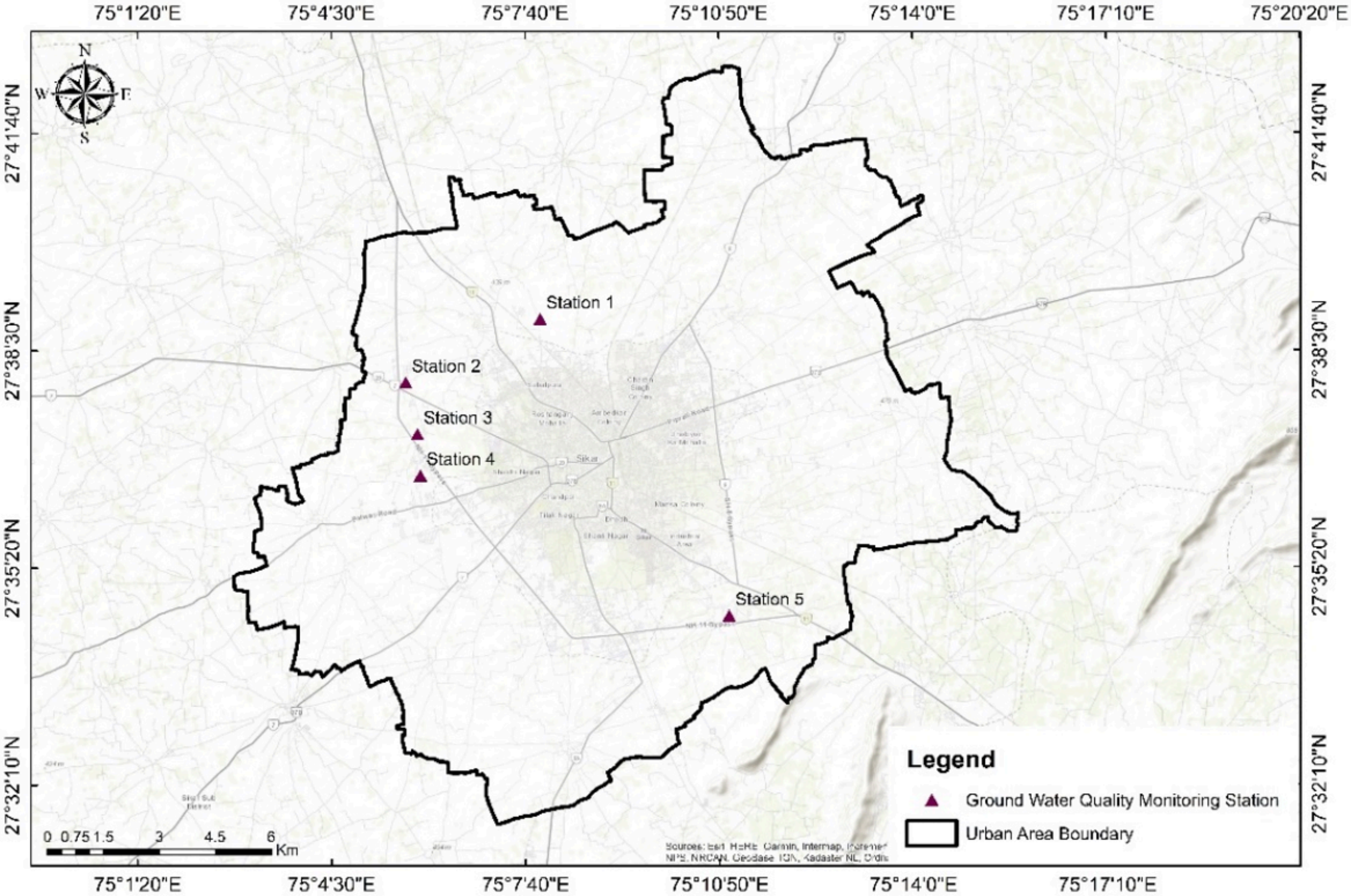
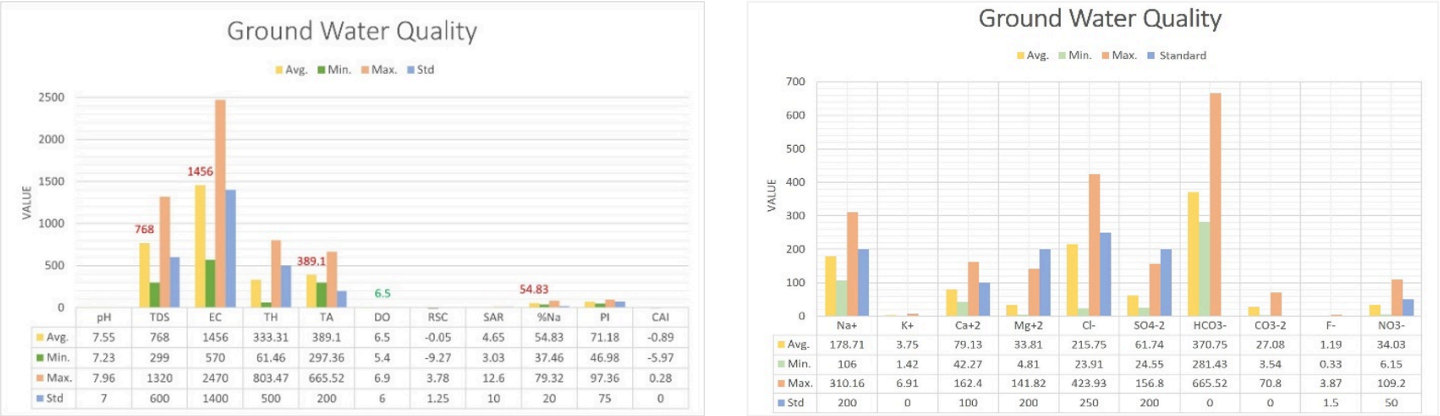


Figure 5

Map shows the Groundwater Quality monitoring stations in Sikar (Source: WRIS portal)



	pH	TDS	EC	TH	TA	DO	RSC	SAR	%Na	PI	CAI
Avg.	7.55	768	1456	333.31	389.1	6.5	-0.05	4.65	54.83	71.18	-0.89
Min.	7.23	299	570	61.46	297.36	5.4	-9.27	3.03	37.46	46.98	-5.97
Max.	7.96	1320	2470	803.47	665.52	6.9	3.78	12.6	79.32	97.36	0.28
Std	7	600	1400	500	200	6	1.25	10	20	75	0

	Na+	K+	Ca+2	Mg+2	Cl-	SO4-2	HCO3-	CO3-2	F-	NO3-
Avg.	178.71	3.75	79.13	33.81	215.75	61.74	370.75	27.08	1.19	34.03
Min.	106	1.42	42.27	4.81	23.91	24.55	281.43	3.54	0.33	6.15
Max.	310.16	6.91	162.4	141.82	423.93	156.8	665.52	70.8	3.87	109.2
Std	200	0	100	200	250	200	0	0	1.5	50

Figure 6

Graphs showing Water Quality in Sikar (Source: Author)