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Spatial and Seasonal Variability of Irrigation Water Quality and Its Influence on Soil Physicochemical Properties

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ABSTRACT
Irrigation water quality is an important factor in regulating soil chemical processes and long-term agricultural sustainability. The study evaluated the spatio-temporal variability of selected irrigation water quality parameters and their relationships with soil nutrient dynamics in the Chite River watershed of Northeast India. Water and soil samples were collected at 5 sites from winter 2022 to autumn 2023 across 4 seasons. Water samples were analyzed for pH, electrical conductivity (EC), nitrite, phosphate and cadmium. Soil samples from three depths were analysed for pH, EC, available nitrogen, available phosphorus, and cadmium. Two-way ANOVA showed significant spatial variations in water EC, nitrite, and phosphate, and seasonal variations in nitrite, phosphate, and cadmium. Three-way ANOVA showed that some soil properties, particularly pH, EC and available nutrients, varied significantly with space and seasons. Regression analysis indicated a positive relationship between irrigation water phosphate and soil available phosphorus, suggesting that irrigation water may contribute to phosphorus transfer to soils. In contrast, nitrite in irrigation water showed a negative relationship with available soil nitrogen, suggesting that internal biogeochemical processes may influence soil nitrogen availability. These results underscore the importance of irrigation water quality in shaping soil nutrient dynamics and emphasise the need for integrated water-soil monitoring to ensure sustainable irrigation management.

Key words: Agroecosystem; Biogeochemical processes; Environmental monitoring; Nutrient dynamics; River basin; Salinity; Seasonal variations

INTRODUCTION

Irrigated agriculture plays a central role in sustaining crop production, particularly in regions with variable rainfall. However, the sustainability of irrigated agriculture is strongly influenced by irrigation water quality, which can affect soil chemical properties, nutrient dynamics, and long-term soil productivity. Irrigation water may contain dissolved salts, nutrients, and trace elements that accumulate in soils and alter their physicochemical characteristics over time. Consequently, understanding the interactions between irrigation water chemistry and soil properties is important for maintaining soil health and sustainable agricultural systems (Ashie et al. 2024, Qabasiyu et al. 2025).

The chemical composition of irrigation water influences soil processes such as ion exchange, nutrient availability, and salinity development. Parameters such as pH and electrical conductivity (EC) are widely used indicators of irrigation water suitability because they regulate soil reactions, nutrient solubility, and plant nutrient uptake. Elevated EC values in irrigation water may lead to salt accumulation in soils, reducing soil permeability and crop productivity (Saleh et al. 2025, Suvendran et al. 2024).

In addition to salinity effects, irrigation water can also be a source of nutrients entering the soil system. Nutrients such as nitrite and phosphate carried in irrigation water can contribute to soil nutrient enrichment and affect both soil fertility and crop performance. Earlier studies have reported that irrigation practices can alter soil nitrogen and phosphorus dynamics and influence plant nutrient availability (Liu et al. 2025, Singh et al. 2025). However, excessive nutrient inputs may disrupt the balance of soil nutrients and increase the risk of nutrient losses or environmental contamination.

The irrigation water chemistry can also vary spatially and seasonally due to variability in geology, land use, rainfall patterns, and agricultural practices, which may in turn influence soil physicochemical properties (Mengiste et al. 2025, Sary et al. 2024). Although irrigation water quality is becoming a growing concern, many existing studies emphasise the properties of either water or soil, and relatively few integrated studies investigate water chemistry and soil responses at spatio-seasonal scales. Such integrated analyses are required to understand the ecological mechanisms linking irrigation water composition with soil nutrient dynamics, salinity development, and trace element accumulation in agricultural soils (Gemeda and Yadeta 2024).

Several studies have assessed irrigation water suitability and water quality in the Chite River watershed. However, there is little information on the relationships between seasonal changes in irrigation water chemistry and soil nutrient responses. Such water–soil interactions are important for sustainable nutrient management and long-term agricultural productivity in tropical mountain watersheds. The present study fills this gap by incorporating analyses of irrigation water chemistry and soil physicochemical properties across several sampling locations and seasons. This study differs from previous work in the same watershed by specifically evaluating spatial and seasonal variability using ANOVA and regression. Therefore, the objectives of this study were to (i) evaluate the spatiotemporal variability of selected parameters of irrigation water quality and soil fertility indicators and (ii) investigate the relationships between irrigation water chemistry and soil nutrient dynamics using regression analysis. We hypothesized that there would be significant spatial and seasonal variability in irrigation water quality and soil nutrients and that nutrient concentrations in irrigation water would be associated with corresponding soil properties.

MATERIAL AND METHODS

Study area

The study was conducted in the Chite River of the Aizawl district of Mizoram, India. The river flows through an alluvial valley affected by agricultural and semi-urban activities and is an important source of irrigation for the adjacent fields. The watershed

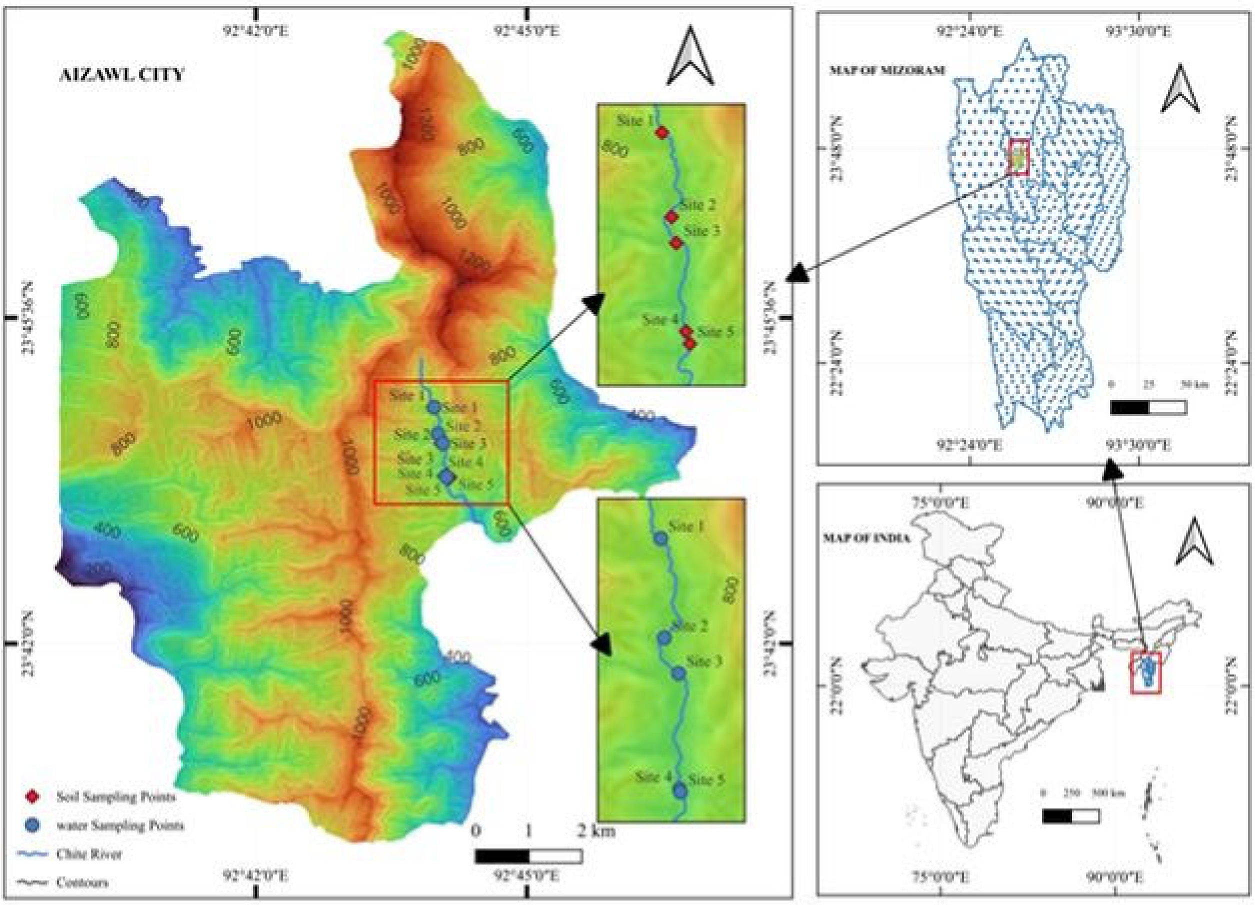

Figure 1. Study area and sampling sites in the Chite River watershed, Mizoram, India

lies between 23°382 -23°462 N and 92°432 -92°492 E, with a total area of about 52.7 km^2. The topography is characterized by steep hill slopes and narrow valleys typical of the Indo-Burma region, with elevations ranging from around 136 to 1159 m. The climate of the area is humid tropical monsoon with high annual rainfall (~300 cm), which occurs mainly from May to September (Barman et al. 2024).

Sample collection

Sampling was carried out from winter 2022 to autumn 2023 (four seasons: winter, spring, summer, and autumn). Water and soil samples were collected periodically from five sites along the river (Fig. 1). River water samples were collected from midstream using pre-cleaned polyethene bottles, transported under cooled conditions (4 °C), and preserved according to standard procedures (Anonymous 2017). Soil samples were obtained from the adjacent irrigated fields at depths of 0–10, 10–20 and 20–30 cm with a stainless-steel auger. Samples were air-dried, homogenized and sieved (2 mm) before analysis (Burt 2011).

Laboratory analysis

Water samples were analysed for pH (electro-metric method) and electrical conductivity (conductometric method); nitrite was determined colourimetrically by diazotisation with sulphanilamide and N-(1-naphthyl)-ethylenediamine; phosphate by the ascorbic acid method; and cadmium by atomic absorption spectrophotometry after filtration (Anonymous 2017). The pH and EC of the soil were determined in a soil-water suspension (Jackson 1973), available nitrogen by the alkaline permanganate method (Bremner and Keeney 1966), available phosphorus by the Olsen method (Olsen et al. 1954), and cadmium by wet digestion (Anonymous 2017).

Statistical analyses were performed using IBM SPSS Statistics software version 22 (IBM Corp., Armonk, NY, USA). We used two-way ANOVA to analyze water parameters for site and season effects, and three-way ANOVA to analyze soil parameters for site, season, and depth (and interactions) effects. Linear regression analysis was used to analyze the relations between selected irrigation water and soil physicochemical parameters.

RESULTS

The irrigation water was generally neutral to slightly alkaline (pH 6.80–7.73) (Table 1) and was variable in electrical conductivity and nutrient concentrations. Electrical conductivity ranged from 128.50 to 791.33 µS cm-1, and nitrite and phosphate concentrations varied widely, indicating high heterogeneity in dissolved salt and nutrient inputs across sampling periods and locations.

Soil properties showed large variability, especially in the concentrations of available nitrogen, available phosphorus, and cadmium. Table 2 shows wide ranges in nutrient concentrations, indicating large differences in soil fertility status and nutrient availability in the agricultural fields sampled.

Two-way ANOVA revealed significant spatial heterogeneity in the chemistry of irrigation water (Table 3). Electrical conductivity, nitrite, and phosphate were significantly different among sites, indicating that the concentrations of dissolved salts and nutrients changed along the river continuum. Differences between seasons were also observed, with nitrite, phosphate and cadmium showing significant temporal variability, suggesting that climatic conditions and runoff processes affected the composition of irrigation water. In contrast, water pH was relatively consistent among sites and seasons with no significant site × season interactions.

Soil physicochemical properties varied mainly with sampling location and season (3-way ANOVA) but not with soil depth (Table 4). The significant site effects for pH, electrical conductivity and available phosphorus indicate spatial heterogeneity in soil chemical conditions. The seasonal effects on pH, electrical conductivity and available nitrogen indicate temporal fluctuations in soil nutrient dynamics. The significant site × season interactions for pH and available nitrogen also suggested that seasonal responses differed among sampling sites.

Linear regression analysis demonstrated contrasting relationships between irrigation water chemistry and soil properties (Table 5). Irrigation water nitrite exhibited a significant negative association with soil available nitrogen ($R^2 = 0.158$, $p < 0.05$; Fig. 2), indicating that higher nitrite concentrations in irrigation water were associated with lower soil available nitrogen concentrations. In

Table 1. Descriptive statistics of physicochemical parameters of water (n = 40)

Parameter	Unit	Mean ± SD	Minimum	Maximum
pH	-	7.31 ± 0.20	6.80	7.73
EC	µS cm^{-1}	504.98 ± 198.10	128.50	791.33
Nitrite (NO_2^- –N)	mg L^{-1}	0.50 ± 0.35	0.02	1.02
Phosphate (PO_4^{3-})	mg L^{-1}	0.48 ± 0.30	0.07	1.20
Cadmium (Cd)	mg L^{-1}	0.008 ± 0.004	0.00	0.01

Table 2. Descriptive statistics of physicochemical properties of soil (n = 120)

Parameter	Unit	Mean ± SD	Minimum	Maximum
pH	-	6.32 ± 0.58	4.78	7.67
EC	dS m^{-1}	0.055 ± 0.047	0.01	0.28
Available nitrogen	mg kg^{-1}	70.57 ± 42.69	5.01	170.60
Available phosphorus	mg kg^{-1}	3.86 ± 1.85	0.41	8.93
Cadmium	mg kg^{-1}	0.204 ± 0.204	0.00	0.60

Table 3. Two-way ANOVA showing the effects of site and season on irrigation water quality parameters

Source of variation	pH (F - value)	EC (F - value)	NO_2^- –N (F - value)	PO_4^{3-} (F - value)	Cd (F - value)
Site	0.75	8.59***	6.08**	14.80***	0.70
Season	1.02	1.83	7.44**	21.38***	5.53**
Site x Season	0.29	0.34	0.54	1.36	1.37

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4. Three-way analysis of variance showing the effects of site, season and soil depth on soil physicochemical parameters

Source of variation	pH (F - value)	EC (F - value)	Available N (F - value)	Available P (F - value)	Cd (F - value)
Site	26.39***	17.31***	0.21	5.12**	0.91
Season	3.94*	8.05**	6.88***	1.68	1.55
Depth	1.13	2.46	0.10	1.04	0.00
Site x Season	2.51*	1.36	2.63**	0.81	0.45
Site x Depth	1.16	0.77	0.15	0.15	0.00
Season x Depth	0.35	0.62	0.22	0.13	0.00
Site x Season x Depth	0.19	0.64	0.27	0.13	0.00

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5. Linear regression analysis showing the influence of irrigation water quality parameters on soil physicochemical properties

Soil variable	Predictor	β	t	p	R^2
Available Nitrogen	**NO_2^- –N**	-0.398	-2.68	0.011*	0.158
Available Phosphorus	**PO_4^{3-}**	0.512	3.67	0.001**	0.262
Soil EC	**EC**	0.305	1.97	0.056	0.093
Soil pH	pH	-0.119	-0.74	0.464	0.014

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

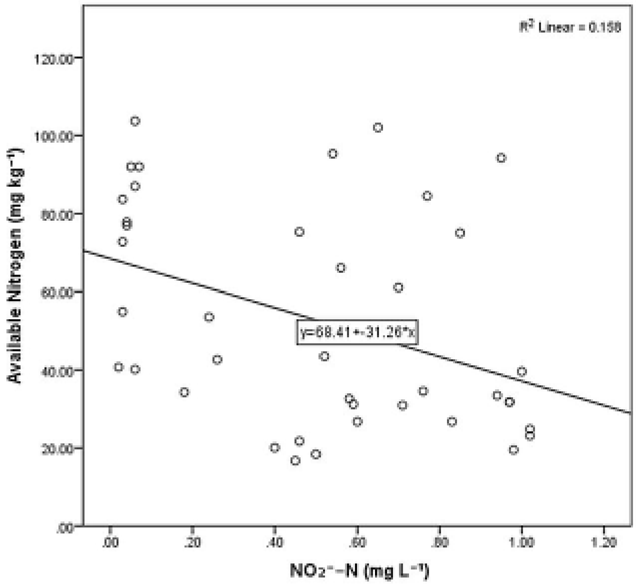

Figure 2. Relationship between nitrite concentration in irrigation water (NO_2^- –N) and soil available nitrogen

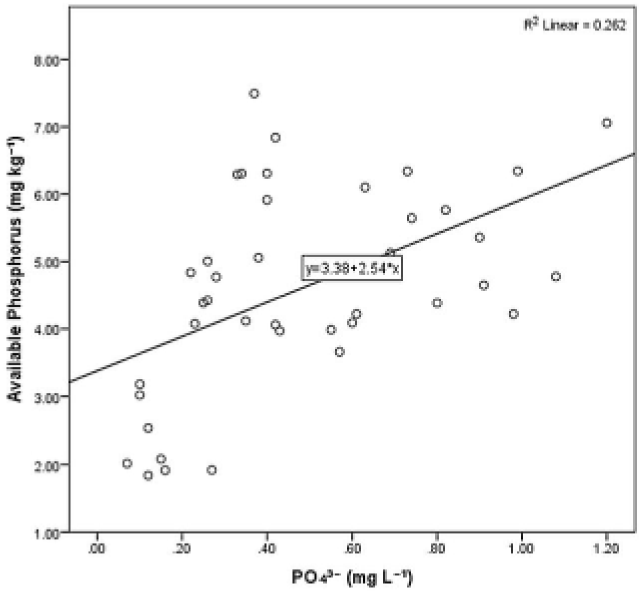

Figure 3. Relationship between phosphate concentration in irrigation water (PO_4^{3-}) and soil available phosphorus

contrast, phosphate in irrigation water showed a moderate positive relationship with available soil phosphorus ($R^2 = 0.262$, $p < 0.01$; Fig. 3), suggesting that irrigation water may contribute to phosphorus enrichment in agricultural soils. However, the relationships between irrigation water EC and soil EC ($R^2 = 0.093$, $p > 0.05$; Fig. 4) and between water pH and soil pH ($R^2 = 0.014$, $p > 0.05$) were weak and statistically non-significant, indicating that additional environmental and soil processes may play a greater role in regulating these soil properties.

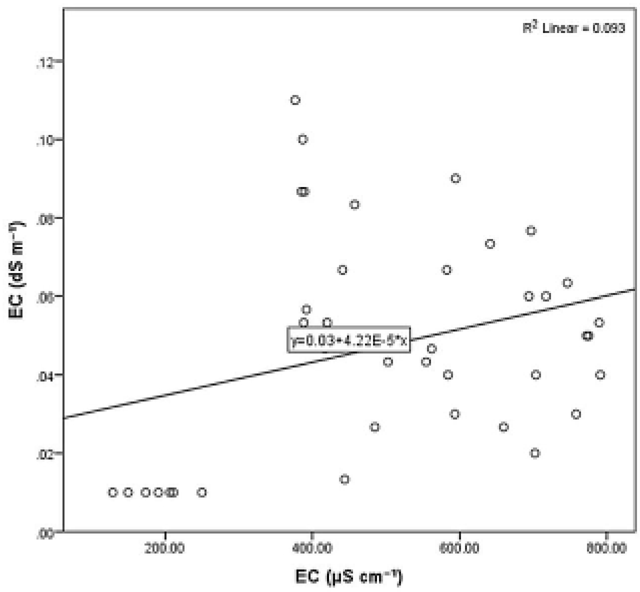

Figure 4. Relationship between electrical conductivity of irrigation water and soil electrical conductivity

DISCUSSION

The irrigation water quality parameters obtained in the present study are mostly neutral to slightly alkaline; thus, river water can be used for irrigation without immediate changes in soil acidity. However, the relatively wide range in electrical conductivity indicates variability in dissolved salt concentrations across sampling periods and locations. Salinity in irrigation water is commonly measured by electrical conductivity, and soil salinity can be affected by repeated irrigation. Natural geochemical processes and land-use activities affect the chemical composition of irrigation sources in agricultural watersheds. Similar spatial and temporal variability in irrigation water EC and nutrient concentrations has been reported (Saleh et al. 2025, Suvendran et al. 2024).

Soil nutrient variability is a symptom of irrigation practices, crop uptake and microbial processes. Irrigation water can also serve as a conduit for nutrient transport to soils, thereby gradually affecting soil nutrient availability over time (Liu et al. 2025, Singh et al. 2025). The large spatial differences in electrical conductivity of the irrigation water, nitrite and phosphate indicate that the water chemistry varied along the river system and probably reflect differences in watershed processes and the effects of land use. Dissolved nutrients and salts can be transported into surface waters through agricultural runoff, soil erosion, and land-use activities, leading to spatial variation in irrigation water quality, as is often reported in river-based irrigation systems. Spatial and temporal studies of irrigation water quality have shown that such variation is common in agricultural watersheds and may affect the suitability of surface water for irrigation purposes (Mengiste et al. 2025, Sani et al. 2025).

Seasonal variability in nitrite, phosphate, and cadmium indicates that climatic and hydrological factors influence the chemistry of irrigation water by changing runoff and agricultural activity. These temporal changes in water chemistry can, in turn, affect chemical conditions in irrigated soils. The considerable spatial and seasonal effects detected in soil pH, electrical conductivity, and available nutrients indicate that soil properties are influenced by both the composition of the irrigation water and the environmental processes occurring within the soil system. The differences in soil chemical properties among sites may be related to differences in irrigation management, soil mineral composition and nutrient inputs. The seasonal differences in soil electrical conductivity and available nitrogen may be related to plant nutrient uptake, microbial nitrogen transformations and irrigation intensity. Earlier studies have shown that the quality of irrigation water and salinity may directly affect the development of soil salinity and nutrient dynamics in irrigated agricultural soils (Jadhav et al. 2025, Qiao et al. 2026).

The regression results suggest that irrigation water nutrients may influence soil nutrient availability, particularly for phosphorus. The positive relationship between irrigation water phosphate and soil available phosphorus suggests that irrigation water may act as an important pathway for phosphorus transfer into agricultural soils, where repeated irrigation may gradually increase soil phosphorus availability through nutrient deposition and soil chemical transformations. Similar responses have been reported in irrigated systems, where water inputs modify soil phosphorus availability and nutrient-supply capacity (He et al. 2023).

In contrast, the negative relationship between irrigation-water nitrite and soil available nitrogen suggests that soil nitrogen availability is regulated by complex biogeochemical processes rather than by direct nitrogen input from irrigation water alone. Nitrogen transformations such as nitrification, denitrification, and microbial immobilisation can regulate soil nitrogen independently of the composition of irrigation water. The absence of significant relationships between irrigation water pH and soil pH, and between water EC and soil EC, further indicates that soil buffering capacity and management practices can moderate the influence of irrigation water chemistry on soil properties. Previous research has shown that irrigation regimes and water management can regulate soil salinity dynamics and nutrient availability, demonstrating that soil responses to irrigation water chemistry depend on interactions between water inputs, soil properties, and management practices (Hui et al. 2025, Liu et al. 2025).

The present study was based on seasonal observations from a single watershed and evaluated only selected water and soil variables. Future studies incorporating additional nutrient fractions, microbial processes, and long-term monitoring across multiple watersheds would provide a more comprehensive understanding of water–soil nutrient interactions in tropical agricultural systems.

CONCLUSIONS

The results of this study indicate that irrigation water chemistry varies among sites and seasons and is associated with variations in soil physicochemical conditions. Spatial and seasonal variations in irrigation water EC, nitrite, phosphate, and cadmium were consistent with variations in soil physicochemical properties. Regression results indicate that irrigation water influences phosphorus transfer and soil phosphorus dynamics, whereas internal biogeochemical processes primarily govern soil nitrogen availability. Soil buffering capacity moderates the impact of irrigation water chemistry, as evidenced by the lack of significant relationships between water pH and EC and soil pH and EC. Overall, the results emphasise the importance of integrated monitoring of irrigation water and soil properties to understand better water–soil interactions and support sustainable agricultural management.

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