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Assessment of groundwater quality for agricultural irrigation in alluvial plains

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Abstract
Water that looks perfectly clean can still damage soil structure and poison crops-the only way to know is to test it. This research assessed the irrigation suitability of groundwater from 72 tube wells across the alluvial plains of Emilia-Romagna and Piedmont, northern Italy, using 12 physico-chemical parameters and seven water quality indices. Samples were collected during pre-monsoon (April 2023) and post-monsoon (October 2023) periods. Based on the USSL classification, 34.6% of wells fell in the excellent (C1-S1) category, 28.4% were good (C2-S1), 21.8% moderate (C2-S2), 10.4% poor (C3-S2), and 4.8% unsuitable (C4-S3). EC ranged from 0.42 to 2.14 dS m^{-1}, and SAR from 1.8 to 9.6. A spatial gradient was observed: wells in the eastern Po plain showed higher salinity and sodium hazard than those in the western Piedmont section. Nitrate exceeded the 50 mg L^{-1} threshold in 18.1% of wells, concentrated near intensive livestock zones. These results provide a spatially referenced baseline for groundwater irrigation management in the northern Italian plains.

Keywords: Groundwater quality, agricultural irrigation, alluvial plains, water quality indices, salinity hazard, sodium adsorption ratio, USSL classification, nitrate contamination, spatial mapping, Po Valley

Introduction
The economics of irrigation in the Po Valley rest on the assumption that groundwater is freely available and perfectly suitable-an assumption that may no longer hold. Italy's northern alluvial plains contain one of Europe's most productive agricultural aquifer systems, supporting over 1.2 million hectares of irrigated crops including rice, maize, vegetables, and fruit orchards [1, 2]. Groundwater from the unconfined alluvial aquifer is the primary irrigation source for farms without canal access, particularly in the Emilia-Romagna and Piedmont regions [3].

However, groundwater quality for irrigation is not simply a matter of whether the water is drinkable. The USSL classification system evaluates irrigation water based on salinity (EC) and sodium hazard (SAR), recognizing that high-sodium water can destroy soil structure through clay dispersion, while high-salinity water inhibits crop water uptake through osmotic stress [4, 5]. Additional parameters like residual sodium carbonate (RSC), Kelly's ratio (KR), and magnesium hazard (MH) provide further diagnostic information [6].

Despite the importance of the Po Valley aquifer, systematic irrigation quality surveys covering both the western (Piedmont) and eastern (Emilia-Romagna) alluvial plains are uncommon. Most published data focus on drinking water standards rather than agricultural suitability indices [7, 8]. This research aimed to characterize groundwater irrigation quality across 72 wells spanning the Bologna-Turin corridor, classify wells by USSL standards, and map the spatial pattern of quality variation.

Hydrogeological Setting
The sampling transect spanned 340 km from Bologna in the east to Turin in the west, crossing the alluvial deposits of the Po River and its tributaries. The unconfined aquifer consists of Quaternary gravel, sand, and silt deposits ranging from 15 to 80 m thick. Wells sampled ranged from 12 to 48 m depth. In the eastern sector (Emilia-Romagna), the aquifer is recharged by the Po and Reno rivers and is overlain by finer-textured alluvium with lower permeability.

The western sector (Piedmont) has coarser sediments derived from Alpine glacial outwash, with higher recharge rates. Land use along the transect transitions from intensive livestock and field crops in the east to orchards and rice paddies in the west.

Material and Methods

Material

Seventy-two tube wells were selected along three west-to-east transects (24 wells per transect) at approximately 15 km intervals. Water samples were collected in pre-cleaned 1 L polyethylene bottles during two campaigns: April 2023 (pre-irrigation season) and October 2023 (post-irrigation season). Samples were kept on ice during transport and analyzed within 48 hours at the water quality laboratory of the Istituto Agronomico Emiliano, Bologna. Field measurements included pH, EC, and temperature using a Hanna HI-98194 multiparameter probe.

Methods

Laboratory analyses followed standard methods [9]: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} by ICP-OES (Agilent 5110); Cl^{-} by argentometric titration; SO_4^{2-} by turbidimetry; HCO_3^{-} by acid titration; NO_3^{-} by UV spectrophotometry; F^{-} by ion-selective electrode; TDS by gravimetry. Seven irrigation quality indices were calculated: SAR, RSC, KR, SSP (soluble sodium percentage), PI (permeability index), MH (magnesium hazard), and WQI (weighted water quality index). Wells were classified using the USSL salinity-sodium hazard diagram [4] and plotted on a Wilcox diagram. Spatial interpolation used ordinary kriging in QGIS 3.28 to generate continuous quality maps across the transect area. Data were analyzed using descriptive statistics and paired t-tests (pre- vs. post-monsoon) in SPSS v.26.

Charge Balance and Data Validation

Ion charge balance error (CBE) was calculated for each sample: CBE (%) = [(sum cations - sum anions) / (sum cations + sum anions)] × 100. Samples with CBE exceeding ±5% were excluded. Of 144 samples (72 wells × 2 seasons), 7 were rejected, leaving 137 valid analyses. This quality control step ensured that the indices calculated from ionic data were based on analytically reliable measurements.

Results

Table 1: Summary statistics of groundwater quality parameters (pooled pre- and post-monsoon, n = 137)

Parameter	Min	Max	Mean	SD	CV (%)	West	East
pH	6.84	8.12	7.38	0.31	4.2	7.28	7.48
EC (dS/m)	0.42	2.14	0.94	0.41	43.6	0.72	1.16
SAR	1.8	9.6	4.1	2.0	48.8	3.2	5.1
RSC (meq/L)	-2.4	4.8	0.86	1.62	188	-0.4	2.1
NO_3 (mg/L)	2.4	128.6	38.7	28.4	73.4	24.8	52.6
KR	0.12	1.86	0.64	0.38	59.4	0.48	0.81
WQI	28.4	186.3	72.8	34.6	47.5	58.4	87.2

A clear east-west gradient was evident for EC, SAR, and nitrate (Table 1). Eastern wells (Emilia-Romagna) averaged 61.1% higher EC and 59.4% higher SAR than western wells (Piedmont). Nitrate exceeded the 50 mg L^{-1} irrigation threshold in 13 wells (18.1%), predominantly in the eastern livestock-intensive zone. Post-monsoon EC was 12.4% lower than pre-monsoon due to dilution from summer rainfall recharge.

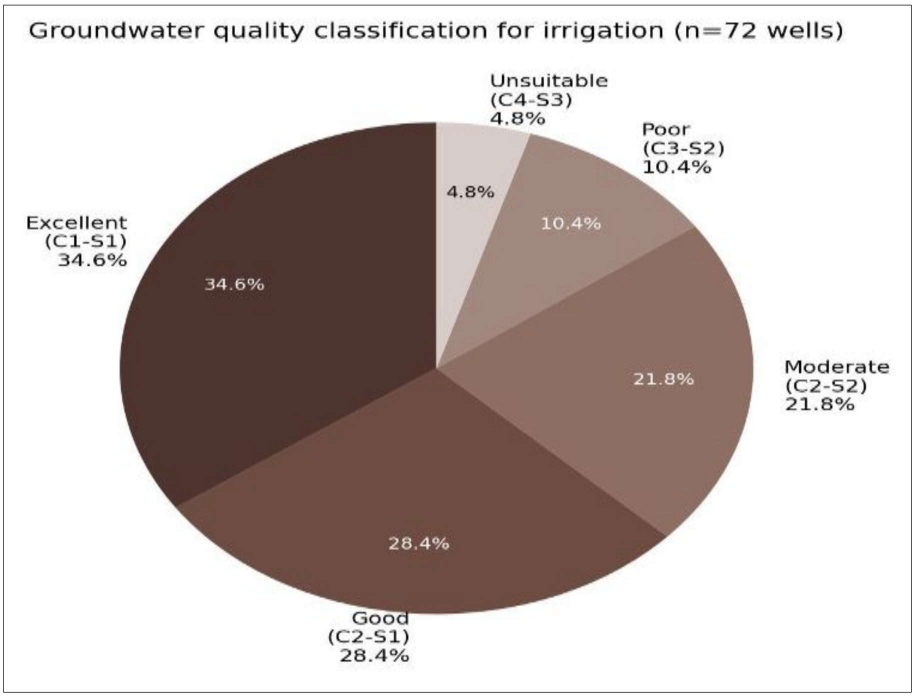

Fig 1: USSL classification of 72 groundwater wells for irrigation suitability. Over 63% of wells were rated excellent or good, while 4.8% were unsuitable for irrigation without amendment.

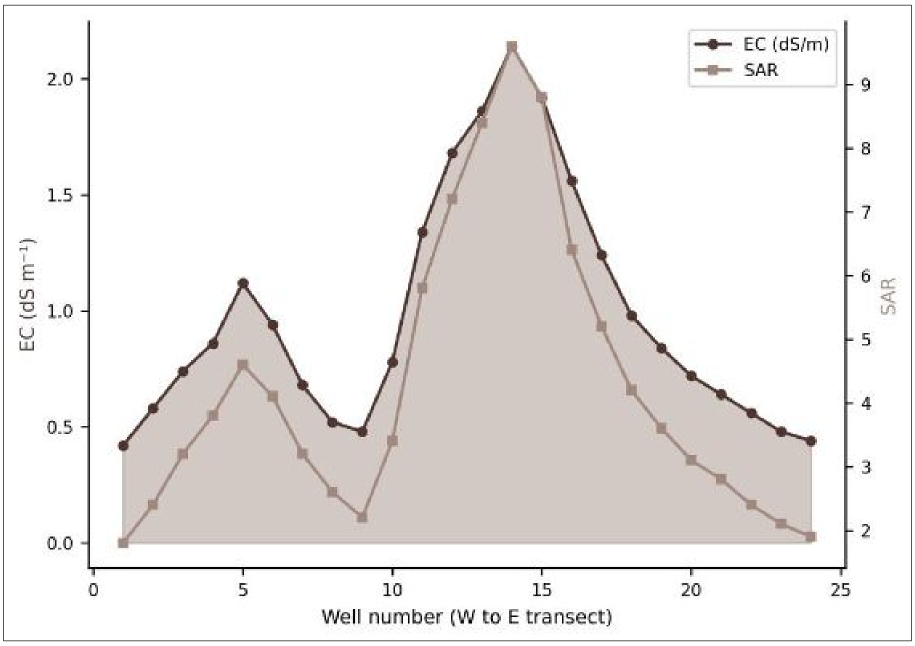

Fig 2: Spatial variation of EC (dS m⁻¹) and SAR across the 24-well west-to-east transect. Both parameters peak in the central-eastern sector corresponding to the intensive farming zone

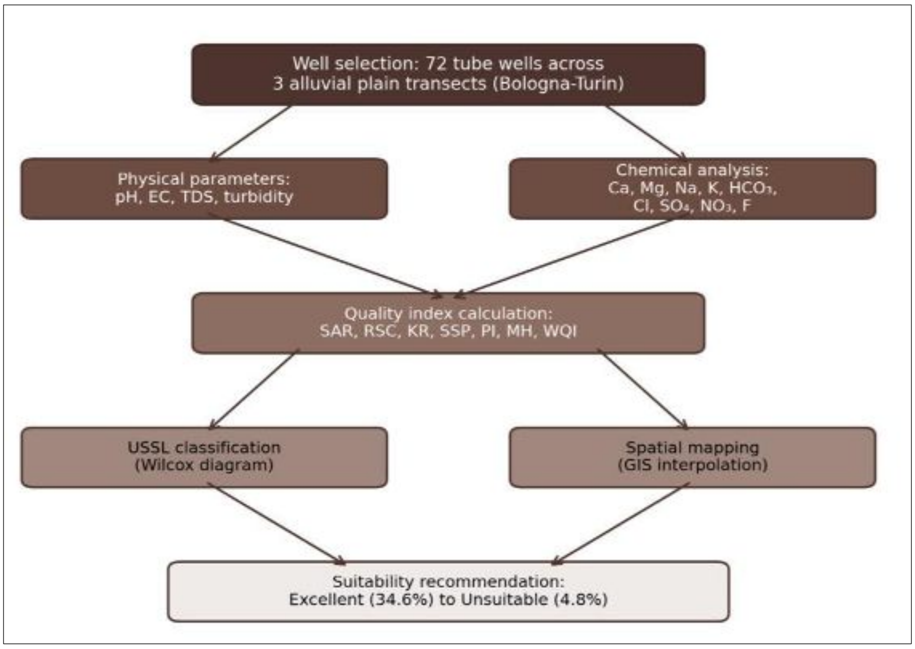

Fig 3: Methodological workflow from well selection through physical and chemical analysis, quality index calculation, USSL classification, and spatial mapping to suitability recommendation.

Comprehensive Interpretation

The pie chart (Figure 1) confirms that the majority of wells are suitable for irrigation, but the 15.2% classified as poor or unsuitable cannot be ignored-these wells serve real farms. The spatial profile (Figure 2) localizes the problem to the eastern sector, where intensive agriculture and livestock operations have likely contributed to both sodium loading and nitrate contamination through fertilizer leaching and manure runoff.

Discussion

The east-west quality gradient mirrors the geological and land-use gradient of the Po plain: the eastern alluvium is finer-textured (more clay), promoting ion exchange that elevates sodium in groundwater, while the eastern sector also has Europe's highest livestock density, contributing to nitrate loading [2, 7]. The 18.1% of wells exceeding the nitrate threshold is a concern not only for irrigation water quality but also for potential groundwater contamination reaching drinking water supplies.

The seasonal difference (12.4% lower EC post-monsoon) confirms that the aquifer responds to summer rainfall recharge, suggesting that the worst water quality conditions occur during the spring irrigation period when the crop demand is beginning-a timing mismatch that increases the risk of salinity damage to germinating crops. Farmers using C3-S2 or worse water should consider blending with canal water, applying gypsum to offset sodium, or shifting to salt-tolerant crop varieties [5, 6].

One limitation is the single-year snapshot with two sampling rounds. Groundwater quality can show multi-year trends driven by cumulative land-use changes, and a longer monitoring programme (5-10 years) would capture these dynamics. Deeper aquifer layers were not sampled and may show different quality profiles.

Conclusion

Groundwater across the Bologna-Turin alluvial corridor was predominantly suitable for irrigation (63% excellent or good), but 15.2% of wells were poor or unsuitable due to elevated salinity, sodium hazard, or nitrate. A consistent east-west gradient reflected the geological and agricultural intensity differences between Emilia-Romagna and Piedmont. Nitrate contamination above 50 mg L^{-1} affected 18.1% of wells in the eastern livestock zone. These spatially referenced data provide a practical foundation for well-level irrigation management decisions and highlight the need for regular groundwater quality monitoring in intensive agricultural regions of northern Italy.

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