Hydrochemical Characterization, Water-Quality Status and Irrigation Suitability of the Tawa Sub-Basin of Narmada River

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Abstract - *The Tawa River, the largest left-bank tributary of the Narmada, serves as a critical water resource in central India. This study evaluates the major-ion chemistry, hydrochemical facies, dominant controls on dissolved solutes, drinking-water status, and irrigation suitability of the Tawa River using the 2022 dataset from 12 sampling stations. Water was mildly alkaline (pH 7.20–8.30) and weakly mineralized, with total dissolved solids (TDS) of 80–280 mg L^{-1} and total hardness of 55.93–161.06 mg L^{-1} as $CaCO_3$. Calcium and bicarbonate were the dominant cation and anion, respectively, and the Piper plot places the samples predominantly in the Ca–Mg–HCO_3 facies. Both cation and anion Gibbs ratios fall in the rock-dominance field, indicating that water–rock interaction/weathering is the principal control on major-ion chemistry. Weighted arithmetic WQI classified 10 of 12 samples (83.3%) as excellent and two samples (16.7%) as unsuitable due to fluoride concentrations above the BIS acceptable value, though both remained below the permissible limit. Irrigation indices indicate low sodium hazard: all samples were excellent by SAR, safe by RSC, suitable by MH and KR, and within Class I–II PI. Standardized PCA explained 86.1% of the total variance in the first two components, separating a mineralization-related group from samples more strongly influenced by pH and sulfate. The Tawa samples show a chemically dilute, Ca–Mg–HCO_3 river system dominated by weathering, with favorable irrigation quality but localized drinking-water constraints.*

Key Words: Tawa River; Narmada Basin; hydrochemistry; Piper diagram; Gibb's diagram; water quality index; irrigation suitability; PCA.

1. INTRODUCTION

River chemistry integrates weathering, atmospheric inputs, hydrological routing, biological processing and human disturbance. Major dissolved ions are particularly useful because their relative abundances retain information on mineral sources and the processes that regulate solute export. Hydrochemical facies and ionic ratios therefore provide a compact way to distinguish broad controls such as rock weathering, precipitation and evaporation, while multivariate methods resolve co-varying chemical signals (Piper, 1944; Gibbs, 1970; Jolliffe, 2002).

The Tawa is the longest tributary of the Narmada, extending for about 172 km and draining a catchment of roughly 5983 km^2 before joining the Narmada in Narmadapuram district (Mehto & Chakrapani, 2013; Gupta et al., 2022). The basin contains the Tawa reservoir and supports irrigation, fisheries and other water-dependent activities. Earlier work on the Tawa identified a silicate-dominated geological setting with a strong contribution from carbonate-rich soils and weathering products; carbonate and silicate weathering were both shown to contribute to dissolved bicarbonate (Mehto & Chakrapani, 2013). Studies of the wider Narmada system likewise report Ca–Mg–HCO_3 dominated waters and a dominant role for rock–water interaction in major-ion chemistry (Gupta et al., 2022).

The present work focuses on the final set of 12 Tawa stations and brings the hydrochemical observations, Piper and Gibbs interpretations, principal component analysis and water-quality indices into one assessment. The objectives were to describe the basic physicochemical and major-ion composition, identify the dominant hydrochemical facies and controlling process, assess drinking-water quality using the weighted arithmetic WQI, and evaluate irrigation suitability using SAR, Na%, RSC, magnesium hazard, Kelley ratio and permeability index.

2. MATERIALS AND METHODS

2.1 Study area and sampling framework

The study area covers the Tawa River sub-basin in central Madhya Pradesh. The Tawa rises in the Satpura–Mahadeo hill region and flows north-westward to its confluence with the Narmada. The final dataset retained 12 stations (NRT-30c to NRT-30n), distributed across the Tawa channel and tributary network (Figure 1). The supplied analytical fields correspond to the 2023 august(monsoon) dataset and include pH, TDS, total hardness, fluoride, chloride, nitrate, sulphate, bicarbonate, Na^+, K^+, Mg^{2+} and Ca^{2+}, together with carbon and nitrogen variables.

2.2 Hydrochemical and statistical treatment

Major-ion concentrations were evaluated in mg L^{-1} for water-quality comparison and converted to milliequivalents per liter (meq L^{-1}) for hydrochemical classification and irrigation indices. The Piper diagram was constructed from the percentage of total cation and anion equivalents and used to identify dominant hydrochemical facies (Piper, 1944). The Gibbs approach uses $(Na^++K^+)/(Na^++K^++Ca^{2+})$ and $Cl^-/(Cl^-+HCO_3^-)$, plotted against TDS, to distinguish broad rock-dominance, evaporation–crystallization and precipitation controls (Gibbs, 1970). These fields are interpreted as first-order controls rather than proof of a single mineral reaction.

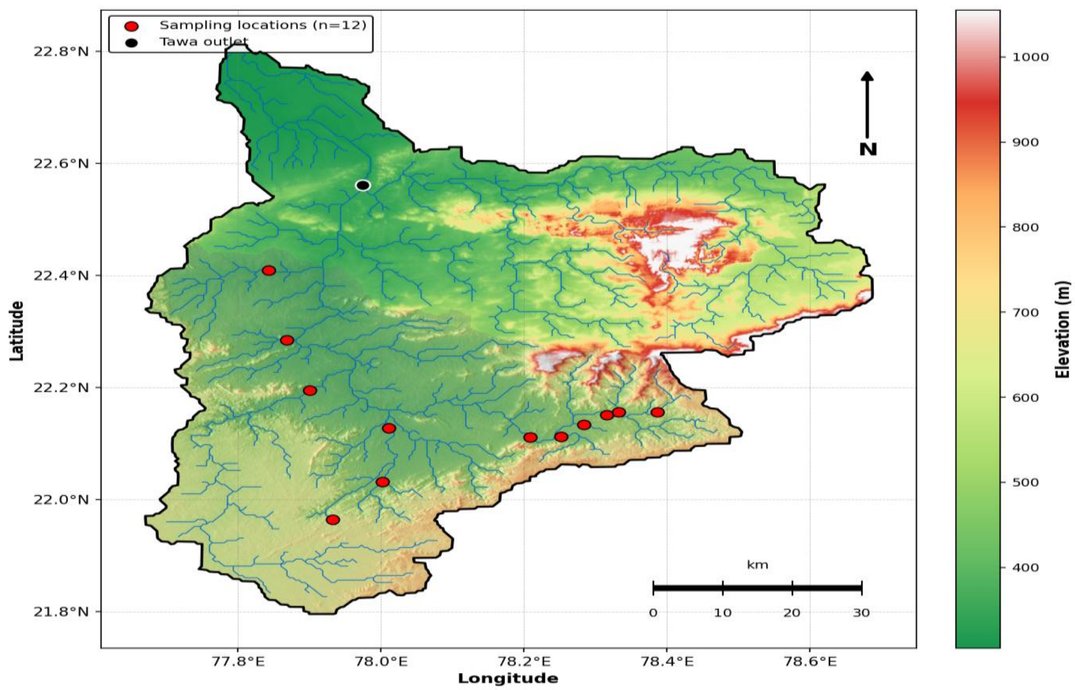

Figure 1. Tawa River catchment and locations of the 12 retained sampling stations. The sampling network spans the tributary-influenced Tawa system shown against catchment elevation and drainage.

BIS IS 10500:2012 provides acceptable and permissible limits in the absence of an alternate source (Bureau of Indian Standards [BIS], 2012). WHO values are shown only where a health-based or operational/acceptability reference is available; WHO does not establish health-based guideline values for several general mineral parameters such as TDS, hardness, calcium, magnesium and sodium (World Health Organization [WHO], 2022).

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Table 1. Basic physicochemical and major-ion characteristics of the Tawa River

Parameter	Unit	Tawa River (n=12) Min–Max	Mean ± SD	BIS acceptable	BIS permissible*	WHO reference†	Compliance
pH	—	7.20–8.30	7.90 ± 0.37	6.5–8.5	6.5–8.5	6.5–8.5 (operational)	All within BIS acceptable limit
TDS	mg L^{-1}	80.00–280.00	171.67 ± 66.17	500	2000	No health-based GV	All within BIS acceptable limit
Total hardness	mg L^{-1} as $CaCO_3$	55.93–161.06	114.04 ± 37.49	200	600	No health-based GV	All within BIS acceptable limit
Ca^{2+}	mg L^{-1}	15.48–40.21	30.30 ± 8.83	75	200	No health-based GV	All within BIS acceptable limit
Mg^{2+}	mg L^{-1}	4.20–15.22	9.33 ± 4.06	30	100	No health-based GV	All within BIS acceptable limit
Na^{+}	mg L^{-1}	6.58–30.27	17.05 ± 8.29	200	—	No health-based GV	All within BIS acceptable limit
K^{+}	mg L^{-1}	0.91–2.55	1.43 ± 0.52	—	—	—	All within BIS acceptable limit
HCO_3^{-}	mg L^{-1}	60.39–225.70	138.98 ± 59.42	—	—	—	All within BIS acceptable limit
SO_4^{2-}	mg L^{-1}	13.21–34.17	20.78 ± 6.11	200	400	500 (acceptability)	All within BIS acceptable limit
Cl^{-}	mg L^{-1}	7.16–38.03	14.17 ± 8.85	250	1000	250 (acceptability)	All within BIS acceptable limit
NO_3^{-}	mg L^{-1}	2.59–10.24	5.20 ± 2.65	45	45	50	All 10 reported values within limits
F^{-}	mg L^{-1}	0.00–1.24	0.20 ± 0.46	1.0	1.5	1.5	10/12 within acceptable; 2/12 above acceptable but below permissible

** Permissible limit applies in the absence of an alternate source. † WHO reference values are not all health-based guideline values; "No health-based GV" means WHO has not established a health-based guideline value. Nitrate was reported at 10 of 12 stations.*

Principal component analysis (PCA) was performed on standardized hydrochemical variables so that parameters with different units and numerical ranges contributed comparably (Jolliffe, 2002). The retained biplot shows PC1 explaining 70.6% and PC2 explaining 15.5% of the variance. Water-quality assessment used the weighted arithmetic WQI framework of Brown et al. (Brown et al., 1972), with BIS acceptable limits as the standard values. Nine complete parameters were used: pH, TDS, total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, Cl^{-} and F^{-}. Nitrate was not included in the WQI because two stations lacked reported NO_3^{-} values; its measured range is nevertheless compared independently with drinking-water standards.

The irrigation indices were calculated from meq L^{-1} concentrations:

$SAR = Na^{+}/[((Ca^{2+}+Mg^{2+})/2)^{0.5}]$; (**Eq.**1)
$Na\% = 100(Na^{+}+K^{+})/(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})$; (**Eq.**2)
$RSC = (CO_3^{2-}+HCO_3^{-})-(Ca^{2+}+Mg^{2+})$; (**Eq.**3)
$MH = 100Mg^{2+}/(Ca^{2+}+Mg^{2+})$; (**Eq.**4)
$KR = Na^{+}/(Ca^{2+}+Mg^{2+})$; and (**Eq.**5)
$PI = 100[Na^{+}+(HCO_3^{-})^{0.5}]/(Ca^{2+}+Mg^{2+}+Na^{+})$. (**Eq.**6)

SAR classes follow Richards (Richards, 1954), PI classes follow Doneen (Doneen, 1964), and KR interpretation follows the conventional threshold of 1 (Kelley, 1951).

3. RESULTS AND DISCUSSION

3.1 Physicochemical characteristics and drinking-water status

The Tawa water was consistently near neutral to mildly alkaline, with pH ranging from 7.20 to 8.30 (mean 7.90 ± 0.37). TDS ranged from 80 to 280 mg L^{-1}, while total hardness ranged from 55.93 to 161.06 mg L^{-1} as $CaCO_3$. Thus, the river was generally weakly mineralized and moderately soft to moderately hard over the sampled reach. Calcium (15.48–40.21 mg L^{-1}) and magnesium (4.20–15.22 mg L^{-1}) remained below BIS acceptable limits, while Na^+, Cl^- and SO_4^{2-} were also low. Nitrate was 2.59–10.24 mg L^{-1} at the 10 stations with reported values and remained well below the BIS and WHO nitrate limits.

Fluoride is the only parameter showing a local departure from the BIS acceptable value. NRT-30d (1.24 mg L^{-1}) and NRT-30m (1.13 mg L^{-1}) exceeded the 1.0 mg L^{-1} acceptable limit but remained below the 1.5 mg L^{-1} permissible limit and WHO fluoride guideline (World Health Organization [WHO], 2022, Bureau of Indian Standards [BIS], 2012) . These two sites should therefore be described as above the acceptable BIS value, not as exceeding the maximum permissible value.

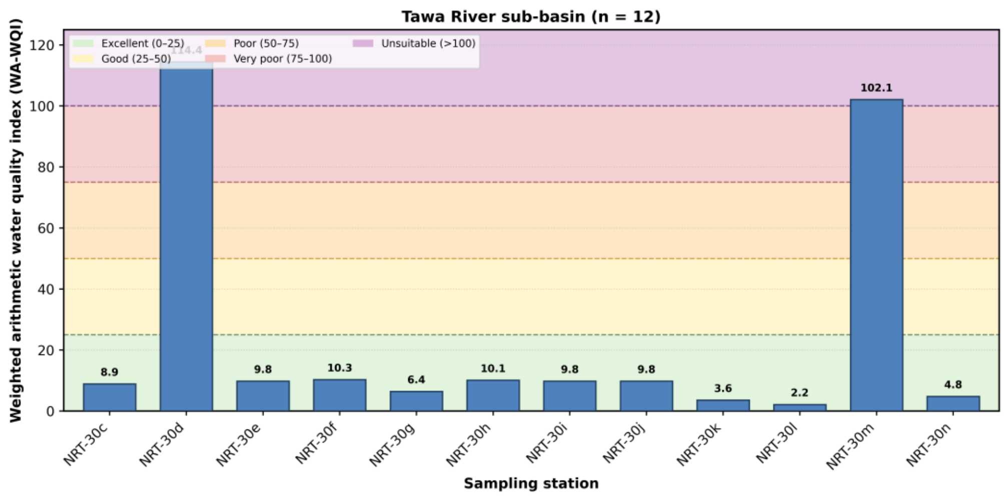

Figure 5. Weighted arithmetic water quality index (WA-WQI) for the 12 Tawa River stations. Background bands show Excellent (0–25), Good (26–50), Poor (51–75), Very poor (76–100) and Unsuitable (>100) classes. The WQI uses nine complete parameters and BIS acceptable limits.

3.2 Hydrochemical facies and major-ion chemistry

The Piper diagram shows a compact distribution of all 12 samples in the Ca–Mg–HCO_3 sector (Fig. 2). On an equivalent basis, Ca^{2+} contributes about 51% of the major cations on average, followed by Mg^{2+} (~25%) and Na^++K^+ (~25%); HCO_3^- accounts for about 70% of the major anions, with SO_4^{2-} and Cl^- contributing much smaller fractions. The resulting Ca–Mg–HCO_3 character is consistent with the earlier Tawa study, which found strong contributions from carbonate-rich soils and weathering of silicate lithologies (Mehto & Chakrapani, 2013). Similar Ca–Mg–HCO_3 dominance and weathering control have also been reported for the upper Narmada (Gupta et al., 2022).

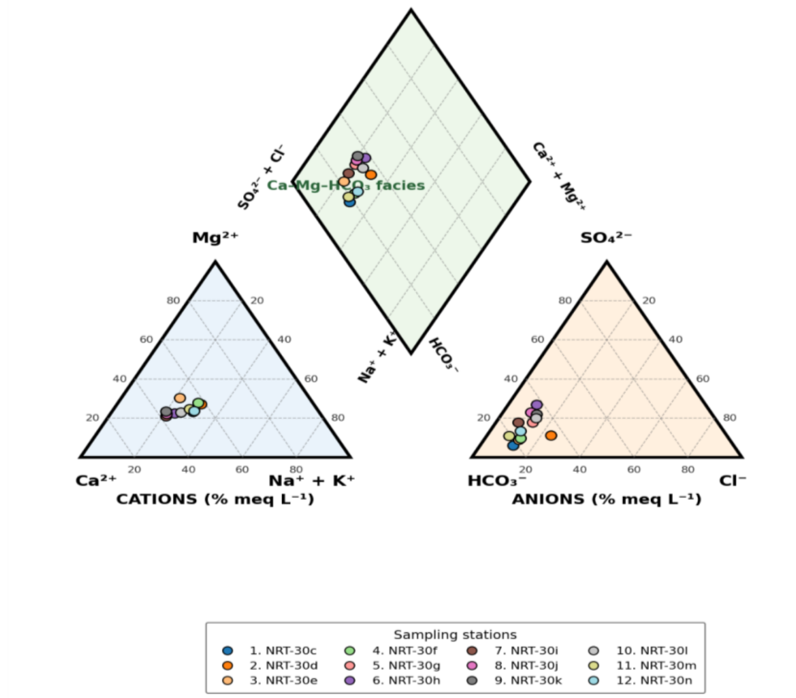

Figure 2. Piper trilinear diagram showing the cation, anion and projected hydrochemical facies of the 12 Tawa River samples. The samples cluster predominantly in the Ca–Mg–HCO_3 facies.

3.3 Hydrochemical controlling processes

The two Gibbs plots place the samples within the rock-dominance/weathering field rather than the evaporation–crystallization or precipitation-dominance fields (Fig. 3). The cation ratio [(Na^++K^+)/(Na^++K^++Ca^{2+})] ranges from 0.251 to 0.421, while the anion ratio [Cl^-/(Cl^-+HCO_3^-)] ranges from 0.093 to 0.267. Together with the low-to-moderate TDS, these positions indicate that dissolved-ion composition is principally inherited from water–rock interaction. This interpretation agrees closely with the longer-term Tawa hydrochemical study, which found carbonate-rich soils over a silicate lithological framework and estimated contributions from both carbonate and silicate weathering (Mehto & Chakrapani, 2013).

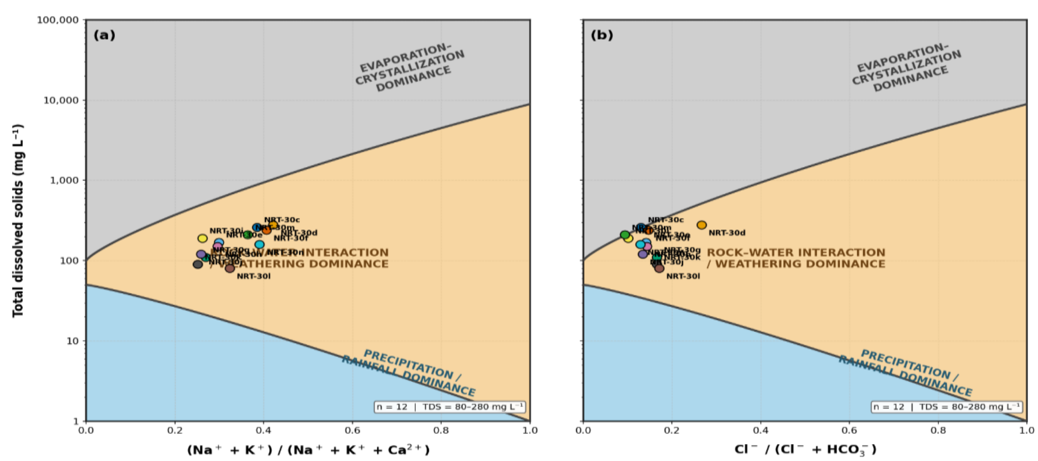

Figure 3. Gibbs diagrams for the Tawa River showing TDS against (a) (Na^++K^+)/(Na^++K^++Ca^{2+}) and (b) Cl^-/(Cl^-+HCO_3^-). The sample distribution indicates predominant rock–water interaction/weathering control.

3.4 Multivariate structure of the hydrochemical dataset

The standardized PCA provides a compact summary of relationships among the measured hydrochemical variables (Fig. 4). PC1 explains 70.6% of the total variance and is associated with the mineralization-related group of variables, including TDS, total hardness, and the major dissolved ions. PC2 explains a further 15.5% and is more strongly influenced by pH and SO_4^{2-}, separating stations with relatively distinct acid–base and sulfate signatures. The first two components therefore explain 86.1% of the variance. Stations on the positive PC1 side generally coincide with higher dissolved-ion concentrations, whereas NRT-30l, NRT-30k, NRT-30g and NRT-30n occupy the lower-mineralization side. The PCA supports the Piper–Gibb's interpretation: the dominant spatial structure is controlled by the dissolved major-ion pool rather than a single nutrient or pollutant variable.

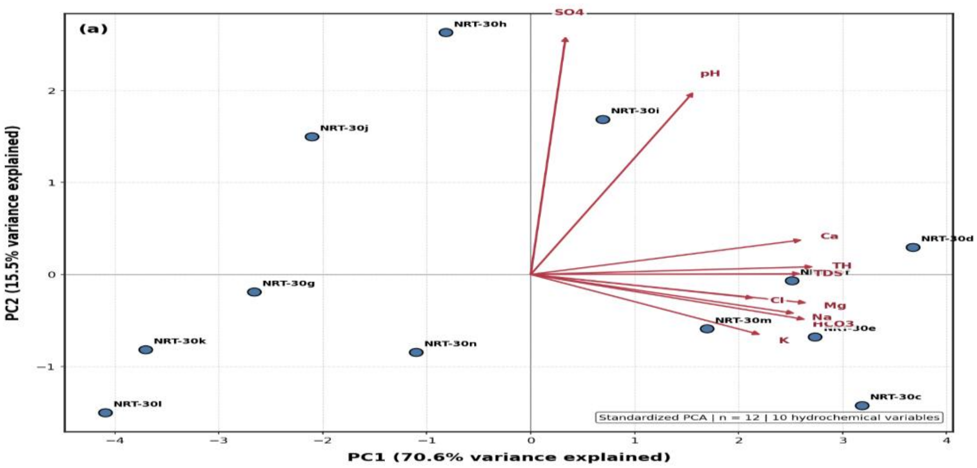

Figure 4. PCA biplot of standardized hydrochemical variables and sampling stations. PC1 and PC2 explain 70.6% and 15.5% of the total variance, respectively.

3.5 Integrated drinking-water and irrigation suitability

Table 2 presents the recalculated station-wise indices. WA-WQI values range from 2.15 to 114.42, with a mean of 24.34. Ten stations fall in the Excellent class (0–25), whereas NRT-30d and NRT-30m fall in the Unsuitable class (>100) (Brown et al., 1972). The two high WQI values coincide with the two fluoride concentrations above the BIS acceptable level.

The irrigation results are consistently favorable. SAR values range from 0.35 to 1.06, placing all 12 samples in the excellent class (<10) (Richards, 1954). Na% ranges from 19.14 to 30.61%; one sample is in the excellent category (<20), while the remaining samples are in the good category (20–40). RSC ranges from −0.37 to 0.69 meq L^{-1}, below the commonly applied 1.25 meq L^{-1} threshold. MH ranges from 26.67 to 39.75%, below the 50% threshold, and KR remains between 0.22 and 0.43, below 1. PI ranges from 64.23 to 91.57%; five samples are class I (>75%), and seven are Class II (25–75%), both generally regarded as suitable for irrigation (Doneen, 1964 , Kelley, 1951).

Table 2. Station-wise drinking-water and irrigation suitability indices for the 12 retained Tawa River samples. Irrigation suitability is based on the individual index criteria.

S.No.	Station	WA-WQI	Drinking class	SAR	Na (%)	RSC (meq L^{-1})	MH (%)	KR	PI (%)	Irrigation
1	NRT-30c	8.88	Excellent	0.98	29.45	0.69	33.31	0.40	74.21	Suitable
2	NRT-30d	114.42	Unsuitable	1.06	30.61	-0.12	39.43	0.43	69.13	Suitable
3	NRT-30e	9.79	Excellent	0.61	20.66	-0.01	38.90	0.24	64.23	Suitable
4	NRT-30f	10.30	Excellent	0.96	29.18	0.30	39.75	0.40	72.55	Suitable
5	NRT-30g	6.41	Excellent	0.44	20.82	-0.20	28.65	0.25	79.76	Suitable
6	NRT-30h	10.09	Excellent	0.56	22.86	-0.37	29.55	0.28	71.43	Suitable

7	NRT-30i	9.80	Excellent	0.57	20.62	-0.24	26.67	0.25	66.50	Suitable
8	NRT-30j	9.81	Excellent	0.44	20.10	-0.28	28.00	0.24	75.69	Suitable
9	NRT-30k	3.59	Excellent	0.35	19.14	-0.29	29.31	0.22	81.14	Suitable
10	NRT-30l	2.15	Excellent	0.46	24.83	-0.13	30.91	0.31	91.57	Suitable
11	NRT-30m	102.08	Unsuitable	0.85	27.35	0.47	34.24	0.36	74.00	Suitable
12	NRT-30n	4.80	Excellent	0.81	29.74	0.18	33.97	0.41	82.11	Suitable

Table 3. Summary statistics and classification of drinking-water and irrigation indices for the Tawa River sub-basin.

Index	Minimum	Maximum	Mean	Interpretation/sample share
WA-WQI	2.15	114.42	24.34	10/12 excellent (83.3%); 2/12 unsuitable (16.7%)
SAR	0.35	1.06	0.67	12/12 excellent (100%)
Na (%)	19.14	30.61	24.61	1/12 excellent; 11/12 good
RSC (meq L^{-1})	-0.37	0.69	-0.00	12/12 safe (100%)
MH (%)	26.67	39.75	32.72	12/12 suitable (100%)
KR	0.22	0.43	0.31	12/12 suitable (100%)
PI (%)	64.23	91.57	75.19	5 Class I; 7 Class II; 100% suitable

4. CONCLUSIONS

The final 12-station Tawa dataset describes a chemically dilute, mildly alkaline river system with TDS of 80–280 mg L^{-1} and total hardness of 55.93–161.06 mg L^{-1} as $CaCO_3$. Ca^2 and HCO_3 dominate major-ion chemistry, and the Piper diagram identifies a predominantly Ca–Mg–HCO_3 water type. Gibbs ratios consistently place the samples in the rock-dominance field, supporting water–rock interaction/weathering as the principal first-order control. It agrees with earlier Tawa observations that combine carbonate-rich soils with silicate lithology as sources of dissolved solutes (Mehto & Chakrapani, 2013)

From a drinking-water perspective, the measured chemistry is generally favorable: pH, TDS, hardness, Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, Cl^- and NO_3^- remain within the relevant standards. Fluoride is the only parameter requiring attention, with two stations exceeding the BIS acceptable value but remaining below the permissible limit. Consequently, the WA-WQI classifies 83.3% of the samples as excellent and 16.7% as unsuitable. For irrigation, all samples show excellent SAR, safe RSC, acceptable magnesium hazard and Kelley ratio, while PI places all samples in Classes I–II. The combined evidence indicates good irrigation quality and predominantly natural weathering control, but highlights the need for continued fluoride monitoring and broader microbial/trace-contaminant assessment before the river is considered potable without treatment.

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