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Landscape-Driven Variations in Runoff Nitrogen and Phosphorus Concentrations and Stoichiometric Ratios in the Chaihe Catchment: Effects of Hydrological Dynamics, Nutrient Export, and Eutrophication Risk

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ABSTRACT

Land-use configuration, hydrological connectivity, and nutrient source characteristics jointly regulate the transport of nitrogen (N) and phosphorus (P) from terrestrial landscapes to receiving waters. However, nutrient concentrations alone may not adequately characterize the ecological consequences of runoff because the relative availability of N and P can alter nutrient limitation and eutrophication potential. This study developed an integrated framework for examining landscape-driven nutrient export in the Chaihe Catchment, an important sub-catchment of Lake Dianchi in Yunnan Province, China. Rather than treating runoff nutrient concentrations as isolated water-quality variables, the analysis integrates four complementary dimensions: nutrient concentrations, dissolved-to-total nutrient fractions, N:P stoichiometry, and temporal–spatial variability across contrasting landscape units. Six representative landscape categories—flatland agricultural areas, greenhouse cultivation areas, tablelands, phosphorus-mining areas, phosphorus-rich forestland, and the downstream Chaihe River—were evaluated using runoff observations collected during six rainfall events between March and June 2026. Total nitrogen (TN), total phosphorus (TP), dissolved nitrogen (DN), dissolved phosphorus (DP), TN:TP, and DN:DP were examined using comparative statistics, correlation analysis, variability analysis, and nutrient-limitation assessment. The results demonstrate pronounced landscape control over nutrient export. Mean TN and DN concentrations were highest in greenhouse and flatland agricultural landscapes, whereas TP and DP were overwhelmingly elevated in phosphorus-mining areas. Across the catchment, mean TN and TP concentrations reached 5.22 and 10.45 mg L^{-1}, respectively, while DN accounted for approximately 60% of TN and DP accounted for approximately 27% of TP, indicating fundamentally different transport pathways for N and P. The catchment-wide mean TN:TP ratio was 4.09, but strong landscape differentiation was evident. Agricultural flatlands and tablelands generally exhibited P limitation, whereas phosphorus-mining areas and phosphorus-rich forests exhibited N limitation. Greenhouse areas and the downstream Chaihe River occupied an intermediate stoichiometric state in which neither nutrient was strongly limiting according to the adopted N:P screening thresholds. Temporal variability was particularly pronounced for N in agricultural and greenhouse landscapes and for P in phosphorus-mining areas, while spatial heterogeneity was strongest during the early wet season for N-related variables. Regression analysis further indicated that DN exerted a stronger statistical influence on DN:DP than DP, although both nutrients contributed significantly to stoichiometric variation.The findings indicate that nutrient management in the Chaihe Catchment should not rely on a single catchment-wide reduction strategy. Agricultural landscapes require measures targeting dissolved N export, whereas phosphorus-rich geological and mining landscapes require erosion and particulate-P control. The downstream convergence of contrasting nutrient sources may create a more balanced N:P environment that potentially enhances eutrophication pressure in Lake Dianchi. The study therefore proposes a landscape–hydrology–nutrient framework for prioritizing non-point-source pollution control and identifying high-risk nutrient pathways.

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1.INTRODUCTION

Freshwater eutrophication is increasingly recognized as a coupled problem involving land-use intensification, hydrological transport, nutrient enrichment, and ecological responses [1]. Nitrogen and phosphorus originating from agricultural land, disturbed soils, mining areas, urbanized landscapes, and other terrestrial sources can be mobilized during rainfall events and transported through surface runoff into rivers, reservoirs, and lakes [2]. Once these nutrients reach receiving waters, they may stimulate primary production and alter aquatic community structure, thereby increasing the probability of harmful algal blooms and other manifestations of eutrophication [3].

The environmental significance of runoff pollution cannot be evaluated solely by measuring the absolute concentration of an individual nutrient. Nitrogen and phosphorus interact through biological uptake, mineralization, adsorption, sedimentation, and other biogeochemical processes [4]. Consequently, the relative availability of N and P may determine which nutrient constrains biological production. Nutrient stoichiometry, particularly the N:P ratio, provides a useful framework for interpreting these interactions because it links nutrient concentrations with potential ecological limitation.

The problem becomes particularly complex in heterogeneous catchments. Agricultural fields generally receive substantial fertilizer inputs and can therefore act as important sources of dissolved and particulate nutrients [5]. Greenhouse cultivation may further modify nutrient transport because fertilization intensity, irrigation, soil disturbance, and rainfall interception differ substantially from conventional agriculture. In contrast, mining landscapes may have elevated nutrient concentrations because of geological background conditions and disturbance of nutrient-rich substrates. Forested landscapes are frequently considered nutrient-retaining systems, but forests located in naturally phosphorus-rich environments may behave differently from nutrient-poor forest ecosystems [6].

Hydrology provides the mechanism connecting these landscape sources to downstream waters. Rainfall intensity, antecedent moisture conditions, runoff generation, surface connectivity, soil erosion, and the timing of rainfall relative to agricultural activity can all influence nutrient mobilization [7]. Previous investigations of Lake Dianchi have demonstrated that rainfall processes, catchment characteristics, runoff volume, and nutrient concentrations jointly determine nutrient delivery to the lake. Early wet-season rainfall can be particularly important because accumulated nutrients and readily mobilizable materials may be flushed from terrestrial surfaces[8].

The Dianchi Basin is a particularly important setting for examining these processes. Agricultural intensification, urbanization, and phosphorus-rich geological formations have historically contributed to nutrient enrichment in the basin. Research has identified agriculture and urbanization as important nutrient sources, while phosphorus mining and processing represent an additional source in southern sub-basins. Moreover, phosphorus remains an important concern for Lake Dianchi because external and internal phosphorus cycling continue to influence eutrophication risk[9].

The Chaihe Catchment represents a particularly informative sub-system because its landscape is characterized by strong contrasts among agricultural areas, greenhouse cultivation, tablelands, phosphorus-mining zones, phosphorus-rich forestland, and downstream river environments [10]. An earlier investigation of the Chaihe Catchment documented substantial differences in runoff N and P concentrations and stoichiometric ratios among landscape types. However, the original investigation primarily emphasized descriptive comparisons of nutrient concentrations, temporal–spatial variability, and N:P limitation [11].

The present study develops a substantially expanded analytical framework around the same underlying observational dataset. The objective is not simply to reproduce the original land-use comparison, but to reinterpret the observations through a landscape–hydrology–nutrient framework. Four specific objectives were established:

1. **To quantify landscape-specific patterns of N and P export**, distinguishing total and dissolved nutrient pools.
2. **To investigate the hydrological and temporal dimensions of nutrient variability**, with particular attention to the transition and progression of the wet season.
3. **To characterize nutrient stoichiometry and identify potential nutrient limitation**, using both TN:TP and DN:DP relationships.
4. **To identify landscape-specific nutrient pathways and their implications for downstream eutrophication risk**, thereby providing a differentiated management framework for the Chaihe Catchment.

The central hypothesis is that **landscape heterogeneity does not merely change nutrient concentrations; it reorganizes the form, ratio, timing, and potential ecological consequences of nutrient export**.

2. Materials and Methods

2.1 Study area

The Chaihe sub-catchment is an important tributary system within the Lake Dianchi Basin in Yunnan Province, southwestern China. The investigated Chaihe sub-catchment extends approximately from 24°36′ to 24°37′ N and 102°41′ to 102°42′ E. The broader Chaihe system has an approximate drainage area of 306.18 km², with elevations in the wider catchment ranging from approximately 1,936 to 2,236 m [12].

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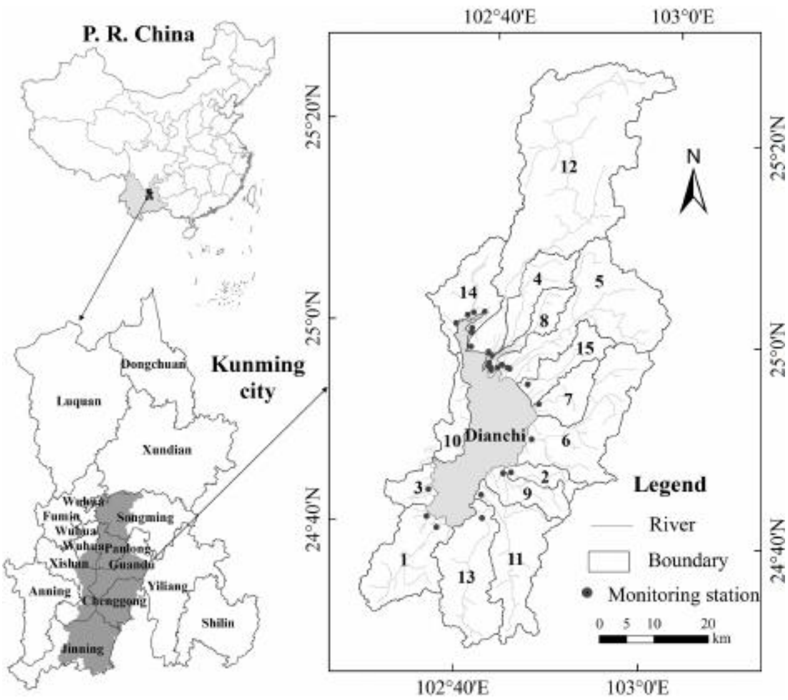


Source: W. Gao, R. W. Howarth, B. Hong, D. P. Swaney, and H. C. Guo, Estimating net anthropogenic nitrogen inputs (NANI) in the Lake Dianchi basin of China, European geosciences union, Volume 11, issue 16, BG, 11, 4577–4586, 2014, https://doi.org/10.5194/bg-11-4577-2014

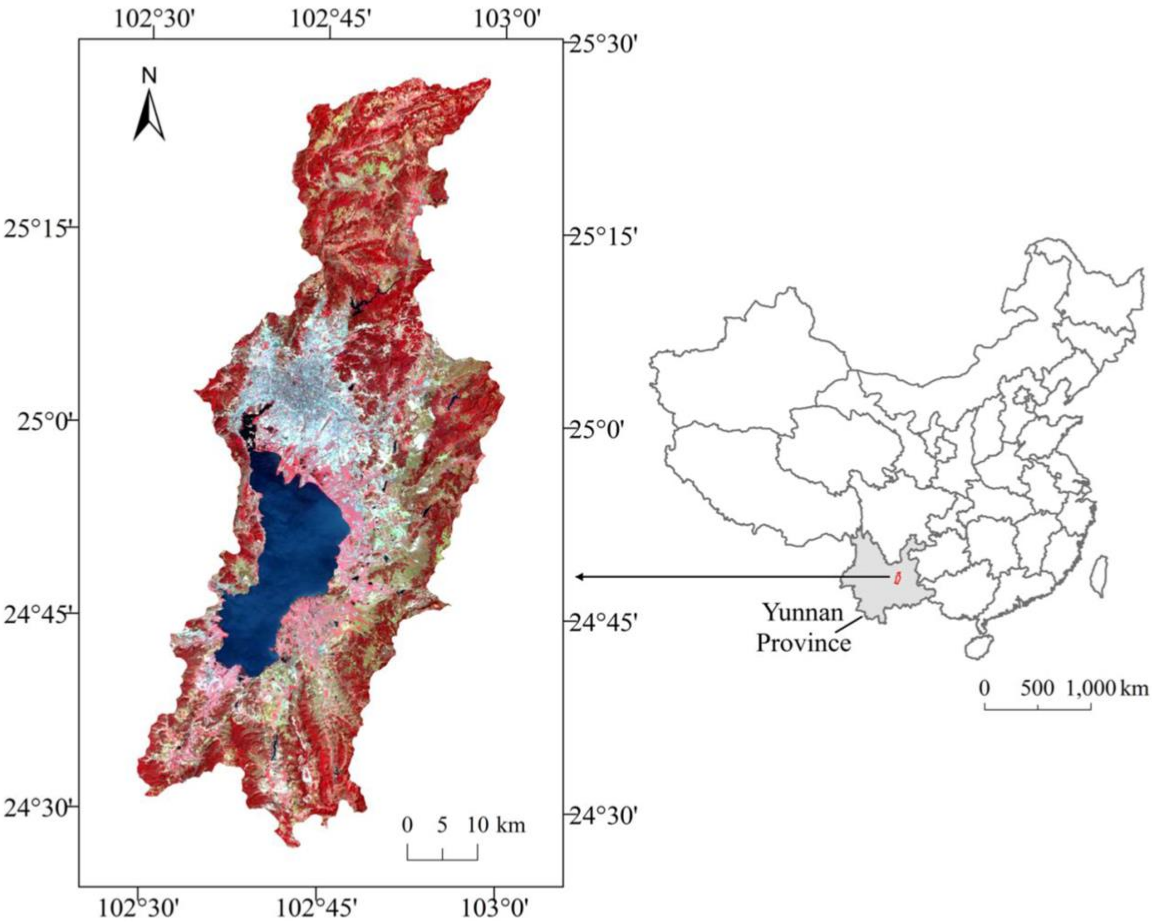
The terrain is dominated by hilly and mountainous landforms, with drainage generally directed toward Lake Dianchi. The study area examined here was located between the Chaihe Reservoir and Guanyin Mountain. Hydrological regulation by the reservoir resulted in limited surface-water flow in parts of the upstream channel, while the Chaihe channel near Guanyin Mountain represented an integrated downstream outlet. This configuration provided an opportunity to examine runoff generated by contrasting landscape units before convergence into the downstream river system [12].

The climate is characterized by a pronounced wet–dry seasonal pattern. The reported mean annual temperature is approximately 14.6 °C and mean annual precipitation is approximately 925.4 mm. Most rainfall occurs between May and October, when rainfall events can generate substantial surface runoff.

The landscape mosaic includes:

- flatland agricultural areas;
- greenhouse cultivation areas;
- tablelands;
- phosphorus-mining areas;
- phosphorus-rich forestland; and

- the downstream Chaihe River.



Note: The extent of the satellite image is restricted to the boundaries of the Dianchi watershed.

Source: Zhao Y, Zhang K, Fu Y, Zhang H. Examining Land-Use/Land-Cover Change in the Lake Dianchi Watershed of the Yunnan-Guizhou Plateau of Southwest China with Remote Sensing and GIS Techniques: 1974–2008. *International Journal of Environmental Research and Public Health*. 2012; 9(11):3843-3865. https://doi.org/10.3390/ijerph9113843

A distinctive characteristic of the region is the presence of phosphorus-rich geological formations associated with the Jinning phosphorus-mining belt. Consequently, phosphorus export cannot necessarily be attributed exclusively to agricultural fertilization; geological background and mining-related soil disturbance may also contribute to elevated P concentrations [12].

2.2 Sampling design

Twenty representative monitoring locations were distributed among six landscape categories:

Landscape category	Number of monitoring sites

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Flatland agricultural area	4
Greenhouse cultivation area	4
Tableland	3
Phosphorus-mining area	3
Phosphorus-rich forestland	5
Downstream Chaihe River	1
Total	**20**

Surface-runoff samples were collected following rainfall events. Six monitoring events were conducted between March and June 2026:

Sampling event	Date	Rainfall (mm)	Hydrological interpretation
E1	24 March	7	Early wet-season event
E2	14 Apr	21	Wet-season development
E3	18 Apr	62	High-rainfall event
E4	24 Apr	6	Low-rainfall event
E5	13 May	10	Mid-wet-season event
E6	05 June	46	Late wet-season event

The original sampling design used relatively enclosed artificial collection structures adapted to local terrain. Each monitoring location represented a comparatively independent runoff-generating landscape unit.

Water samples were acidified where appropriate and transported to the laboratory for analysis.

2.3 Nutrient measurements

Six primary variables were considered:

- total nitrogen (TN);
- total phosphorus (TP);
- dissolved nitrogen (DN);
- dissolved phosphorus (DP);
- TN:TP ratio; and
- DN:DP ratio.

Concentrations are expressed as mg L^{-1}.

Two complementary nutrient fractions were retained because N and P displayed markedly different physical and biogeochemical transport characteristics. Dissolved nutrient fractions are generally more immediately mobile in runoff, whereas particulate nutrient transport can be strongly associated with erosion and suspended sediment.

The following ratios were calculated:

$$TN : TP = \frac{[TN]}{[TP]}$$

And

$$DN : DP = \frac{[DN]}{[DP]}$$

where concentrations are expressed on the same mass basis.

2.4 Nutrient-limitation classification

For comparative interpretation, the study adopted the following screening framework:

$$N : P < 7 \Rightarrow \text{potential nitrogen limitation}$$

$$7 \leq N : P \leq 30 \Rightarrow \text{relatively balanced or weakly constrained}$$

$$N : P > 30 \Rightarrow \text{potential phosphorus limitation}$$

These thresholds should be regarded as screening indicators rather than universal ecological boundaries. Nutrient limitation in natural waters can also depend on temperature, light availability, residence time, hydrodynamics, dissolved organic matter, biological demand, and nutrient bioavailability.

2.5 Statistical analysis

The analytical framework was expanded beyond simple comparison of mean concentrations.

First, descriptive statistics were used to characterize nutrient distributions within each landscape type.

Second, correlation analysis was applied to evaluate relationships among TN, TP, DN, DP, and stoichiometric ratios.

Third, spatial variability was evaluated by comparing landscape categories within individual rainfall events, whereas temporal variability was evaluated by examining changes within each landscape category across the six sampling events.

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Fourth, temporal trends were assessed through linear fitting of nutrient concentrations across the monitoring sequence.

Finally, log-transformed relationships between dissolved nutrient concentrations and DN:DP were examined:

$$\log_{10}(DN : DP) = a \log_{10}(DN) + b$$

And

$$\log_{10}(DN : DP) = c \log_{10}(DP) + d$$

This framework allowed the analysis to distinguish whether changes in stoichiometry were more strongly associated with changes in dissolved N or dissolved P.

3. Results

3.1 Overall nutrient status of the Chaihe runoff system

The runoff system displayed substantial N and P enrichment.

TN concentrations ranged from **0.12 to 135.10 mg L^{-1}**, with a mean of **5.22 mg L^{-1}**.

TP concentrations ranged from **0.11 to 112.00 mg L^{-1}**, with a mean of **10.45 mg L^{-1}**.

Relative to the values reported for Class V surface water under GB 3838–2002, the mean TN and TP concentrations were approximately 2.61 and 26.13 times the corresponding limits, respectively.

The contrast between the two nutrient fractions was particularly informative. DN averaged **3.69 mg L^{-1}**, representing approximately **60% of TN**, whereas DP averaged **0.81 mg L^{-1}**, representing approximately **27% of TP**.

This indicates that the dominant transport pathway differed between nitrogen and phosphorus:

Nitrogen was predominantly transported in dissolved form, whereas phosphorus was predominantly associated with particulate material.

This distinction has direct implications for management because measures targeting dissolved N are unlikely to provide equivalent control of particulate P.

The mean TN:TP ratio was **4.09**, while the mean DN:DP ratio was **14.68**. The large difference between total and dissolved stoichiometry demonstrates that considering only dissolved nutrients would produce a substantially different interpretation of nutrient balance.

Table 1. Catchment-wide characteristics of runoff nutrients

Variable	Range (mg L^{-1})	Mean	Principal interpretation
TN	0.12–135.10	5.22	Strong N enrichment
TP	0.11–112.00	10.45	Very strong P enrichment

DN	0.05–10.75	3.69	Major N transport fraction
DP	0.02–14.42	0.81	Smaller fraction of total P
TN:TP	0.003–13.20	4.09	Catchment-wide tendency toward N limitation
DN:DP	0.01–104.63	14.68	Strong spatial and temporal variability

3.2 Landscape-specific nutrient signatures

The six landscape categories exhibited clearly differentiated nutrient signatures.

Table 2. Mean nutrient concentrations and stoichiometric ratios among landscape types

Landscape type	TN (mg L^{-1})	TP (mg L^{-1})	DN (mg L^{-1})	DP (mg L^{-1})	TN:TP	DN:DP
Flatland	9.06 ± 4.33^{a}	3.20 ± 1.18^{b}	5.47 ± 2.77^{b}	0.14 ± 0.06^{b}	2.93 ± 1.48^{c}	45.35 ± 34.57^{ab}
Downstream Chaihe	4.70 ± 1.73^{b}	0.40 ± 0.14^{c}	4.50 ± 1.64^{b}	0.37 ± 0.14^{ab}	11.63 ± 0.83^{a}	12.36 ± 0.97^{ab}
Greenhouse	9.77 ± 3.12^{a}	2.00 ± 0.36^{b}	8.39 ± 2.77^{a}	0.82 ± 0.38^{ab}	4.82 ± 1.03^{b}	10.63 ± 2.17^{b}
Phosphorus-mining	1.11 ± 0.94^{c}	52.73 ± 45.75^{a}	0.33 ± 0.24^{d}	3.02 ± 5.61^{a}	0.09 ± 0.15^{d}	1.31 ± 1.71^{c}
Phosphorus-rich forest	0.68 ± 0.42^{c}	2.67 ± 0.74^{b}	0.23 ± 0.15^{d}	0.45 ± 0.45^{ab}	0.24 ± 0.13^{d}	1.00 ± 1.06^{c}
Tableland	5.99 ± 1.39^{b}	1.72 ± 0.86^{b}	3.23 ± 1.23^{bc}	0.08 ± 0.04^{b}	4.83 ± 3.30^{b}	46.21 ± 0.39^{a}

Different superscript letters within the same column indicate statistically significant differences among landscape types at $P < 0.05$.

Three major nutrient-source patterns emerged.

3.2.1 Agricultural and greenhouse landscapes as dissolved-N hotspots

TN concentrations were highest in the greenhouse and flatland landscapes, reaching means of **9.77 and 9.06 mg L^{-1}**, respectively.

DN showed an even stronger differentiation. The greenhouse landscape exhibited the highest mean DN concentration (**8.39 mg L^{-1}**), indicating that a substantial proportion of its N export was dissolved.

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This pattern suggests that intensive agricultural management, fertilizer inputs, irrigation, and repeated soil disturbance may promote highly mobile forms of N.

3.2.2 Phosphorus-mining landscapes as particulate-P hotspots

The phosphorus-mining landscape represented the strongest P hotspot.

Mean TP reached **52.73 mg L^{-1}**, far exceeding all other landscape categories.

In contrast, mean **TN** was only **1.11 mg L^{-1}** and DN was **0.33 mg L^{-1}**.

The resulting **TN:TP** ratio of only **0.09** indicates an extreme P-dominated nutrient signature.

The difference between **TP** and **DP** is particularly important. Although DP was elevated in mining areas, the much greater **TP** concentration indicates that a large proportion of the exported phosphorus was associated with particulate material.

Thus, the dominant mechanism in this landscape appears to be fundamentally different from the dissolved-N pathway observed in agricultural areas.

3.3 Contrasting nutrient transport regimes

The landscape comparison reveals at least three distinct nutrient-export regimes.

Regime I: Dissolved-N dominated agricultural export

Characteristic landscapes:

- flatlands;
- greenhouse cultivation;
- partly tablelands.

Dominant characteristics:

$$DN/TN \uparrow$$

and relatively high **TN:TP.**

Regime II: P-dominated mineral and erosion export

Characteristic landscapes:

- phosphorus-mining areas;
- phosphorus-rich forestland.

Dominant characteristics:

$$TP \gg TN$$

and low **TN:TP.**

Regime III: Integrated downstream nutrient signal

Characteristic landscape:

The downstream river showed a considerably lower **TP** concentration than the mining areas but a relatively high TN:TP ratio of **11.63**. This suggests that transport, mixing, sediment retention, and differential nutrient transformation modify the original landscape signatures before nutrients reach the downstream system.

4. Hydrological Dynamics and Temporal Variability

4.1 Rainfall-event effects

The six rainfall events covered a broad range of rainfall conditions, from only **6 mm** to **62 mm**.

The highest event occurred on 18 July with 62 mm of rainfall, whereas the lowest event occurred on 24 July with only 6 mm.

However, nutrient concentration did not vary simply as a direct function of rainfall amount. This observation is important because runoff concentration represents the interaction between rainfall and the availability of nutrients on or near the land surface.

A large rainfall event may dilute dissolved nutrients while simultaneously increasing erosion and particulate-P mobilization. Conversely, a smaller rainfall event occurring after a dry period may mobilize highly concentrated soluble nutrient pools.

Therefore:

$$\text{Nutrient export} \neq f(\text{rainfall amount alone})$$

Instead:.

$$\textbf{Nutrient export} = \boldsymbol{f}(\textbf{rainfall}, \textbf{antecedent conditions}, \textbf{landscape}, \textbf{soil nutrient pool}, \textbf{hydrological connectivity})$$

This provides an important conceptual expansion of the original concentration-based interpretation.

4.2 Early wet-season nutrient pulses

Spatial variability in TN and DN was particularly pronounced during the early wet season.

This pattern can be interpreted as a **first-flush effect**. During the preceding dry period, soluble nutrients, fine sediment, fertilizer residues, and other mobilizable materials may accumulate on or near the land surface. The first effective rainfall events then connect these sources to drainage pathways.

The effect should be particularly strong where agricultural management and soil disturbance are intense.

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Accordingly, the early wet season should be regarded as a critical period for dissolved-N control rather than merely another sampling period.

4.3 Mid-season phosphorus variability

TP showed comparatively stronger spatial variability during the middle part of the wet season.

This pattern is consistent with the increasing importance of erosion and sediment mobilization after repeated rainfall events. In phosphorus-rich landscapes, rainfall can detach soil particles and mining-derived materials containing high P concentrations.

Consequently, P export may increase even when dissolved P remains comparatively modest.

4.4 Temporal decline in nutrient concentrations

Across the monitoring period, TN, DN, and DP displayed an overall declining tendency, whereas TP and the two stoichiometric ratios were comparatively stable.

This pattern suggests progressive depletion of readily mobilizable dissolved nutrient pools during the wet season.

Conceptually, the sequence can be expressed as:

This temporal behavior reinforces the importance of event-based monitoring rather than relying exclusively on monthly or seasonal averages.

5. Spatial Heterogeneity and Landscape Connectivity

One of the most important findings is the strong spatial heterogeneity among landscape units.

The difference between the mean TP concentration in phosphorus-mining areas and greenhouse areas was more than an order of magnitude. Similarly, DN concentration in greenhouse areas was dramatically greater than that in phosphorus-rich forestland.

These contrasts indicate that catchment-scale nutrient averages can conceal highly localized nutrient hotspots.

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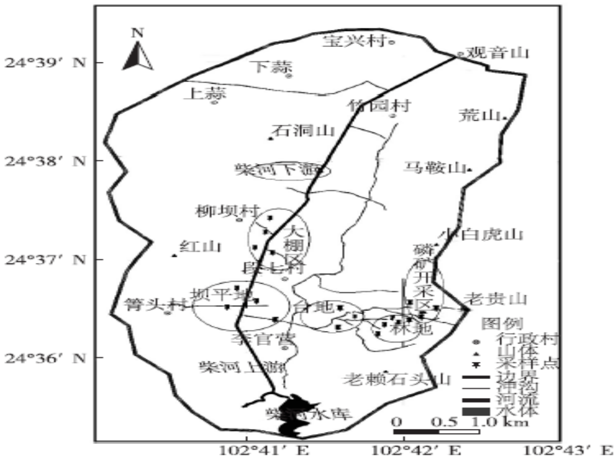

图 1 柴河流域径流水样采样点分布
Fig. 1 Distribution of water sampling points in the Chaihe Catchment

Figure 1. Conceptual landscape–hydrological connectivity framework for the Chaihe Catchment

Suggested figure design:

Rainfall events

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| **Landscape mosaic** |

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Agriculture Greenhouse Mining

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Dissolved N Particulate P

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Landscape connectivity

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Chaihe River

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Lake Dianchi

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The conceptual model emphasizes that nutrient export is not determined exclusively by the amount of nutrient stored in a landscape. Connectivity between source areas and receiving waters is equally important.

A high nutrient concentration in an isolated landscape may have limited downstream influence if runoff is retained. Conversely, a moderately enriched landscape with strong hydrological connectivity may contribute disproportionately to downstream nutrient loading.

6. Stoichiometric Structure of Runoff Nutrients

6.1 TN:TP ratio

The TN:TP ratio displayed a striking landscape gradient.

Landscape	TN:TP	Nutrient status
Flatland	2.93	N limitation
Greenhouse	4.82	N limitation
Tableland	4.83	N limitation
Phosphorus-mining	0.09	Strong N limitation
Phosphorus-rich forest	0.24	Strong N limitation
Downstream Chaihe	11.63	Intermediate/no strong limitation

Using the adopted thresholds, the extremely low ratios in phosphorus-mining and phosphorus-rich forest landscapes indicate strong potential N limitation.

The downstream river, however, shifted toward an intermediate stoichiometric condition.

This transition is ecologically meaningful because the downstream system represents the integrated effect of multiple landscapes.

6.2 DN:DP ratio

The DN:DP ratio revealed a different pattern.

The highest mean values occurred in tablelands and flatlands, reaching **46.21 and 45.35**, respectively.

These values indicate strong P limitation under the screening framework.

The mining and phosphorus-rich forest landscapes had very low DN:DP ratios, approximately **1.31 and 1.00**, respectively.

Thus, the two ratio metrics collectively demonstrate that:

Agricultural landscapes export relatively N-rich runoff, whereas phosphorus-rich landscapes export disproportionately P-rich runoff.

This complementarity is central to understanding the downstream eutrophication problem.

7. Dissolved Nutrient Controls on Stoichiometric Variability

The regression results provide additional evidence that dissolved nutrient dynamics are important determinants of nutrient stoichiometry.

The relationship between DN and DN:DP was:

$$\log_{10}(DN:DP) = 0.98\log_{10}(DN) + 0.61$$

with:

$$R^2 = 0.66, \quad P < 0.05$$

By comparison:

$$\log_{10}(DN:DP) = -0.95\log_{10}(DP) + 0.28$$

with:

$$R^2 = 0.31, \quad P < 0.05$$

The stronger coefficient of determination for DN indicates that changes in dissolved nitrogen explained a larger proportion of variation in DN:DP than changes in dissolved phosphorus.

This does not mean that phosphorus was ecologically unimportant. Rather, it suggests that the short-term variability in dissolved nutrient stoichiometry was more strongly associated with fluctuations in DN.

This distinction is important because total phosphorus remained strongly influenced by particulate transport, particularly in phosphorus-rich landscapes.

8. Nutrient Export and Eutrophication Risk

8.1 From source heterogeneity to downstream convergence

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The ecological significance of the Chaihe Catchment does not arise solely from individual nutrient hotspots.

The more important mechanism is the **convergence of contrasting nutrient sources**.

Agricultural and greenhouse landscapes contribute relatively N-rich runoff:

$$\text{Agricultural landscapes} \rightarrow N\text{-rich runoff}$$

while phosphorus-mining and phosphorus-rich landscapes contribute strongly P-rich runoff:

$$\text{P-rich landscapes} \rightarrow P\text{-rich runoff}$$

When these waters mix:

$$N\text{-rich runoff} + P\text{-rich runoff} \rightarrow \text{more balanced downstream nutrient supply}$$

The downstream Chaihe River exhibited a TN:TP ratio of approximately **11.63**, substantially higher than the ratios observed in mining landscapes but lower than the P-limitation threshold.

This mixing process may increase the ecological availability of both nutrients relative to a situation in which only one nutrient dominates.

8.2 Implications for Lake Dianchi

The Chaihe Catchment ultimately contributes water to Lake Dianchi, an ecosystem with a long history of nutrient enrichment.

Previous research has shown that nutrient loading to Dianchi is controlled by rainfall, runoff characteristics, land use, and catchment-specific processes. Other studies have identified agriculture, urbanization, and phosphorus mining as important contributors to nutrient pollution in the Dianchi watershed.

Phosphorus remains a particularly important concern because Dianchi continues to experience pressure from phosphorus enrichment and internal phosphorus cycling.

The present analysis therefore suggests that the Chaihe Catchment should not be viewed simply as a uniform nutrient source. Instead, it functions as a **spatially differentiated nutrient-processing system** in which different landscapes contribute different nutrient forms and ratios.

9. Integrated Risk Assessment

To translate the findings into a management-oriented framework, the landscapes can be classified according to nutrient concentration, dominant nutrient form, stoichiometric status, and potential downstream significance.

Table 3. Landscape-specific nutrient-risk classification

Landscape	Dominant	Main transport	Stoichiometric	Priority risk

	nutrient signal	form	condition	
Flatland	High N	Dissolved N	P limitation	High N export
Greenhouse	Very high N	Dissolved N	P limitation	High dissolved-N export
Tableland	Moderate N	Mixed	P limitation	Variable N/P export
Phosphorus-mining	Extremely high P	Predominantly particulate P	Strong N limitation	Critical P hotspot
P-rich forest	P enrichment relative to N	P-associated transport	N limitation	Diffuse P export
Downstream Chaihe	Integrated N–P signal	Mixed	Intermediate	Receiving-water risk

This classification demonstrates why a uniform pollution-control strategy would be inefficient.

10. Discussion

10.1 Why landscape type matters

Land use influences nutrient export through several interacting mechanisms:

1. nutrient inputs;
2. soil disturbance;
3. vegetation cover;
4. infiltration capacity;
5. runoff generation;
6. sediment detachment;
7. nutrient adsorption;
8. biological uptake; and
9. hydrological connectivity.

Agricultural landscapes can therefore act as dissolved nutrient sources, while disturbed mineral landscapes can function as sediment-associated nutrient sources.

The present findings support the broader understanding that land-use composition and landscape pattern significantly influence water quality within the Dianchi Basin.

10.2 Why phosphorus requires landscape-specific control

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The exceptionally high TP concentration in the phosphorus-mining landscape demonstrates that phosphorus management cannot focus exclusively on agricultural fertilizer reduction.

Where geological P-rich materials are exposed or disturbed, erosion control may be more important than fertilizer management.

The predominance of particulate phosphorus further suggests that interventions should focus on:

- soil stabilization;
- erosion reduction;
- sediment interception;
- restoration of disturbed mining surfaces;
- vegetative buffers; and
- retention ponds or sedimentation structures.

This interpretation is consistent with the continuing importance of geological phosphorus-rich areas in the Dianchi Basin.

10.3 Why nitrogen control should focus on agricultural landscapes

The highest **TN** and **DN** concentrations occurred in flatland and greenhouse landscapes.

Because **DN** represented approximately 60% of **TN** at the catchment scale, measures that reduce dissolved-N mobilization are likely to have substantial benefits.

Potential measures include:

- optimized fertilizer application;
- reduction of excessive N inputs;
- controlled irrigation;
- improved soil organic matter management;
- vegetated drainage strips;
- constructed wetlands; and
- interception of agricultural drainage before entry into the river network.

The objective should be to reduce both the source strength and hydrological connectivity of dissolved nitrogen.

10.4 Hydrological timing as a management variable

A major implication of the study is that management effectiveness may depend on **when** interventions are implemented.

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Because early wet-season runoff exhibited strong spatial variability in N and DN, the beginning of the rainy season represents a potentially critical period.

A management system based exclusively on annual nutrient averages could therefore overlook short-lived but environmentally significant nutrient pulses.

A more effective strategy would integrate:

$$\text{landscape} + \text{rainfall} + \text{antecedent dry period} + \text{runoff connectivity}$$

into event-based pollution control.

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11. Proposed Landscape-Based Pollution Control Framework

Based on the integrated interpretation, a four-zone management framework is proposed.

Zone I: Agricultural N-control zone

Target: flatlands and greenhouse areas.

Primary pollutant: dissolved nitrogen.

Priority measures:

- precision fertilizer management;
- nutrient budgeting;
- drainage interception;
- vegetated buffer strips;
- constructed wetlands;
- runoff retention.

Zone II: Phosphorus source-control zone

Target: phosphorus-mining landscapes.

Primary pollutant: particulate and total phosphorus.

Priority measures:

- erosion control;
- mining-area rehabilitation;
- sediment traps;

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- runoff diversion;
- stabilization of exposed soils;
- restoration of vegetation.

Zone III: Ecological retention zone

Target: phosphorus-rich forestland and sensitive slopes.

Primary objective: maintain nutrient retention and prevent erosion.

Priority measures:

- forest conservation;
- slope stabilization;
- prevention of unnecessary soil disturbance;
- maintenance of riparian vegetation;
- monitoring of phosphorus export.

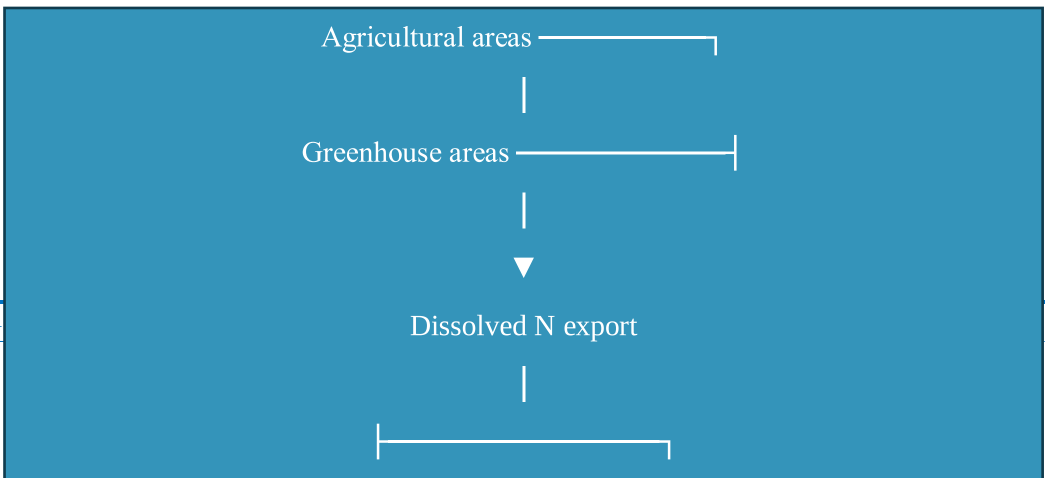
Zone IV: Downstream interception zone

Target: lower Chaihe River.

Primary objective: intercept mixed nutrient loads before they reach Lake Dianchi.

Priority measures:

- ecological wetlands;
- sediment retention;
- nutrient interception;
- continuous water-quality monitoring;
- event-based early-warning systems.



12. Conceptual Advancement of the Study

The principal contribution of this expanded analysis is the shift from a conventional **"landscape type → nutrient concentration"** relationship toward a broader conceptual model:

$$land\ scape \rightarrow nutrient\ source \rightarrow hydrological\ mobilization \rightarrow nutrient\ form \rightarrow n{:}p\ stoichiometry \rightarrow down\ stream\ ecological\ risk$$

This framework recognizes that the ecological significance of a nutrient source depends on four characteristics:

1. **magnitude** — how much nutrient is exported;
2. **form** — dissolved versus particulate;
3. **timing** — when export occurs;

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4. **ratio** — how N and P are supplied relative to each other.

This provides a more comprehensive basis for watershed management than concentration-based assessment alone.

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13. Limitations and Future Research

Several limitations should be acknowledged.

First, the underlying observations were collected during six rainfall events in 2026. Consequently, the dataset represents a valuable event-based snapshot but does not constitute a contemporary long-term monitoring series.

Second, the number of monitoring locations differed among landscape categories. In particular, the downstream Chaihe River was represented by only one monitoring location. Conclusions regarding this category should therefore be interpreted cautiously.

Third, concentration measurements alone cannot directly quantify nutrient loads. A complete export assessment requires simultaneous discharge measurements:

$$Load = Concentration \times Runoff\ Volume$$

Future studies should therefore combine continuous discharge monitoring with high-frequency nutrient sampling.

Fourth, the N:P thresholds used in this study are screening criteria rather than universal indicators of phytoplankton limitation. Biological experiments, chlorophyll-a measurements, dissolved oxygen, water temperature, light availability, and phytoplankton community composition would improve the ecological interpretation.

Fifth, the original dataset did not include detailed measurements of rainfall intensity, antecedent dry-period duration, soil moisture, suspended sediment concentration, fertilizer application, or mining activity. Incorporating these variables would allow hydrological and source-process models to distinguish source limitation from transport limitation.

Finally, contemporary land-use patterns may differ from those observed during the original monitoring period. Future work should therefore combine field monitoring with GIS and remote sensing to quantify changes in landscape composition and connectivity.

14. Conclusions

This study developed an integrated landscape–hydrology–stoichiometry framework to reinterpret nutrient export patterns in the Chaihe Catchment and their potential implications for Lake Dianchi.

The principal conclusions are as follows:

1. **The Chaihe runoff system exhibits substantial nitrogen and phosphorus enrichment.** Mean TN and TP concentrations reached 5.22 and 10.45 mg L^{-1}, respectively, demonstrating a pronounced non-point-source pollution problem.

2. **Nitrogen and phosphorus are transported through different dominant pathways.** Approximately 60% of TN occurred as dissolved N, whereas only about 27% of TP occurred as dissolved P. This indicates a predominantly dissolved pathway for N and a stronger particulate pathway for P.

3. **Landscape type strongly determines nutrient signatures.** Greenhouse and flatland landscapes were characterized by high TN and DN, whereas phosphorus-mining landscapes exhibited exceptionally high TP and DP concentrations.

4. **The Chaihe Catchment contains contrasting nutrient hotspots.** Agricultural landscapes represent major dissolved-N sources, while phosphorus-mining landscapes constitute critical P hotspots.

5. **Hydrological timing influences nutrient export.** Early wet-season runoff displayed strong spatial variability in N-related variables, consistent with first-flush mobilization of accumulated nutrients. Phosphorus variability became particularly pronounced during the middle wet season.

6. **N:P stoichiometry reveals strong landscape differentiation.** Agricultural flatlands and tablelands tended toward P limitation, whereas phosphorus-mining areas and phosphorus-rich forestland exhibited strong N limitation. The downstream Chaihe River occupied an intermediate stoichiometric condition.

7. **Dissolved nitrogen was strongly associated with variation in dissolved nutrient stoichiometry.** The DN–DN:DP relationship explained a greater proportion of variability than the corresponding DP relationship, although both dissolved nutrients contributed significantly.

8. **Nutrient convergence may increase downstream eutrophication risk.** The mixing of N-rich agricultural runoff with P-rich runoff from phosphorus-rich landscapes can generate a more balanced nutrient environment downstream, potentially increasing the capacity of receiving waters to sustain excessive primary production.

9. **Pollution control should be landscape-specific.** Dissolved-N control should prioritize agricultural and greenhouse areas, while particulate-P control should focus on mining areas, erosion-prone slopes, and sediment pathways.

10. **The most effective management strategy should combine source control with hydrological interception.** Protecting Lake Dianchi requires reducing nutrient generation at source, limiting transport connectivity, and intercepting nutrient-rich runoff before it reaches the downstream river and lake.

Overall, the Chaihe Catchment should be regarded not as a homogeneous nutrient-export system but as a **spatially heterogeneous nutrient network in which agricultural, geological, mining, forest, and downstream processes interact to determine nutrient concentration, form, timing, stoichiometry, and ecological risk**. This perspective provides a stronger scientific basis for

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prioritizing non-point-source pollution control and developing targeted strategies for protecting Lake Dianchi.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(N):nitrogen ; (P):phosphorus; (TN):Total nitrogen; (TP):total phosphorus; (DN):dissolved nitrogen, (DP):dissolved phosphorus

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Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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Conflicts of Interest:

"The authors declare no conflict of interest."

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