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Research on the Dynamics and Ecological Thresholds of Groundwater-dependent Vegetation in the Plain Area of the Golmud River Basin

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Abstract

In arid inland river systems, surface water and groundwater interact and transform frequently, exerting profound effects on vegetation distribution in inland basins—a pattern mirrored by groundwater-dependent vegetation in the Golmud River Basin plain. By integrating field-monitored groundwater depth and TDS data with remote sensing-derived Normalized Difference Vegetation Index (NDVI) imagery, this study examines the dynamic influences of groundwater depth and TDS on vegetation cover. Key findings indicate that the ecological threshold for oasis vegetation dependence on groundwater in the Golmud River Basin plain is a depth of 4 m and TDS of 2.8 g/L. Beyond 4 m depth, vegetation cover declines precipitously, with growth exhibiting minimal groundwater influence. Depths <0.5 m are optimal for aquatic vegetation but prone to soil salinization. Suitable groundwater depths for dominant species are: *Phragmites australis* (0.10–3.95 m), *Tamarix chinensis* (0.90–4.62 m), *Nitraria sibirica* (1.0–3.28 m), and *Apocynum venetum* (0.90–3.95 m). When TDS exceeds 2.8 g/L, high NDVI values diminish sharply, reducing vegetation cover; growth ceases entirely at 6.5 g/L TDS.

Keywords Groundwater, Vegetation; Threshold; Ecology; TDS

Introduction

The Qaidam Basin in the northeastern Qinghai-Tibet Plateau harbors exceptionally rich mineral and energy resources, functioning as a national pilot zone

for circular economy development while shouldering key responsibilities for ecological civilization on the plateau. The Golmud River Basin, along the basin's southern margin, abuts the Kunlun Mountains to the south and connects to Dabson Lake to the north, exhibiting a pronounced south-to-north topographic gradient at an average elevation of 2800 m—the second-largest river system in the basin. Its southern reaches are dominated by bedrock mountains, progressing northward through piedmont Gobi gravel belts, fine-soil plains, oasis zones, salt marshes, and terminal lakes. Defined by a quintessential plateau continental climate in an arid inland context, the basin faces severe climatic rigors and ecological fragility, which critically impede economic progress in Golmud City within the northern plain.

Golmud City, nestled in the basin plain, records a multi-year mean annual precipitation of merely ~40 mm, versus ~150 mm in the mountains. However, pan evaporation averages ~2500 mm annually—dwarfing precipitation—and fosters acute surface drought and water scarcity, rendering vegetation predominantly reliant on groundwater sustenance. This groundwater is chiefly replenished by river infiltration in alluvial-proluvial fans, yet cascaded hydropower construction and intensified extractions amid urban expansion have variably depressed levels, with repercussions for surface water, groundwater regimes, and ecosystems. Studies on oasis vegetation ecology in the Golmud River Basin plain are comparatively sparse, especially concerning interactions with groundwater depth and TDS, falling short of supporting coordinated socioeconomic development and ecological sustainability. Leveraging Landsat remote sensing data and local hydrogeological monitoring, this study elucidates oasis vegetation cover dynamics relative to groundwater depth and TDS, furnishing references for sustainable water resource exploitation and ecological protection planning in Golmud City.

1. Study Site

Golmud City, in Qinghai Province, is situated along the southern margin of the Qaidam Basin at the interface between the northern Kunlun Mountains alluvial-proluvial fan and the adjacent plain, with terrain sloping from south to north

at elevations of 2700–3000 m (Figure 1) . The region exemplifies an arid continental climate, characterized by a mean annual temperature of 4.9°C and multi-year average precipitation of merely 44 mm—substantially below evaporative demand. Water resources depend predominantly on surface runoff from the southern plateau, with the Golmud River as the principal waterway. Originating in the Kunlun Mountains, the Golmud River arises from the confluence of the Naijin River (also known as Kunlun River) and Xueshui River, discharging from the mountain pass toward Golmud City at a multi-year mean flow of $\sim 26 \text{ m}^3/\text{s}$. En route through the alluvial-proluvial fan, substantial river leakage recharges groundwater, constituting the foremost pathway for Golmud City's groundwater formation. This groundwater is primarily hosted in thick Quaternary porous aquifers, manifesting as phreatic flow through gravel-sand layers from south to north in the fan zone, before surfacing at the southern plain margin to form spring complexes such as Jinqi River.(Zhu et al. 2012; Lv et al. 2013; Wang et al. 2017; Huang et al. 2019; Wang and Wang 2019; Qi et al. 2021) 。 In the plain zone, aquifer lithology fines progressively, incorporating multiple low-permeability layers of silty sand and clayey silt that engender confined groundwater. Potentiometric heads of this confined water frequently surpass ground surface, facilitating artesian flow wells. Shallow phreatic groundwater in the plain undergoes substantial depletion through evapotranspiration. North of Golmud City, surface water systems flow onward northward, terminating in saline lakes such as Dabson Lake, whereas deep confined groundwater circulates extensively, ultimately recharging lakes or phreatic aquifers in the central Qaidam Basin.(Yang et al. 2019; Cao et al. 2021) 。 Groundwater peripheral to the salt lakes is characteristically brine, laden with potash and other mineral resources. It provides essential sustenance to Golmud City's oases, plain grasslands, wetlands, and associated ecosystems.(Wang et al. 2017; Rampheri et al. 2023) 。

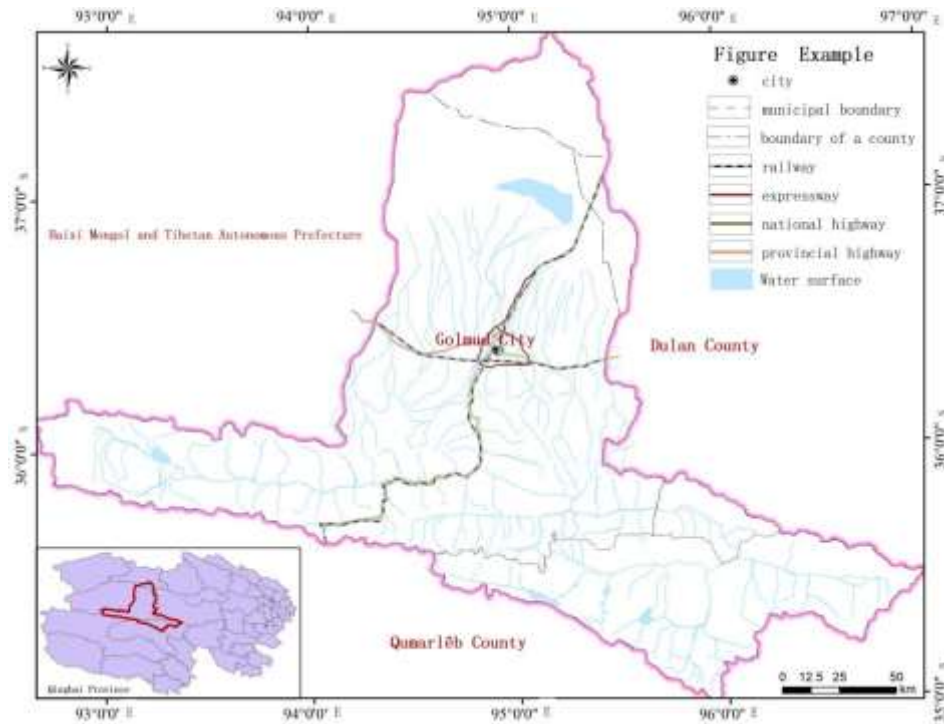


Figure 1. Location map of the study site.

2. Groundwater Dynamics and Vegetation Distribution Characteristics

2.1 Groundwater Recharge Characteristics

Groundwater recharge conditions can be analyzed from perspectives including recharge zone delineation, sources, and mechanisms. In the Golmud River alluvial-proluvial fan zone—situated at relatively low elevations with scant precipitation and intense evaporation—groundwater is deeply buried, rendering atmospheric precipitation negligible for phreatic recharge. However, the upstream bedrock mountainous catchment is expansive and precipitation-rich, continuously replenishing river water via rainfall, glacial/snowmelt, and bedrock fissure discharge, thereby augmenting discharge at the mountain outlet. Post-outlet, the mid-upper Golmud River channel—composed largely of cobbles or boulders with minimal silt/clay content—facilitates extensive leakage, converting surface flow to groundwater and furnishing a prolific recharge source. Principal recharge components encompass: vertical percolation from southern mountain streams, canal leakage, agricultural irrigation return flow, and lateral influx from bedrock fissure water.(N and M 2015). In the southern mountains, climatic altitudinal zonation elevates precipitation relative to the basin interior; Qinghai Province isohyetal maps indicate >220 mm

annual rainfall in the Kunlun Mountains, increasing southward. High-elevation groundwater relies primarily on solid-phase ice/snowmelt recharge, constrained by perennial permafrost and topography, manifesting mainly as springs that feed valley rivers. Mid- to low-elevation groundwater draws chiefly from liquid water, with most forming surface runoff and lesser amounts infiltrating bedrock fissures (Yuan X P et al. 2013). Phreatic groundwater in mountain valleys accrues primarily from blended recharge involving snowmelt, active layer (frozen soil) water, bedrock fissure water, and surface runoff. Recharge modalities in the mountains are predominantly dictated by topography and landforms, engendering circuitous recharge patterns.

2.2 Groundwater Flow Characteristics

Groundwater flow is chiefly bifurcated into mountainous and basin (piedmont inclined plain) regimes. Mountainous groundwater types are diverse, with complex flow dynamics; bedrock fissure water exhibits intricate patterns dominated by pulsating or turbulent flow. Limited development of weathering fissures and constrained density/depth of structural fractures preclude a unified free water table, favoring instead an interconnected groundwater network. Phreatic flow in mountains is highly permeable, with gradients mirroring valley slopes. Pronounced uplift in mountains prompts aggressive valley incision, lowering relative base levels and aggregating most mountainous groundwater—though in narrowed valleys or locally uplifted bedrock, phreatic water may partially discharge to augment river flow.

In the piedmont basin, groundwater flow is intimately linked to geomorphic-lithofacies zones and aquifer lithostratigraphy. The Gobi belt harbors deep phreatic water under unconfined free surfaces, advancing at hydraulic gradients of ~1‰. Flow direction is largely unidirectional south-to-north, though axial zones of major alluvial fans radiate northward from river outlets (Zhao et al. 2005; Zhu Y H et al. 2019; Hartfield et al. 2020; Bai et al. 2024). Inter-fan depressions commonly converge groundwater from the margins of adjacent alluvial fan axes, yielding convergent flow regimes. Finer lithology curtails transmissivity, elevating water tables at fan fronts and facilitating surface discharge via springs—a defining trait of local groundwater behavior.

North of the fine-soil belt, groundwater manifests as stratified aquifer complexes. In upper phreatic layers, finer lithology decelerates flow while steepening hydraulic gradients to 1‰–7‰. Proceeding from the fine-soil belt leading edge to the basin center, gradients moderate again (4‰–2‰), linked to coarsening lithology in northern phreatic aquifers. Subjacent confined aquifer ensembles advance northward under potentiometric drive, exhibiting south-to-north and top-to-bottom head increases, consonant with alluvial fan equipotential contours.

2.3 Groundwater Discharge Characteristics

Groundwater discharge accompanies flow processes, exemplified by bedrock fissure water emanating as seepage springs into rivers or valley phreatic zones. Piedmont groundwater discharge is multifaceted, encompassing three primary modes: (1) Effluent discharge: Shallow groundwater overflow bands align principally with the fine-soil belt forefront. Absent deep incised valleys at fan fronts and lacking major topographic breaks, axial fan overflow is rare—minor occurrences manifest as patchy, low-yield seeps. Thus, effluent discharge concentrates in inter-fan depressions, prolifically venting via spring complexes and clusters. (2) Evapotranspiration: Extreme aridity yields 1000–2300 mm annual evaporation from mountains to plains, intensely depleting shallow groundwater. In the southern Gobi gravel belt (>10 m phreatic depth), evaporation is negligible. North of the 10 m isodepth contour, depths plummet over short distances, with vast expanses <3 m burial; capillary rise in surface soils (1.5–1.8 m) renders most depths subcritical, propelling moisture upward for evaporation—rendering shallow phreatic evapotranspiration substantial. (3) Deep outflow: Quantifies deep seepage discharging northward to basin peripheries and lake centers. Deep groundwater permeates gravel aquifers capped by clay aquitards, exhibiting confined traits. Additionally, in alluvial-proluvial fine-soil plains, phreatic and artesian free-flowing waters encounter deteriorating transmissivity during downgradient transit, with sluggish exchange. Shallow phreatic water feeds rivers, while artesian underflow sustains overlying phreatic zones.

2.4 Groundwater Circulation Characteristics

Groundwater level dynamics encapsulate the integrated response of aquifer

systems to recharge, discharge, and intrinsic attributes within specific natural settings. Minimal regional precipitation yields negligible direct recharge; mountain valley and piedmont alluvial-proluvial fan groundwater derives chiefly from vertical river percolation and lateral runoff. Thus, Golmud River discharge—proxying river stage and infiltration—principally drives level fluctuations. From 2018–2023 hydrological station data, annual discharge trended upward, yet upstream cascaded reservoirs attenuated peak flows (and maxima), diminishing river-groundwater head differentials and curtailing recharge. Consequently, fan-zone groundwater levels declined overall commensurate with peak flow abatement.

In the fine-soil plain, fluvial influence wanes, with evapotranspiration variability dictating superficial phreatic fluctuations. Confined water dynamics correlate less tightly with river flows, responding primarily to recharge/discharge perturbations. Per dominant controls and hydrogeological unit-specific traits, phreatic dynamics classify as: hydrological, hydrological-extraction, hydraulic engineering, and meteorological-agricultural extraction types. Confined water exhibits distinctive hydrographs, illustrated via prototypical monitoring sites.

2.5 Hydrochemical Evolution Characteristics of Groundwater

Mountainous recharge zone: Hydrochemistry is relatively simple, dominated by $\text{HCO}_3\text{-Cl}$ facies in river and groundwater, with Na^+ , Ca^{2+} , and Mg^{2+} as prevailing cations. TDS is mostly <500 mg/L, governed principally by rock weathering (elution), robust hydrodynamics, and locally Tertiary clastic influences elevating SO_4^{2-} proportions in phreatic and river waters.

Piedmont plain flow zone: Water quality remains favorable, chiefly $\text{HCO}_3\text{-Cl}$ type, with Na^+ and Mg^{2+} dominant. Substantial phreatic thickness fosters strong hydrodynamics and muted mineralization; rock dissolution controls riverine and most phreatic chemistries. At downstream piedmont fronts and fan flanks—prolonged flow paths and diminished river recharge—mineralization intensifies, alongside confined water emergence. Spatial-temporal evolutions mirror those of river water, underpinned by intimate hydraulic connectivity.

Effluent zone: Partial groundwater vents as springs into rivers. Phreatic

hydrochemistry shifts from piedmont baselines, with $\text{SO}_4\text{-Cl}$ facies proliferating while cation dominance (Na^+ , Mg^{2+}) persists. Confined water retains $\text{HCO}_3\text{-Cl}$ primacy. Genesis reflects conjoint rock weathering, evaporative concentration, and cation exchange adsorption. Central effluent tracts benefit from riverine influence, strong hydrodynamics, and subdued mineralization; eastern/western flanks—scarce surface water and lithologic effects—exhibit pronounced mineralization.

Fine-soil plain: TDS escalates with flow path prolongation, river TDS surpassing 1000 mg/L amid overt surface salinization. Cl-type waters surge across river, phreatic, and confined domains, supplanting prior facies; evaporative concentration exerts paramount influence, especially on river and phreatic waters.

Salt marsh plain: Profound surface salinization features vast salt crusts, hypermineralized groundwater, and TDS maxima. River and groundwater are uniformly Cl-type, with Na^+ overwhelmingly dominant. Evaporative concentration prevails, augmented by abundant halite in aquifer lithologies, peaking Na^+ and Cl^- . As the basin's ultimate discharge sink—Dabson Lake preeminent—surface/phreatic linkages are robust, while confined ties weaken.

2.6 Characteristics of Vegetation Dynamics

In the plain zone downstream of the southern mountain outlet, landforms comprise Gobi gravel belts, marsh-wetland zones, and salt marshes. Desert landscapes include Gobi gravel and salt marsh belts: phreatic depths >100 m in Gobi gravel sporadically sustain drought-resilient, non-groundwater-dependent vegetation such as *Ephedra przewalskii*, whereas salt marshes form barren dry salt flats devoid of vegetation. Groundwater-dependent ecosystem dominants in marsh wetlands include *Phragmites australis*, *Tamarix chinensis*, *Nitraria sibirica*, and *Apocynum venetum*. Notably, *Apocynum venetum* distribution ties to geological controls, associated with Golmud River alluvial-proluvial fan-base uplifts that deepen groundwater. Leveraging eight field hydro-ecological profiles and remote sensing classifications, this section analyzes variations in plain groundwater-dependent ecosystems (Figure 2) .

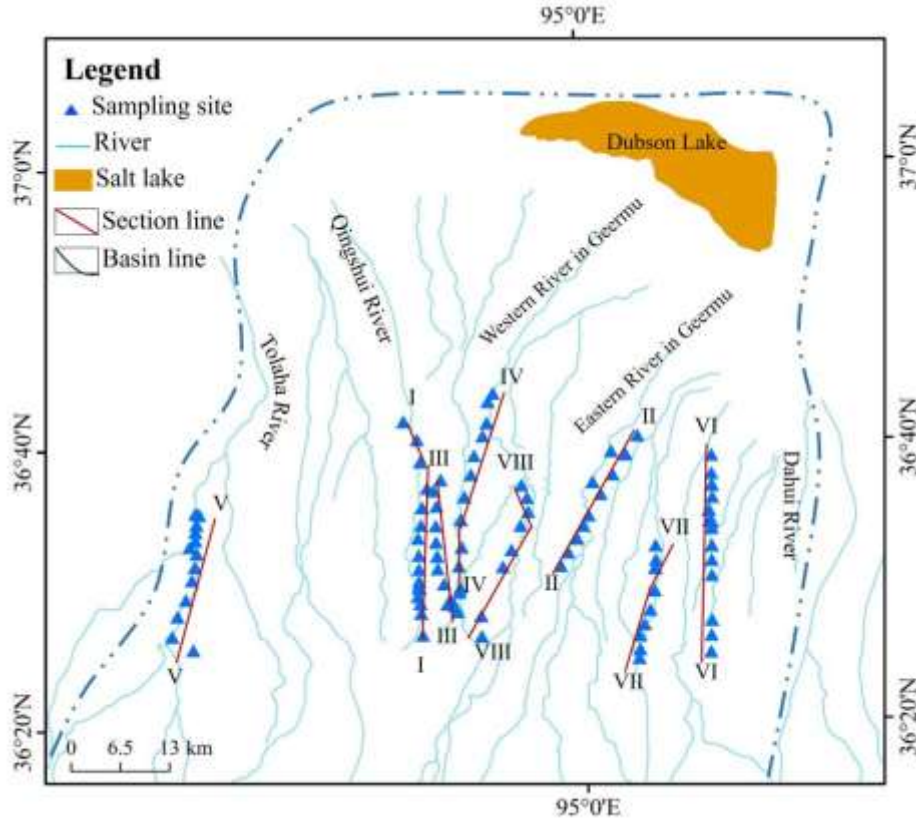


Figure 2. Hydro-ecological geological survey profile lines in the piedmont plain.

Plain ecosystems are principally categorized into desert, natural oasis, wetland, and artificial oasis systems. Desert ecosystems—encompassing bare soil in central piedmont inclined dry alluvial plains, northern lacustrine-alluvial sodic flats, and patchy aeolian desertification in central/southern exposures—display pronounced north-south zonation, occupying ~17.38% of the study area. Natural oases, comprising grasslands and woodlands, cluster in piedmont alluvial-proluvial plains under loose porous aquifer influence, exhibiting vigorous growth and high cover (~7.74%). Wetlands—including shrub marshes, rivers, lakes, inland tidal flats, marsh grasslands, and mires—prevail in intermontane valley lows, piedmont groundwater effluent alluvial/lacustrine plains with aquifer abundance and peripheral vegetation (~4.95%). Artificial oases (cropland, built-up areas, water bodies) concentrate at the juncture of piedmont dry inclined alluvial and alluvial-proluvial plains in near-east-west bands (~1.83%).

Vegetation patterns across the plain are governed chiefly by precipitation, evaporation, topography, temperature, groundwater depth, and salinity—factors often

intertwined to dictate landscape assemblages. From piedmont alluvial fan rears to the fine-soil plain, diminished precipitation drives runoff subsurface, with deep phreatic depths impeding vegetation sustenance and yielding gravel deserts and barren expanses; only fan fronts host sparse, hyper-drought-tolerant needle-leaf shrublands/grasslands. In the fine-soil plain, phreatic elevations rise conspicuously, spawning spring outcrops that foster natural/artificial oases; despite intense evaporation, relative groundwater plenitude nurtures patchy vegetation, dubbing the upper fine-soil plain the "oasis belt." Downgradient, resubmergence, vigorous evaporation-induced surface salinization, and hypermineralization propel succession to salinity-driven halophytes: fine-soil plain salt meadows and salinized deserts.

Influenced by precipitation, soil salinity, and groundwater depth, plain vegetation assemblages evolve in concert with hydrology. Piedmont Gobi (~50 mm annual rainfall, 15–100 m depths) supports dunes and xerophytic shrublands dominated by *Tamarix ramosissima* (strange willow) and *Nitraria sibirica*. Between Gobi and salt marshes lies the alluvial-proluvial fine-soil plain—favorable water/soil/climate hosting salt meadow halophytes like *Lycium barbarum*, *Phragmites australis*, and reeds. Basin lacustrine plains bear salt meadows; salt/brackish lake peripheries lack extensive cover, save localized dwarf reeds, sparse *Nitraria*, and *Alhagi sparsifolia*. Ubiquitous types include *Nitraria sibirica*, *Tamarix spp.* (red willow), *Alhagi sparsifolia*, reeds, *Carex*, *Achnatherum splendens*, with admixtures of *Leymus secalinus*, *Karelinia caspia*, *Haloxylon ammodendron*, etc. Major river valleys harbor poplar groves, chiefly *Populus euphratica* and *Populus nigra* var. stands.(Pérez Hoyos et al. 2016; Guan Z L et al. 2018; Zhang et al. 2018; Dang X Y et al. 2019; Huang et al. 2019; Cao L et al. 2020; Zhang et al. 2022).Vegetation distribution patterns are presented in Table 1 and Figure 3.

Table 1. List of Vegetation Types in the Plain Area of the Golmud River Basin

Geomorphic / Groundwater Features	Type	Community Classification	Community Characteristics
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Piedmont Gobi Groundwater recharge belt	Dwarf subshrub, shrub gravel desert	<i>Ephedra przewalskii</i> community	Develops along rainflood channels and fan rears; dominants: deep-rooted evergreen shrub <i>Ephedra przewalskii</i> and dwarf subshrub <i>Chenopodium acuminatum</i> .
		<i>Artemisia</i> leaf pigweed, composite grass, and red sand community	Develops on gentle inter-channel flats; dominants: salt-accumulating succulent dwarf subshrubs (<i>Artemisia leaf pigweed</i>), composite grass, and salt-exuding dwarf subshrub red sand.
Oasis zone groundwater effluent-spring complex belt	Dwarf subshrub, dwarf shrub desert	Composite grass, Mongolian sand jujube, <i>Nitraria</i> community	Develops on upper sand belts; strong wind erosion, plant tussocks accumulate no sand.
		Composite grass, Mongolian sand jujube, <i>Nitraria</i> community	Develops in mid-sand belts; <i>Tamarix ramosissima</i> roots reach groundwater table.
		<i>Tamarix ramosissima</i> , <i>Haloxylon</i> , <i>Nitraria</i> community	Develops in lower sand belts; deep roots access groundwater; <i>Tamarix ramosissima</i> forms 5–10 cm high fixed dunes with inter-dune reeds and <i>Apocynum venetum</i> ; surface crusts present.
		Reed, <i>Phragmites</i> , <i>Nitraria</i> , <i>Tamarix ramosissima</i> salt meadow	Distributed in alluvial plain fine-soil belts (silt loam texture), TDS up to 10 g/L; growth wholly groundwater-dependent.
Low plain fine-soil downgradient belt	Reed and diverse salt-tolerant hygrophyte marshy salt meadow		Distributed at fine-soil belt forefront; poor drainage, TDS >10 g/L; dominants: reeds and salt hygrophytes (e.g., <i>Zostera</i> , sea milkweed, <i>Juncus</i> , <i>Suaeda</i> spp.).
Terminal salt marsh evaporation discharge belt	Exposed sodic land, salt crusts, salt lakes		Sparse <i>Nitraria</i> and <i>Suaeda</i> on bare sodic grounds.

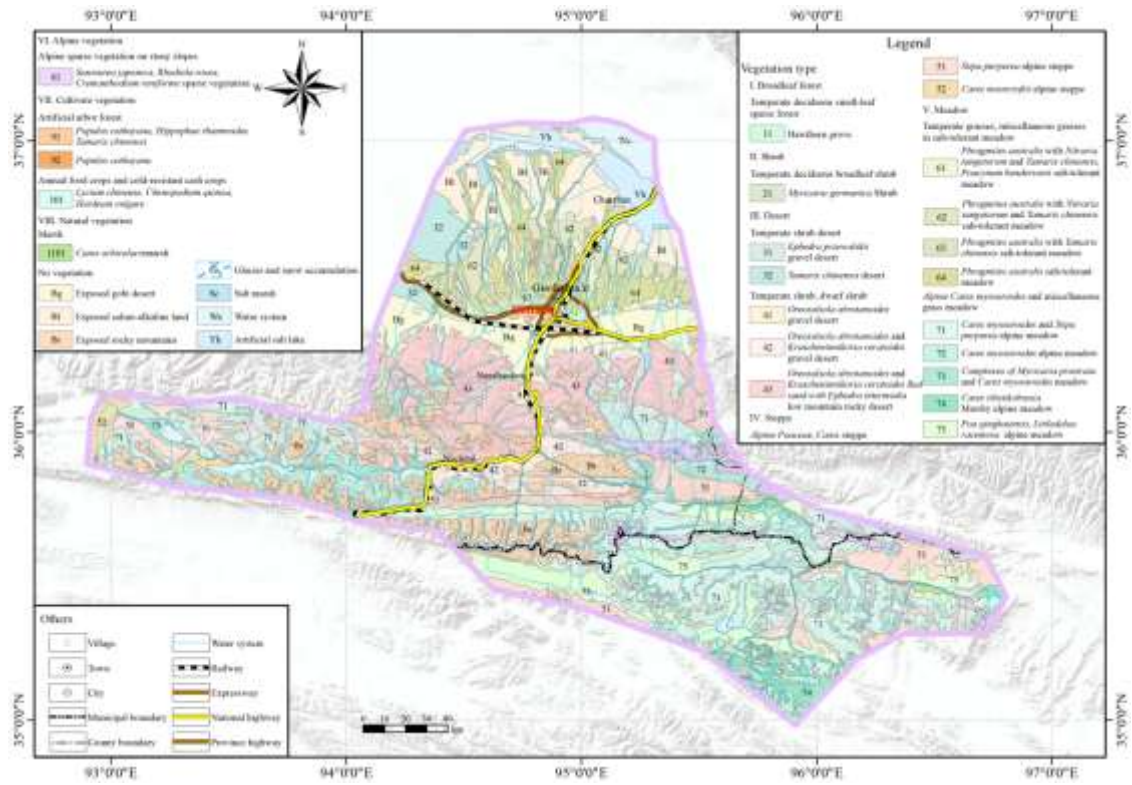


Figure 3. 2020 remote sensing classification map of vegetation types in the study area.

3.Data Processing and Methods

3.1 Research Methods

This study integrates hydrogeological surveys, ecological inventories, and quantitative remote sensing analyses. Groundwater depth and TDS data derive from field measurements during the 2023–2025 Golmud River Basin groundwater-dependent ecosystem assessment project, targeting the July–September growing season. Depth data were acquired from private wells, project boreholes, national monitoring wells, and provincial stations via manual measurements and automated loggers: manual at 6 times/month (intensified to 15/month in wet periods); automated at daily intervals. TDS stemmed from laboratory assays (National Center for Groundwater, Mineral Springs, and Environmental Monitoring, Ministry of Natural Resources) of field-sampled hydrochemical specimens. Remote sensing principally employed Landsat TM, ETM+, OLI, and OLI-2 imagery (Landsat 4–5 TM, 7 ETM+, 8 OLI, 9 OLI-2), totaling 49 scenes across 7 epochs, prioritizing July–September phenology. Recent 0.5 m high-resolution images served as interpretive

references. Native Landsat resolution is 30 m (15 m post-pansharpening). NDVI pixel values range -1 to 1, with higher values denoting superior vegetation cover and vice versa. Field surveys revealed >10 m depths concentrated beyond southern oasis margins with poor cover; analyses thus focused on <10 m depths.(Orellana et al. 2012; Imin et al. 2021; Zhai J Q et al. 2021; Mpakairi et al. 2022).

3.2 Data Processing

Field ecological surveys indicated principal species roots generally <4 m (Mongolian sand jujube <6 m; red willow and *Tamarix ramosissima* <10 m), with optimal depths of 3–4 m (4–5 m for deep-rooted red willow/*Tamarix ramosissima*). Accordingly, <10 m monitoring points met study requisites, permitting correlation analyses of filtered groundwater depth, TDS, and NDVI datasets.

The Normalized Difference Vegetation Index (NDVI)—ubiquitously applied to assess vigor—ranges -1 to 1, wherein higher values signify robust growth and lower values sparse cover. For clearer depiction of regional cover traits, Vegetation Cover Fraction (VCF) served as a key growth proxy:

$$VCF = (NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min})$$

where VCF is vegetation cover fraction; NDVI is the normalized difference vegetation index; $NDVI_{min}$ and $NDVI_{max}$ are regional minima/maxima.

NDVI–groundwater depth/TDS analyses proceeded as follows: depth data underwent differencing; ArcGIS 10.7 interpolated/resampled depths to NDVI-equivalent resolution and projection. Fishnet tool extracted site coordinates, depths, TDS, and coincident NDVI values. Filtered points informed scatterplots (depth–NDVI; TDS–NDVI), elucidating relationships and ascertaining study area ecological thresholds.

4. Results and Discussion

4.4 Distribution Characteristics of NDVI and Vegetation Cover

4.4.1 Spatial Distribution Characteristics of Vegetation Cover

Growing-season NDVI datasets facilitated Golmud River Basin vegetation cover (VFC) computation and classification to evaluate trends across categories. Synthesizing regional literature and field observations, a five-tier scheme was adopted: low (VFC 0–10%), lower (10–30%), moderate (30–50%), higher (50–70%), and high

(70–100%). Statistics for 1990–2020 (Table 2) indicate low cover averaged 33.2% (10,234.3 km²), lower 40.0% (12,328.3 km²); moderate, higher, and high covers comprised smaller fractions at 17.1% (5,280.2 km²), 5.7% (1,751.6 km²), and 4.0% (1,225.0 km²), respectively. Low and lower covers aggregated 73.2%, signifying generally poor basin-wide vegetation.

The 2020 cover map (Figure 4) reveals low/lower cover predominating three zones: northern lacustrine-alluvial salt marsh plains with elevated topsoil salinity supporting only localized halophytes; central dry Gobi gravel belts featuring permeable sandy-gravel lithology conducive to drought-tolerant species; and southern mid-high mountains where excessive groundwater depths stabilize low cover. Moderate-to-high cover coincides spatially with NDVI maxima in water-favored areas: farms flanking the northern urban zone, marsh wetlands along southern mountain channels, and glacio-nival troughs near snowlines in central highlands—regions exhibiting markedly superior cover and vigor. Overall, low/lower cover dominance (73.2%) underscores suboptimal vegetation status across the study area.

Table 2. Area and proportion of vegetation cover levels in the study area, 1990–2020.

Year	Low Cover		Lower Cover (0–30%)		Moderate Cover (30– 50%)		Higher Cover (50–70%)		High Cover (70–100%)	
	Area		Area		Area		Area		Area	
	0~10%		0~30%		30~50%		50~70%		70~100%	
	Area	%	Area	%	Area	%	Area	%	Area	%
1990	13478.6	43.7%	10730.6	34.8%	4326.1	14.0%	1366.9	4.4%	917.1	3.0%
1995	10762.3	34.9%	12889.3	41.8%	4731.2	15.4%	1424.6	4.6%	1012.0	3.3%
2000	13393.9	43.5%	10568.9	34.3%	4199.3	13.6%	1517.2	4.9%	1140.0	3.7%
2006	12059.6	39.1%	12426.7	40.3%	3996.5	13.0%	1320.0	4.3%	1016.6	3.3%
2010	10049.5	32.6%	12757.7	41.4%	5158.5	16.7%	1500.7	4.9%	1352.8	4.4%
2015	7430.8	24.1%	14508.4	47.1%	5742.7	18.6%	1696.8	5.5%	1440.7	4.7%
2020	4465.4	14.5%	12416.5	40.3%	8807.0	28.6%	3434.8	11.1%	1695.6	5.5%
Mean	10234.3	33.2%	12328.3	40.0%	5280.2	17.1%	1751.6	5.7%	1225.0	4.0%

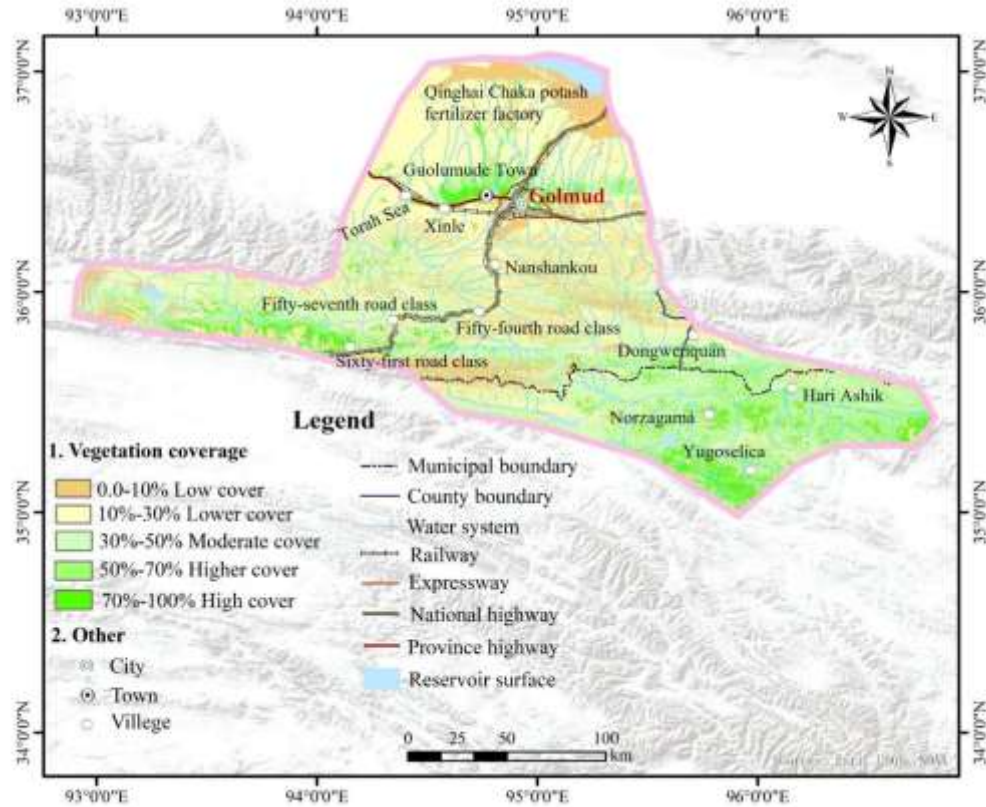


Figure 4 Distribution map of remote sensing extraction of vegetation coverage (VFC) in the working area in 2020

4.4.2 Trends in Vegetation Cover Dynamics

1990–2020 mean VFC trajectories (Figure 5) evince persistently low cover (multi-year mean 22.26%, peak 30.9%). Nonetheless, a basin-wide uptrend prevailed over ~30 years—accelerating post-2006 (~15 years)—indirectly attesting warming-wetting climate shifts (rising temperature/precipitation, declining evaporation) fostering vegetation in the Golmud River Basin.

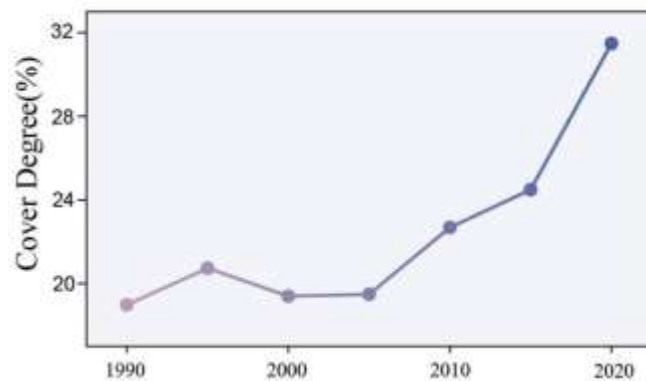


Figure 5. Trends in mean vegetation cover fraction in the study area, 1990–2020.

1990–2020 tiered cover statistics (Table 3) reiterate low cover averaging 33.2% (10,234.3 km²), lower 40.0% (12,328.3 km²); moderate/higher/high at 17.1% (5,280.2 km²), 5.7% (1,751.6 km²), 4.0% (1,225.0 km²). Low/lower aggregation (73.2%) confirms suboptimal cover.

Interannual tier dynamics (Figure 6, Golmud Basin) reveal mixed 30-year trajectories: low cover contracted overall—accelerating post-2000 (13,478.6 to 4,465.4 km²; 43.7% to 14.5%); lower fluctuated modestly with net gain; moderate stabilized 1990–2006 before sustained post-2006 expansion (+4,481 km²); higher surged post-2015; high expanded steadily.

The 1990–2020 cover differential (Figure 7) highlights marked amelioration along Naijin River banks, northern urban alluvial-proluvial plains, extensive mild gains north of Shurgan River east tributary (Jiagariqu River), and pronounced enhancements in croplands/riverine zones from agrarian and natural vegetation increments.

Table 3. Area and proportion of vegetation cover levels in the study area, 1990–2020.

Year	Low Cover		Lower Cover (0–30%)		Moderate Cover (30– 50%)		Higher Cover (50–70%)		High Cover (70–100%)	
	Area		Area		Area		Area		Area	
	0~10%		0~30%		30~50%		50~70%		70~100%	
	Area	%	Area	%	Area	%	Area	%	Area	%
1990	13478.6	43.7%	10730.6	34.8%	4326.1	14.0%	1366.9	4.4%	917.1	3.0%
1995	10762.3	34.9%	12889.3	41.8%	4731.2	15.4%	1424.6	4.6%	1012.0	3.3%
2000	13393.9	43.5%	10568.9	34.3%	4199.3	13.6%	1517.2	4.9%	1140.0	3.7%
2006	12059.6	39.1%	12426.7	40.3%	3996.5	13.0%	1320.0	4.3%	1016.6	3.3%
2010	10049.5	32.6%	12757.7	41.4%	5158.5	16.7%	1500.7	4.9%	1352.8	4.4%
2015	7430.8	24.1%	14508.4	47.1%	5742.7	18.6%	1696.8	5.5%	1440.7	4.7%
2020	4465.4	14.5%	12416.5	40.3%	8807.0	28.6%	3434.8	11.1%	1695.6	5.5%
Mean	10234.3	33.2%	12328.3	40.0%	5280.2	17.1%	1751.6	5.7%	1225.0	4.0%

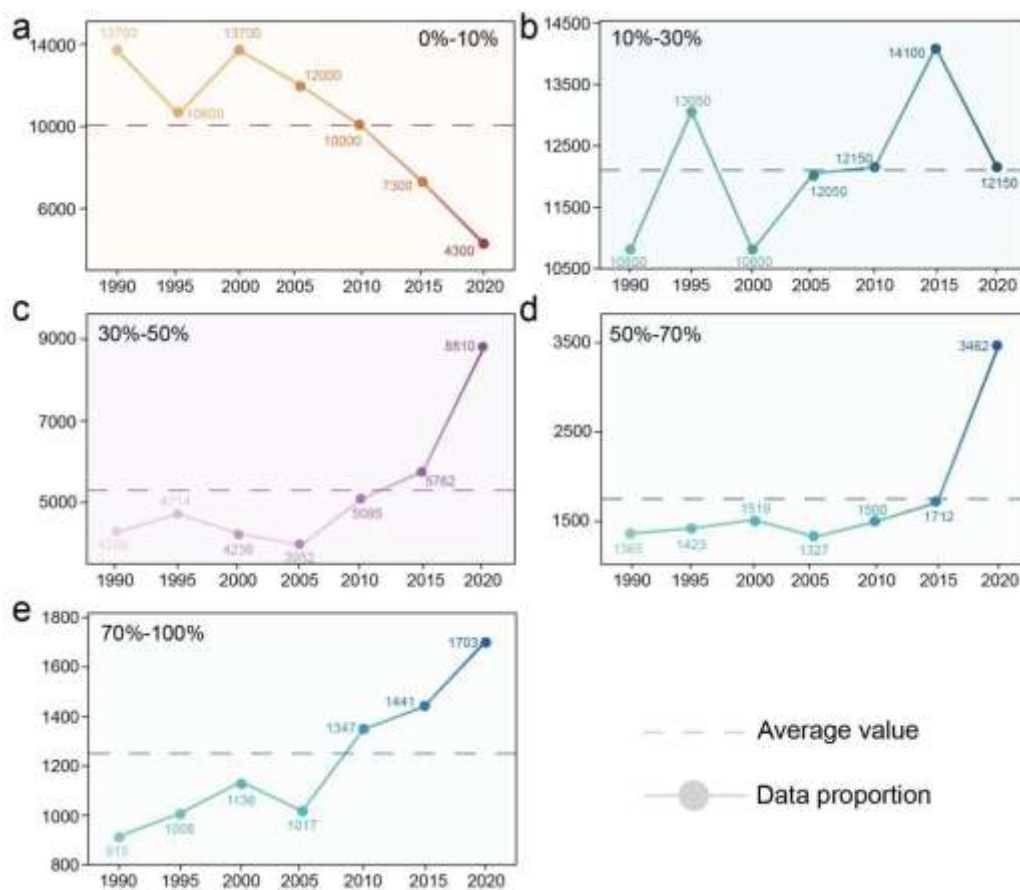


Figure 6. Trends in area by vegetation cover class in the study area, 1990–2020.

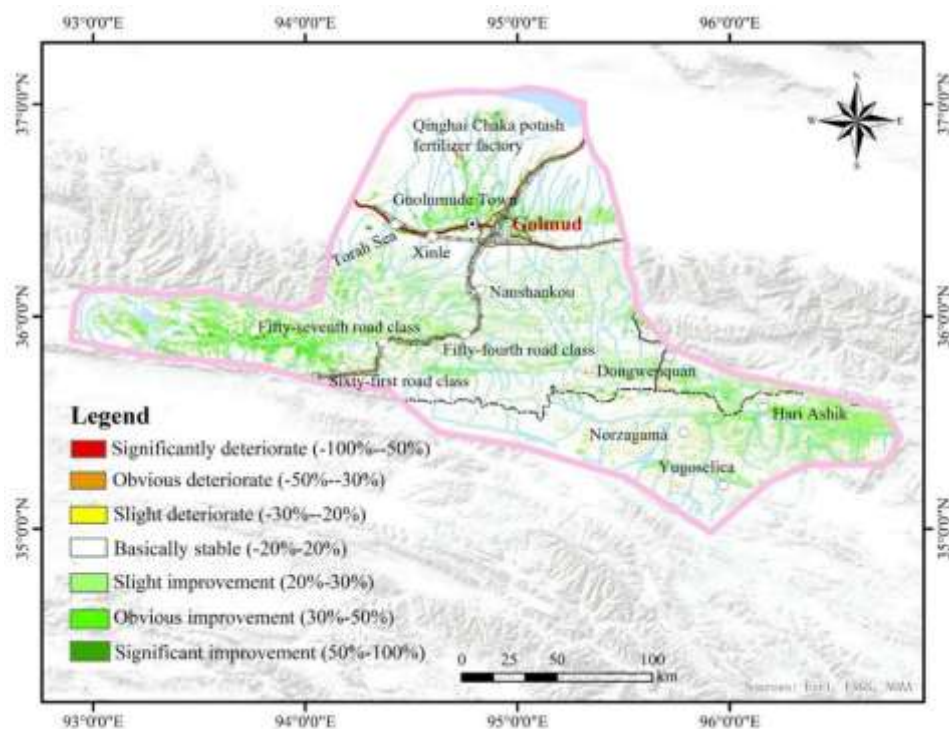


Figure 7. Vegetation cover change map for the study area, 1990–2020.

4.5 Responses of Different Vegetation Types to Groundwater

4.5.1 Relationships between Vegetation Community Growth Metrics and Groundwater Depth

(1) Vegetation Density

Binned by 0.5 m depth intervals, frequencies of vegetation counts at survey points yield histograms and scatterplots (Figure 8), peaking at 1–2 m depth.

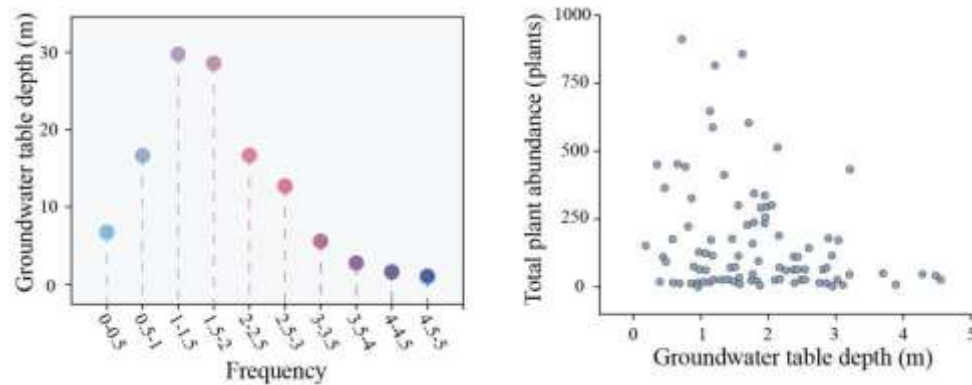


Figure 8. Histograms and scatterplots of vegetation density frequency distribution.

(2) Stem Diameter

Binned by 0.5 m depth intervals, frequencies of vegetation stem diameters at sites yield histograms and scatterplots (Figure 9). Diameters predominantly span 1.5–2.0 cm, reflecting generally modest growth.

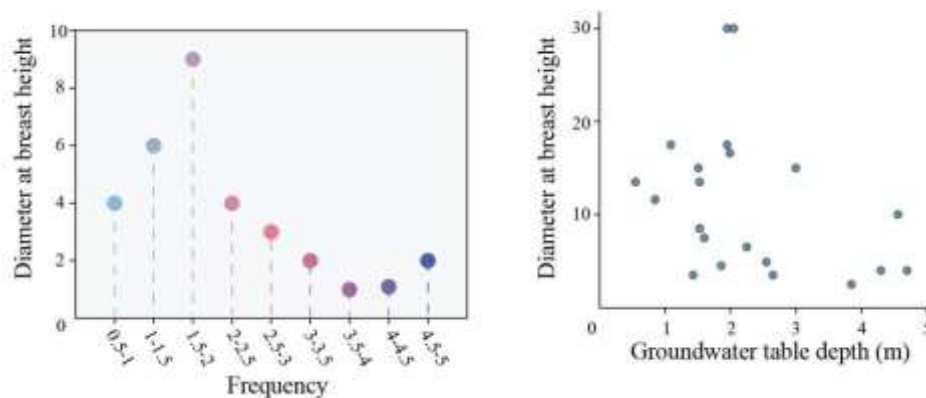


Figure 9. Histogram and scatterplot of stem diameter frequency distribution.

(3) Biomass

Survey points were grouped by 0.5 m groundwater depth intervals for biomass frequency tabulation, depicted in histograms and scatterplots (Figure 10). Peak

frequencies occur at 1.5–2.0 m depth (biomass 0.06–0.816 kg/m³); maximum biomass (1 kg/m³) registers at 0.45 m depth.

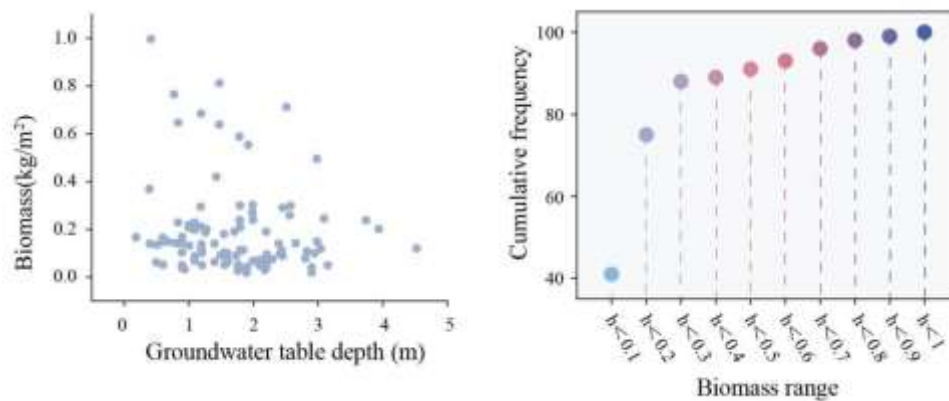


Figure 10. Histogram and scatterplot of biomass frequency distribution.

(4) Shrub Height

Binned by 0.5 m depth intervals, shrub height frequencies at survey points are shown in probability histograms and scatterplots (Figure 11). Dense distributions and vigorous growth characterize 1–2.0 m depths. Analyses confirm skewed distributions. Probability density curves (Figure 12) indicate modal heights of 30–60 cm (frequency 25.93%).

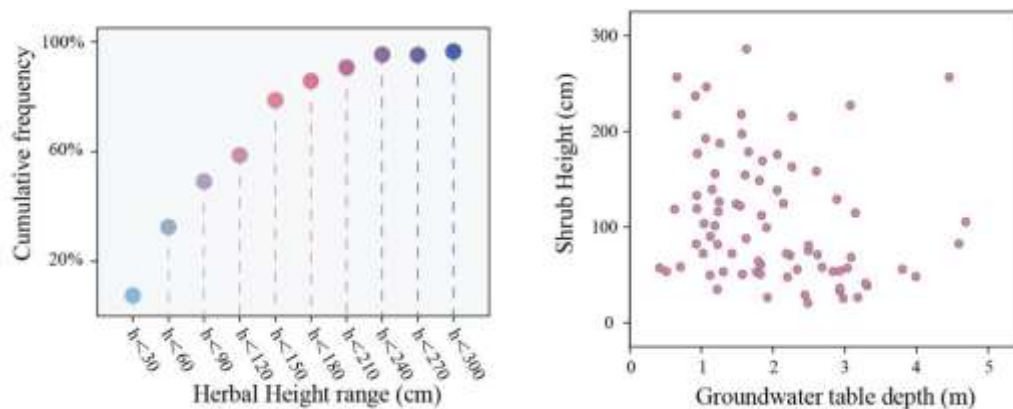


Figure 11. Cumulative frequency histogram and scatterplot of shrub height distribution.

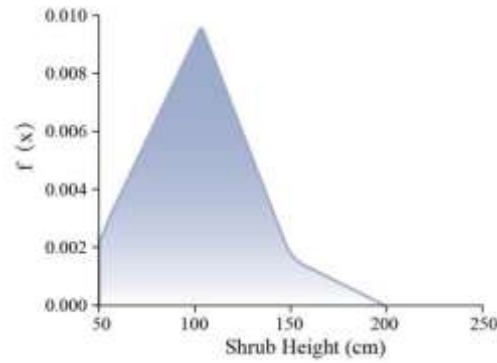


Figure 12. Probability density curve of shrub height distribution.

(5) Herbaceous Height

Survey points, binned by 0.5 m groundwater depth intervals, yielded herbaceous height frequency distributions via cumulative curves and scatterplots (Figure 13). Optimal density and vigor occur at 1.5–2.0 m depths (noted original "cm" as probable typographic error for consistency with metrics). Distributions conform to skewed patterns. Probability density curves (Figure 14) peak at 30–40 cm heights (20% frequency; original "m" rectified per context).

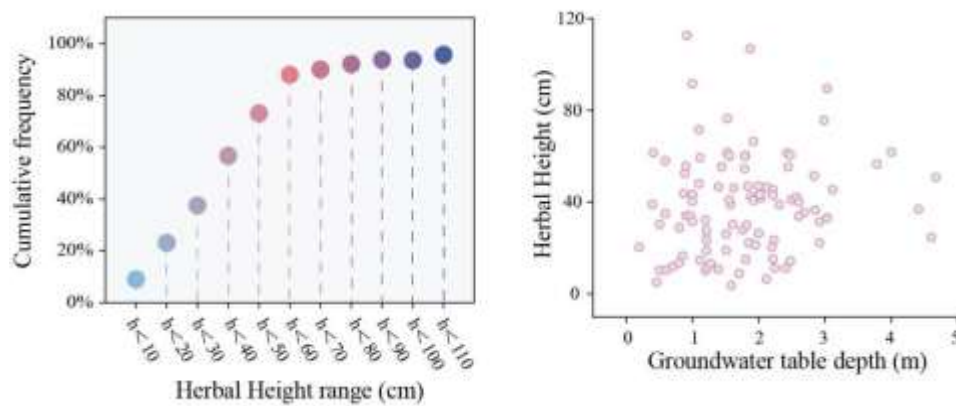


Figure 13. Cumulative frequency histogram and scatterplot of herbaceous height distribution.

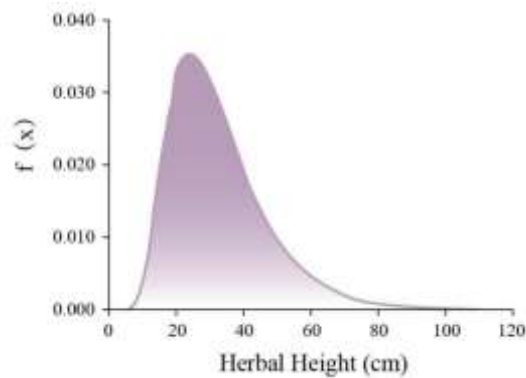


Figure 14. Probability density curve of herbaceous height distribution.

4.5.2 Dominant Vegetation and Their Suitable Groundwater Depths

Based on field vegetation quadrat surveys and eco-hydrogeological investigation data, the occurrence frequency of dominant vegetation in the piedmont plain area—along with the corresponding maximum, minimum, and average groundwater depths—was statistically analyzed (Table 4). Remote sensing interpretations of vegetation ecological changes indicate no evident degradation in the natural oases within the watershed at present. Thus, the survey results can be used as the suitable groundwater depth ranges for these dominant species: *Phragmites australis* (0.10–3.95 m), *Tamarix chinensis* (0.90–4.62 m), *Nitraria sibirica* (1.0–3.28 m), and *Apocynum venetum* (0.90–3.95 m). Subsequently, the groundwater depth distribution patterns for each dominant species were further examined to identify their optimal suitable depths.

Table 4 Suitable Groundwater Depths for Dominant Vegetation Communities

Vegetation Type	Total Samples	Occurrences	Maximum GWD (m)	Minimum GWD (m)	Average GWD (m)	Suitable GWD Range (m)
<i>Phragmites australis</i> community	84	30	3.95	0.11	1.57	0.10~3.95
<i>Tamarix chinensis</i> community	32	13	4.62	0.90	2.15	0.90~4.62
<i>Nitraria sibirica</i> community	9	7	3.28	1.00	1.75	1.0~3.28
<i>Apocynum venetum</i> community	19	11	3.95	0.90	2.34	0.90~3.95

Notes:

‘GWD’ refers to the depth of Groundwater .

"Occurrences" refers to the number of samples where the dominant vegetation was observed

(1) *Phragmites australis* Population

Groundwater depths were grouped at 0.2 m intervals to generate the frequency distribution histogram for *P. australis* at varying depths (Figure 15). Statistical analysis of the distribution patterns reveals a skewed distribution, which can be described using a logarithmic model, yielding the probability distribution curve under different groundwater depth conditions (Figure 15). The results indicate that the occurrence frequency of *P. australis* peaks at a groundwater depth of 1.10 m, with a frequency of 78.65%, representing its optimal suitable depth.

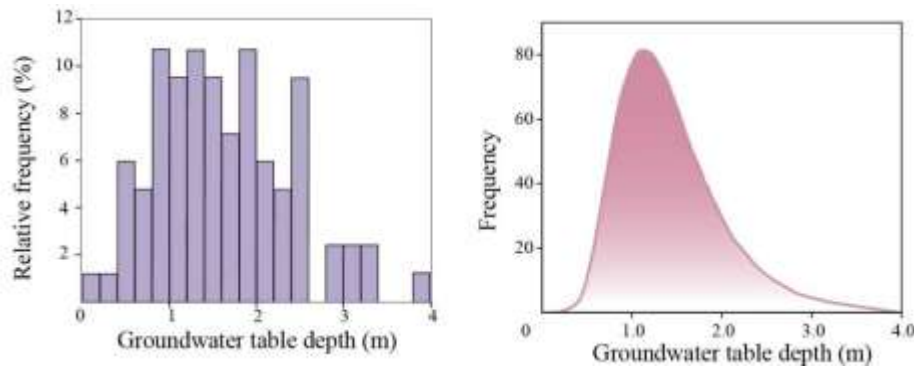


Figure 15 Absolute frequency histogram and probability distribution curve of *P. australis* at different groundwater depths

(2) *Tamarix chinensis* Population

Groundwater depths were grouped at 0.5 m intervals to quantify the occurrence frequency of *T. chinensis* (Figure 16). The distribution patterns exhibit a skewed distribution, modeled logarithmically to derive the probability distribution curve (Figure 16). The cumulative probability curve shows that the optimal suitable groundwater depth for *T. chinensis* is 1.86 m, with a peak frequency of 28%.

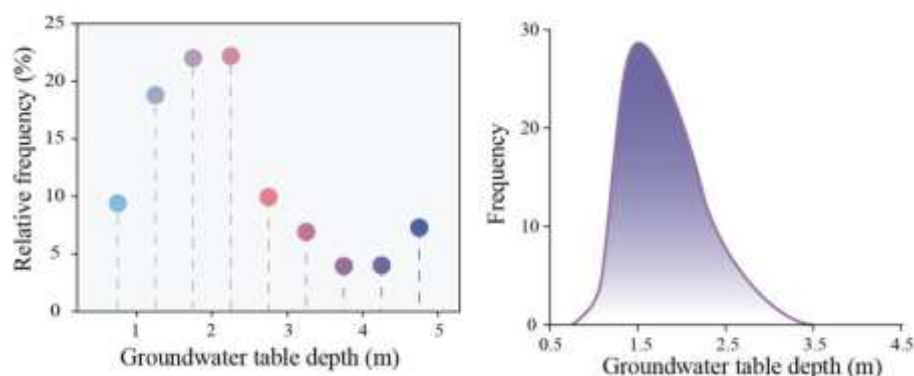


Figure 16 Relative frequency histogram and probability distribution curve of *T. chinensis* at different groundwater depths

(3) *Nitraria sibirica* Population

Groundwater depths were grouped at 0.4 m intervals to produce the frequency histogram for *N. sibirica* occurrences (Figure 17). The logarithmic distribution curve indicates that the optimal growth depth is 1.60 m, with a probability of 91.73%.

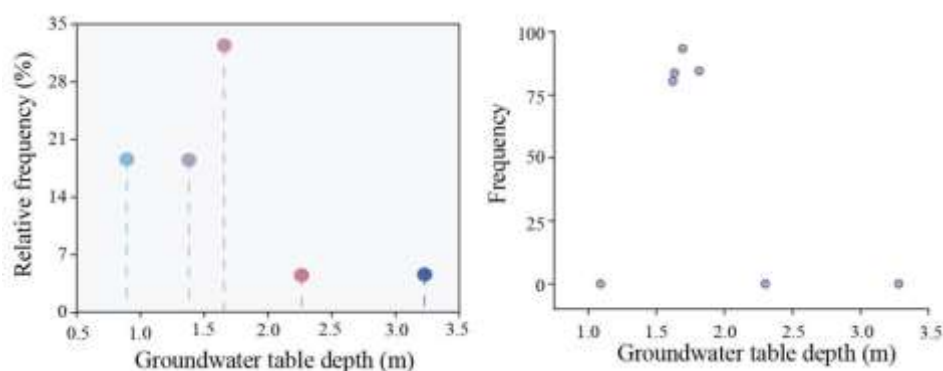


Figure 17 Relative frequency histogram and probability distribution curve for *N. sibirica*

(4) *Apocynum venetum* Population

Groundwater depths were grouped at 0.5 m intervals to generate the frequency histogram for *A. venetum* occurrences (Figure 18). The distribution patterns conform to a logarithmic model (corrected from original reference to *T. chinensis*). The probability distribution curve reveals that the optimal suitable groundwater depth is 2.45 m, with a peak frequency of 74.5%.

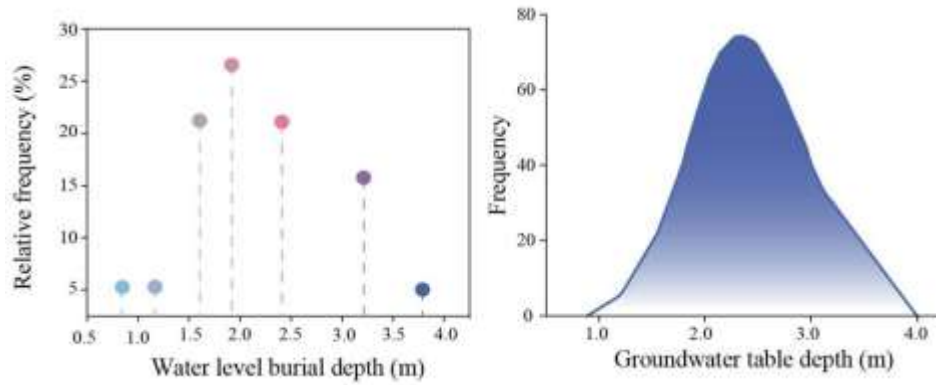


Figure 18 Relative frequency histogram and probability distribution curve for *A. venetum*

4.6 Ecological Thresholds of Phreatic Groundwater Depth

4.6.1 Distribution Characteristics of Groundwater Depth

In arid and semi-arid inland basins, groundwater exerts a profound influence on vegetation distribution. Groundwater depth directly affects soil moisture and nutrient availability, governing vegetation growth, distribution patterns, and community succession, and serving as the primary determinant of oasis survival in desert regions. While some plants are highly dependent on groundwater, others are relatively insensitive to its fluctuations, resulting in complex interactions between vegetation and groundwater in arid zones. The Golmud River Basin exemplifies a typical highland inland basin, characterized by arid climate, low rainfall, high winds, and intense evaporation—particularly in the piedmont plain, where much of the natural vegetation relies on groundwater support.

Based on unified groundwater level measurement data, a groundwater depth zonation map was produced (Figure 19). The distribution map reveals that groundwater depths in the Golmud River Basin gradually shallow from the southern desert toward the northern salt lakes, with localized deepening along river channels—a typical dynamic feature in arid/semi-arid piedmont plains. Monitoring wells are concentrated in the vegetated areas east and west of Golmud City, corresponding to the phreatic overflow zone with well-developed oases, where depths primarily range from 0–10 m. Southward from Golmud City lies the deep phreatic zone, with depths progressively increasing to over 100 m. Northward extension forms the phreatic depression zone, featuring flat terrain, fine soil particles, shallow depths

(primarily 0–6 m), yet slight deepening due to intense evaporation and associated soil salinization.

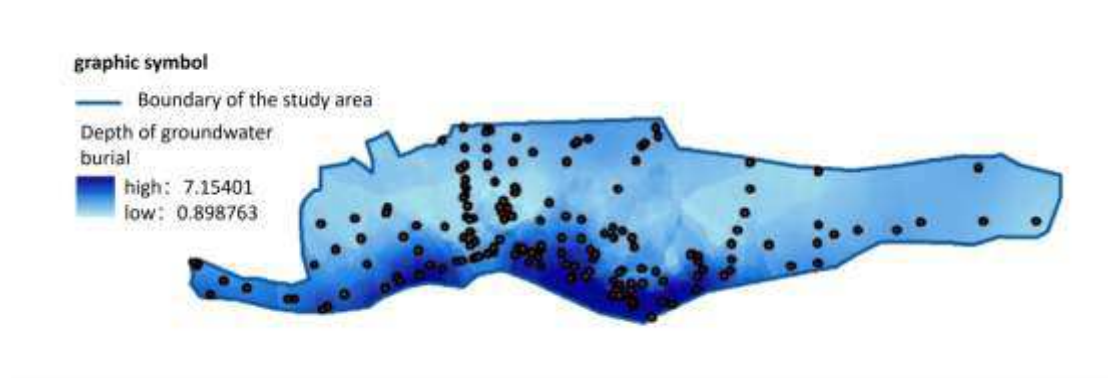


Figure 19 Zonation map of groundwater depths in the piedmont plain

4.6.2 Relationship between NDVI and Groundwater Depth

In ArcGIS, pixel pairs of mean NDVI values and groundwater depths were extracted to generate a scatter plot (Figure 20). The plot demonstrates a clear correlation between NDVI and groundwater depth, with concentrated high NDVI values primarily occurring at depths <8 m. Overall, NDVI tends to decrease as groundwater depth increases; however, at very shallow depths, soil salinization suppresses vegetation growth, resulting in lower NDVI values. NDVI values are predominantly distributed at depths of 0.5–4 m, with moderate distribution at 4–7.2 m and minimal presence at 7.2–10 m. The NDVI-groundwater depth curve exhibits a multi-peak wavy pattern: values are sparse <0.5 m, largely due to northern saline-alkali flats observed in field surveys. In the northern Jinshui River area, shallow depths combined with severe salinization inhibit vegetation, yielding low NDVI; a first peak emerges at ~1 m, driven by river recharge, supporting extensive reed beds along the Jinshui River banks, while distal areas away from channels show bare white saline soils. As depths deepen to 1–4 m, NDVI coverage improves overall, with a pronounced high-value zone at 2.7–4 m featuring reeds (*Phragmites australis*), *Apocynum venetum*, distorted willow (*Tamarix* spp.), and diverse, well-covered vegetation. Within 0–4 m, NDVI peaks at 0.9 m and 4 m (values 0.27–0.43). Beyond 4 m, NDVI fluctuates and declines sharply from 0.43 to 0.1; >8 m, values are mostly <0.1, with sparse outliers in saline flats and deserts supporting drought-tolerant

deep-rooted plants reliant on minimal rainfall or seepage from artificial channels around Golmud City.

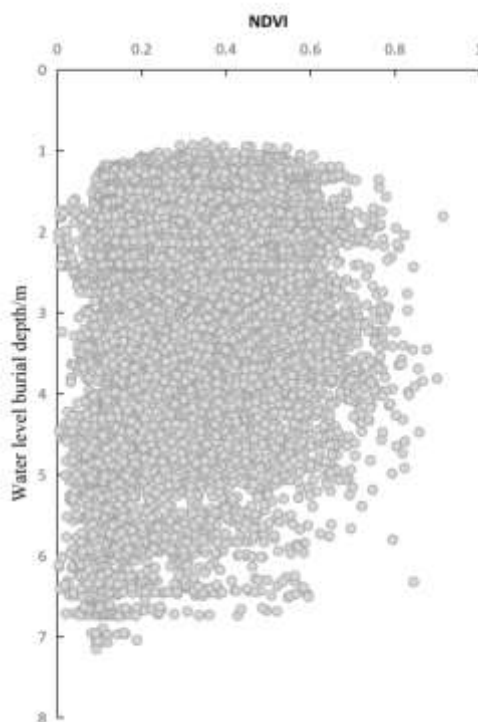


Figure 20 Scatter plot of NDVI versus groundwater depth correlation in the Golmud River Basin

Field surveys corroborate that NDVI peaks at a mean of 0.4 when groundwater depth <4 m (centered at ~3–4 m), with consistently high values across 0–4 m, dominated by tall *Phragmites australis*, *Nitraria sibirica*, and distorted willow (*Tamarix* spp.) in natural vegetation zones. Between 4–8 m, mean NDVI fluctuates downward from 0.4 to 0.08. A secondary peak at ~6.5 m (NDVI = 0.27) occurs in farmlands east and west of Golmud City, supporting crops such as red goji (*Lycium barbarum*), quinoa, and naked barley.

Integrating ground surveys, pit probing, and drilling results, NDVI-groundwater depth relationships vary by vegetation type due to differing sensitivities and responses. Root system analyses reveal: at ~5 m, shrubs like distorted willow, *N. sibirica*, and sea-buckthorn prevail; <2 m features tall *P. australis* with minor shrubs, exhibiting vigorous growth and high coverage; in salt-crust lake-marsh plains, shallow depths and intense evaporation cause severe salinization, transitioning to dwarfed salt-tolerant reeds and distorted willow. Crops and plantations at 6–10 m largely rely

on irrigation.

Synthesizing these patterns with field and experimental data, the ecological groundwater depth thresholds impacting vegetation are: 0–0.5 m: Critical depth for aquatic reeds; 0.5–2 m: Optimal range for *P. australis*, *N. sibirica*, distorted willow, etc.; 2–5.0 m: Survival range for distorted willow and *N. sibirica* with substantial vigor variation; 5.0 m: Domain for xerophytes and irrigation-dependent species.

4.6.3 Relationship between NDVI and TDS Content

TDS distribution closely corresponds to groundwater depth patterns (Figure 21): in the central-southern study area with deeper groundwater, TDS is relatively low; in shallower eastern, western, and southern zones, intense evaporation elevates TDS levels.



Figure 21 Zonation map of groundwater TDS in the piedmont plain

The NDVI-TDS relationship in the study area is illustrated in Figure 22. As TDS increases, NDVI scatter density decreases, with high-value points diminishing. At TDS <0.5 g/L, NDVI is low, primarily in the southern gravel Gobi-oasis transition zone where excessive depths limit growth to sparse deep-rooted distorted willow (*Tamarix* spp.); at 0.5–2 g/L, scatters are dense with optimal vegetation development—suitable depths foster diverse shrubs and herbs with vigorous growth. Above 2 g/L, NDVI declines, concentrating at 0.1–0.6 with fewer high values; >2.8 g/L sees a sharp drop in high-value points, severely impairing vegetation growth.

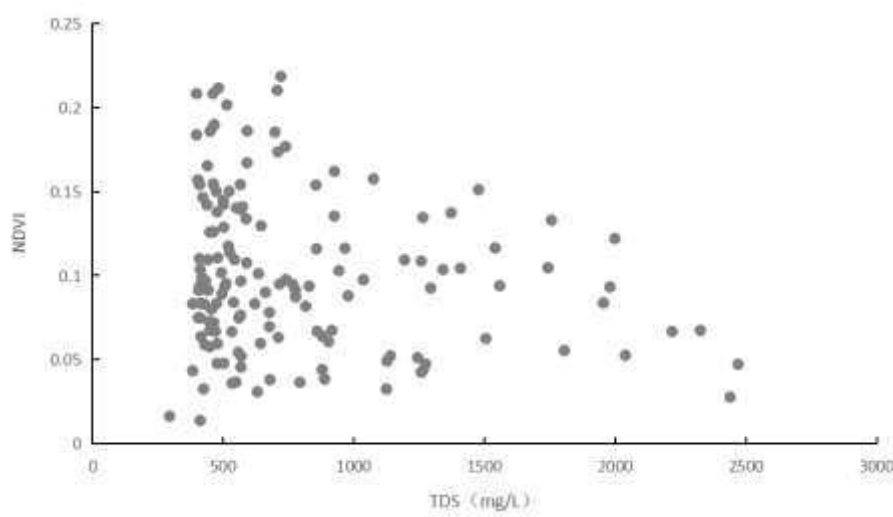


Figure 22 Scatter plot of NDVI versus TDS content in the study area

4.7 Discussion

Both groundwater depth and TDS significantly influence groundwater-dependent vegetation. The overall groundwater depth gradient—from deeper levels in the southern gravel Gobi belt to shallower depths in the northern terminal lake zone—establishes a northern depth-controlled threshold boundary for vegetation cover in the oasis belt and a southern TDS-controlled salinity boundary, forging interactive relationships among depth, TDS, and vegetation coverage. Although precipitation in the Golmud plain is scarcer than in mountainous areas, runoff from mountain precipitation forms the Golmud River, whose substantial leakage in the gravel Gobi zone—combined with basin topography—provides ample recharge, converting surface water to sustain oasis vegetation around Golmud City. Thus, oasis vegetation dynamics in the Golmud River Basin are governed by multiple factors (precipitation, evaporation, groundwater, surface water), with river scale and discharge dominating; flow magnitude and Gobi lithology dictate surface-to-groundwater recharge, shaping regional vegetation patterns.

Integrating NDVI values with springs-fed river distributions, beyond the south-to-north topographic gradient influencing groundwater-vegetation patterns, local springs-fed river configurations drive fine-scale dynamics. Vegetation coverage exhibits pronounced spatial heterogeneity: high-to-moderate coverage prevails along main channel banks, transitioning to low-moderate and low coverage with increasing

distance perpendicular to channels and the presence of tributaries, modulating localized variations.

5. Conclusions

(1) Desert vegetation predominates in the Golmud River Basin plain. Oasis vegetation is primarily influenced by precipitation, surface water, and groundwater, with the latter mainly recharged via river leakage and the former comprising springs-fed rivers from phreatic overflow at the plain forefront.

(2) In the Golmud River Basin oasis plain, the groundwater depth ecological threshold is 0–4 m (vegetation persists within 4–8 m, optimal at 1–4 m). Suitable depth ranges for dominant species are: *Phragmites australis* (0.10–3.95 m), *Tamarix chinensis* (0.90–4.62 m), *Nitraria sibirica* (1.0–3.28 m), and *Apocynum venetum* (0.90–3.95 m). The TDS threshold spans 0.5–2.8 g/L, beyond which vegetation development is severely impaired.

(3) Southern oasis plain fringes are predominantly controlled by groundwater depth, northern fringes by TDS, together delineating ecological thresholds for oasis vegetation under their synergistic effects. Northern springs-fed rivers impose localized distance-dependent controls perpendicular to channels, yielding heterogeneous coverage patterns.

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Data Availability declaration: The data in this article are all derived from the field investigations conducted by the project participants. The field water level and vegetation surveys, among others, were all carried out independently by the project

team members. The remote sensing image maps mainly use Landsat TM, ETM+, OLI, OLI-2, etc. as the main remote sensing data sources to extract and interpret the relevant element information. The water quality test data were all obtained through the laboratory of the author's affiliated unit and have original records retained.

Declarations Competing interests The authors declare no competing interests.

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