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Water-Resource Sustainability and Adaptive Management in a Cryosphere-Dependent Endorheic Basin: A Case Study of the Cherchen River, NW China

Aishajiang Aili [1], Qiao Xu [2,3,4,*], Yan Xu [5], Dong Cui [2,3], Tao Lin [4] and Kamalitdin Idirisov [6]

[1] Research Center of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[2] College of Resources and Environment, Yili Normal University, Yining 835000, China
[3] Institute of Resources and Ecology, Yili Normal University, Yining 835000, China
[4] Desert-Oasis Ecological Monitoring and Restoration Engineering Technology Innovation Center, Ministry of Natural Resources, Urumqi 830002, China; 25531170@163.com
[5] Xinjiang Uygur Autonomous Region Ecological Water Resources Research Center, Urumqi 830000, China
[6] Institute of Agriculture and Agrotechnologies of Karakalpakstan, Nukus 230100, Uzbekistan
* Correspondence: 15739036377@sina.cn

Abstract

The Cherchen River Basin (CRB), a cryosphere-dependent endorheic basin in northwestern China, faces strong competition among agricultural, groundwater, and ecological water demands under pronounced seasonal runoff variability. This study integrates multi-source hydrological records, groundwater-resource assessment, sectoral water-use statistics, and groundwater-quality constraints to diagnose water-resource sustainability under 2020 reference-year conditions and develop an adaptive assessment-to-management framework. Total water supply was 471.85 million m^3, of which surface water and groundwater contributed 77.3% and 22.6%, respectively. Agriculture accounted for 96.8% of socioeconomic water use, with an average irrigation application of 659 m^3/mu and high-efficiency irrigation covering 41.1% of cropland. Groundwater abstraction reached 106.69 million m^3, equivalent to approximately 72% of the estimated exploitable groundwater resource, indicating high groundwater dependence but not, by itself, long-term aquifer depletion. Annual gross water supply corresponded to approximately 47% of the estimated available water-resource base; because return flows were not consistently quantified, this value is treated as an annual water-resource utilization ratio rather than a formal WEI^+. Benchmark calculations indicate that reducing mean irrigation application toward regional levels of 616–558 m^3/mu could lower gross agricultural demand by approximately 27.8–65.4 million m^3 yr^{-1}. Based on these diagnostics, we propose a four-stage framework comprising resource diagnosis, pressure identification, management prioritization, and adaptive implementation. Management measures beyond the irrigation benchmark scenarios are presented as policy options requiring monitoring and further hydrological, ecological, or economic evaluation rather than as predetermined outcomes.

Keywords: water resource management; cryosphere-dependent basin; groundwater overextraction; irrigation efficiency; arid inland river; Cherchen River Basin; sustainable allocation

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1. Introduction

Arid inland regions, where water scarcity is a long-standing challenge, are increasingly under threat due to the dual pressures of climate change and escalating human demand [1]. These areas are characterized by low precipitation, high evaporation, and limited renewable freshwater sources. Among these, endorheic basins, hydrologically closed systems that do not drain to the ocean, are especially vulnerable because they rely predominantly on local surface runoff and groundwater, much of which is sustained by cryospheric contributions such as glacier and snowmelt [2]. With the global climate warming at an unprecedented rate, these cryospheric sources are retreating rapidly, threatening the very foundation of water availability in such regions [3]. Inland river basins in northwestern China have always been considered as the most ecologically fragile and socioeconomically important regions, where water scarcity directly impacts agricultural productivity, rural livelihoods, and ecological health [4]. The Cherchen River Basin (CRB), located in the hyperarid southeastern margin of the Tarim Basin in Xinjiang, China, is a prime example [5,6]. Covering an area of approximately 47,400 km^2, the CRB is bordered by the Kunlun and Altun Mountains to the south and the Taklimakan Desert to the north (Figure 1). The basin has an extremely arid climate, with annual precipitation averaging just 25.7 mm and evaporation exceeding 1500 mm, making water management a critical issue for the region's survival and development [7]. The hydrological regime of the CRB is dominated by meltwater contributions, with over 87% of annual runoff sourced from glaciers and snowmelt in the southern mountains. This creates significant temporal variability in water availability, with nearly half of the annual flow occurring in summer months [8]. However, climate-induced glacier retreat and warming temperatures have begun to alter meltwater timing and reduce long-term runoff volumes, amplifying uncertainty and risk. These shifts are particularly concerning given the basin's heavy reliance on this runoff to support agriculture, domestic use, and ecological flows [9,10]. The socioeconomic dynamics of the CRB further compound these hydrological challenges. Agriculture is the dominant water consumer, accounting for 96.8% of the basin's total water use, with irrigation water consumption per unit area significantly exceeding both regional and national averages [11]. Despite this, the adoption rate of water-saving technologies such as drip irrigation remains low (41.1%), trailing behind the Xinjiang average (59.3%). Groundwater provides an important buffer during periods of reduced surface-water availability; however, abstraction in 2020 was approximately 72% of the estimated exploitable groundwater resource, indicating substantial dependence on groundwater, particularly in downstream areas where salinity constrains its usability [12]. Industrial and domestic sectors, though smaller in volume, also exhibit inefficiencies: for instance, industrial water use per 10,000 yuan of added value (133 m^3) is nearly four times the regional average, while urban per capita domestic water use (167 L/day) remains below expected benchmarks [13].

In addition to natural and technical limitations, water governance in the basin is constrained by institutional fragmentation, weak enforcement of water use regulations, inadequate monitoring infrastructure, and insufficient integration of socioeconomic development plans with ecological needs [14]. These systemic gaps hinder the region's ability to respond effectively to ongoing and future water-related risks. The situation is further complicated by increasing land use intensity, population growth, and policy emphasis on agricultural expansion, all of which escalate water demand and reduce system resilience [15]. In response to these complex challenges, there is a growing recognition of the need for integrated water resource management (IWRM) frameworks that combine hydrological, environmental, and socioeconomic dimensions [16]. System dynamics modeling has emerged as a promising approach to assess water resource allocation scenarios, explore feedback, and support informed decision-making under uncertainty. However,

successful implementation requires comprehensive datasets, robust modeling tools, and stakeholder engagement mechanisms tailored to the specific socio-hydrological context of arid inland basins like the CRB [17]. Against this backdrop, the present study aims to develop a comprehensive assessment of water-resource availability, use efficiency, and sustainability in the Cherchen River Basin by integrating multi-source hydrological data, socioeconomic statistics, and system-level modeling approaches. Specifically, the study investigates current water supply structures and consumption patterns, evaluates sectoral inefficiencies and sustainability thresholds, and identifies the drivers of overexploitation and ecological degradation.

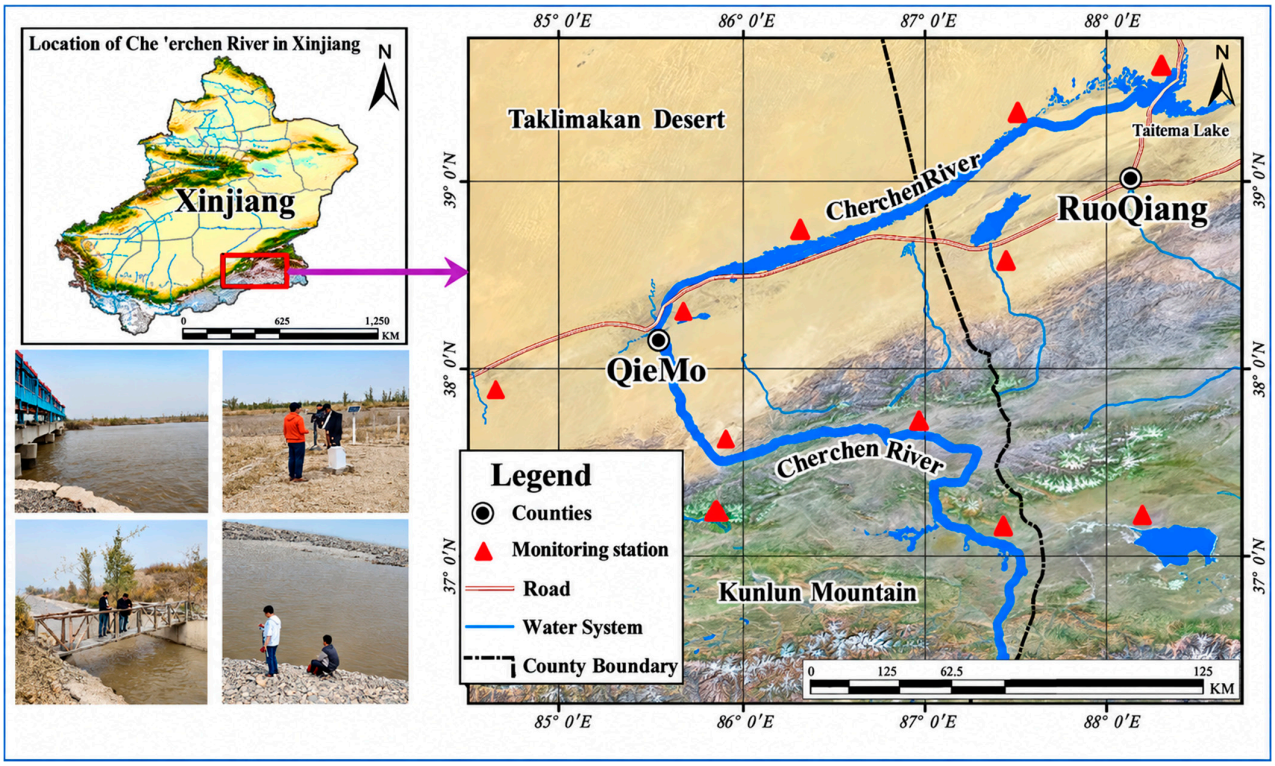

Figure 1. Location and hydrographic setting of the Cherchen River Basin in northwestern China.

Previous research in the Cherchen (Qarqan) River Basin has substantially advanced understanding of individual components of the water system, but has generally followed several distinct research directions [18]. Hydrological studies have examined cryosphere-driven runoff generation, groundwater recharge, and surface-water–groundwater interactions using process-based and water-balance approaches [19,20]. Hydrogeochemical investigations have examined groundwater salinization, contaminant enrichment, aquifer conditions, and the sources and transport of dissolved constituents [21]. More recent studies have also quantified agricultural irrigation requirements and examined their sensitivity to climate variability and changes in crop structure [22]. These studies provide an increasingly detailed understanding of individual hydrological, hydrochemical, and agricultural processes. However, comparatively few basin-scale assessments have jointly connected surface-water-resource and groundwater-resource accounting, sectoral socioeconomic water demand, groundwater-quality constraints, and management responsibilities within a common diagnostic framework.

Accordingly, this study addresses three research questions: (1) How are surface water, exploitable groundwater resources, and sectoral water withdrawals structured in the Cherchen River Basin under the 2020 reference-year conditions? (2) Which major water-management pressures emerge when resource availability, sectoral water-use effi-

ciency, groundwater-quality constraints, and seasonal runoff characteristics are evaluated together? (3) How can these diagnostic results be translated into an adaptive assessment-to-management framework that links identified pressures with management options, stakeholder responsibilities, monitoring, and periodic reassessment? By addressing these questions, the study aims to provide an integrated basin-scale diagnosis rather than introduce a new hydrological or optimization methodology.

2. Data and Methods

2.1. Study Area Description

The Cherchen River Basin (CRB) is located in southeastern Xinjiang, China, encompassing parts of the Qiemo County and the Ruoqiang County within the Bayingolin Mongol Autonomous Prefecture [3]. Geographically, the basin lies between 84°55′–88°20′ E and 36°10′–39°45′ N, covering a total area of approximately 47,400 km^2. It is bordered by the Kunlun and Altun Mountains to the south and extends into the Taklimakan Desert to the north (Figure 1). The CRB also connects with adjacent basins, including the Kalamilan River Basin to the west, and the Jianggasay River Basin to the east, and ultimately merges with the Tarim River Basin in the northeast, terminating at Lake Taitema.

Lake Taitema represents the terminal receiving water body of the downstream river system and is therefore an important ecological receptor of upstream water allocation and river-flow regulation. In this study, the lake is considered primarily as a downstream ecological endpoint rather than as an independently modeled water-storage component. To avoid ambiguity in spatial terminology, three spatial domains are distinguished. The broader study region covers approximately 47,400 km^2; the hydrological catchment contributing to the Cherchen River covers approximately 24,692 km^2; and the groundwater-resource evaluation covers 45,504 km^2, including mountainous, plain, and lower Sanwei River evaluation zones. These spatial domains serve different analytical purposes and should not be interpreted as equivalent catchment boundaries.

In the Chinese administrative system, a "county" is a county-level administrative unit. The Qiemo County and the Ruoqiang County are therefore administrative jurisdictions rather than hydrological subdivisions of the basin. The 37th Regiment is distinguished because it represents a separate agricultural and administrative water-use unit within the study area rather than a hydrological subdivision of the basin. As an agricultural production unit administered under the Xinjiang Production and Construction Corps (XPCC), it operates with distinct water-allocation and irrigation-management arrangements from the surrounding county-level system. Although its total water use is smaller than that of the Qiemo County, distinguishing it allows the analysis to preserve the administrative structure through which water allocation, irrigation management, and water-use statistics are reported. It is therefore retained as a separate unit for accounting and management interpretation, rather than being treated as an independent hydrological system.

The basin features a distinct south-to-north topographical gradient, transitioning from mountainous headwater zones to alluvial fans, plains, and desert landscapes. The region experiences a warm-temperate extreme arid continental desert climate, influenced by its inland location, surrounding high mountains, and minimal maritime influence. Long-term climatological data indicate a mean annual temperature of 10.9 °C, with seasonal extremes ranging from −27.4 °C in winter to 41.6 °C in summer. Mean annual precipitation is only 25.7 mm, whereas E601 pan evaporation averages 1526.2 mm yr^{-1}, illustrating the extremely arid hydroclimatic setting of the basin. Annual evaporation, measured via E601 pan evaporation, averages 1526.2 mm. Sunshine duration averages 2700.7 h per year, and the frost-free period is approximately 193 days.

The Cherchen River itself is 813 km long, with 353 km comprising its upper mountainous reaches. The river drains a catchment area of approximately 24,692 km^2 and is predominantly fed by glaciers and snowmelt, which account for 87% of its annual runoff. Although interannual flow variability is relatively stable, intra-annual variability is substantial, with nearly half of the total discharge occurring in the summer months. This hydrological regime reflects the basin's high dependence on cryospheric inputs.

The Cherchen River, stretching 813 km with a 353 km headwater reach above the mountain outlet, drains a catchment area of 24,692 km^2. As a glacier- and snowmelt-dominated river, 87% of its annual runoff originates from glacial runoff and permanent snowmelt. While interannual streamflow variability is relatively stable, intra-annual distribution is highly uneven, with nearly half of the total discharge occurring during summer months. This unique hydrological regime underscores the critical role of cryospheric resources in sustaining water availability across the basin.

2.2. Data Sources

2.2.1. Surface Water Data

The data used in the study are publicly available. Hydrological data for surface water analysis were obtained from both national basic hydrological stations and specialized local monitoring stations. The primary station within the basin is the Qiemo National Hydrological Station. Additional data were collected from seven adjacent national stations, including Niya, Tongguzluk, Heishan, Cele, Nuer, Keliya, and Bayiba stations, covering various tributaries such as the Niya, Qira, Nuer, Keliya, and Yurungkash Rivers.

Supplementary data were sourced from four specialized stations within or near the basin: Dashimen, Moleqie, Enlik, and Bayiba. All national stations adhere to China's national hydrological monitoring standards, and their data are archived in the National Secondary Hydrological Database. These datasets were utilized to generate runoff depth contour maps and to extend time series records using interpolation techniques when necessary. Table 1 summarizes the locations, establishment years, and coordinates of all monitoring stations used in this study.

Table 1. Hydrological monitoring stations used in the surface-water assessment.

Station	River Basin/Location	Established	Station Type	Longitude	Latitude
Qiemo	Cherchen River Basin	1956	Basic	85°34′	37°33′
Dashimen	Cherchen River Basin	2014	Specialized	85°48′	37°35′
Moleqie	Moleqie River Basin	2004	Specialized	84°28′37″	37°10′34″
Niya	Niya River Basin	1960	Basic	82°38′	36°50′
Bayiba	Niya River Basin	2010	Specialized	82°40′	36°37′
Keliya	Keliya River Basin	1956	Basic	81°28′51″	36°27′06″
Nuer	Nuer River Basin	1960	Basic	80°59′	36°15′
Cele	Qira River Basin	1958	Basic	verify	36°51′48″
Enlik	Qira River Basin	2004	Specialized	80°33′	verify
Heishan	Yurungkash River Basin	1959	Basic	79°46′	36°15′
Tongguzluk	Yurungkash River Basin	1962	Basic	79°55′	36°49′

Note: Basic stations are national routine hydrological monitoring stations operated according to standardized national monitoring procedures and generally provide long-term hydrological records. Specialized stations are supplementary local or project-specific monitoring stations used to improve spatial coverage or provide observations for particular tributaries or river reaches.

2.2.2. Groundwater Data

(1) Scope of Evaluation: Groundwater-resource evaluation focused on the plain areas of the CRB, specifically within the Qiemo County and the Second Division's 37th Regiment, covering an area of 45,504 km^2. The total evaluated area comprises 25,494.6 km^2 of moun-

tainous terrain, 13,456.7 km^2 of plains, and 6552.7 km^2 in the lower Sanwei River segment. The assessment primarily targeted Quaternary shallow pore aquifers (depth $\leq$ 200 m) with salinity levels $\leq$ 2 g/L. Zones exceeding this salinity threshold were excluded from exploitable-resource estimations but were considered for recharge calculations.

(2) Evaluation Principles: Groundwater resource quantification was conducted using a recharge-based approach in conjunction with basin-scale water balance analysis. The methodology aligns with the technical guidelines set forth in the Third National Water Resources Survey and Evaluation. Key hydrological processes such as infiltration, lateral groundwater flow, and precipitation recharge were evaluated to establish estimates of exploitable resources. Groundwater dynamics were analyzed under quasi-equilibrium assumptions, where long-term changes in water levels are considered negligible.

2.3. Analytical Methods

2.3.1. Water Balance Analysis

A water balance framework was applied to assess both surface and groundwater systems. The general water balance equation is defined as:

$$Wa - Wb = Wc$$

where

- Wa = total inflows (e.g., precipitation, surface water, and groundwater recharge);
- Wb = total outflows (e.g., surface and groundwater discharge);
- Wc = net water consumption (e.g., evaporation and transpiration).

A separate groundwater balance equation was used to quantify recharge and extraction dynamics:

$$Q_{recharge} - Q_{discharge} = \pm \mu F\ (\Delta h / \Delta t)$$

where

- $Q_{recharge}$ = groundwater recharge;
- $Q_{discharge}$ = total discharge or extraction;
- $\mu F(\Delta h/\Delta t)$ = change in groundwater storage over time.

Assuming quasi-steady-state conditions, the change in storage ($\mu F \Delta h/\Delta t$) was considered negligible for equilibrium zones.

2.3.2. Key Parameters and Coefficients

Critical parameters used in the water balance and groundwater resource calculations included:

- Hydraulic conductivity (k);
- Specific yield and transmissivity (T);
- Infiltration coefficients for rivers, canals, and irrigation systems.

These parameters were derived from field tests, regional hydrological reports, and historical datasets, particularly from Xinjiang Groundwater Resources.

2.3.3. Groundwater Flow Components

Groundwater recharge components included:

- Surface water infiltration from rivers and gullies such as Tatlekesu, Hadilukesayi, Munabulake, Akeyasayi, and others.
- Storm flood infiltration from intermittent runoff events, calculated as:

$$Q_{flood} = F \cdot A$$

where F represents the catchment area (431.11 km^2) and A the runoff depth.

- Precipitation recharge was estimated using average annual rainfall data (0.0257 m) and the plains area (13,456.7 km^2), though its contribution was considered negligible due to the low intensity of effective precipitation events (<10 mm/event).
- Lateral groundwater inflow from surrounding boundaries was also calculated, with southern boundaries acting as recharge zones and northern/eastern boundaries serving as discharge zones. Eastern and western boundaries were assumed to be zero-flux. The principal variables, hydrogeological parameters, adopted criteria, data sources, and associated uncertainties used in the groundwater-resource assessment are summarized in Table 2.

2.3.4. Assumptions, Uncertainty, and Interpretation of the Assessment

The assessment integrates hydrological observations, regional statistical records, hydrogeological parameters, and interpolated information derived from datasets with different spatial and temporal resolutions. Consequently, the resulting water-balance estimates should be interpreted as basin-scale diagnostic estimates rather than as exact representations of local water availability. Several sources of uncertainty are particularly relevant. First, the density and record length of hydrological observations vary among stations, and interpolation of runoff information may smooth local spatial variability. Second, groundwater calculations depend on hydraulic conductivity, specific yield, transmissivity, and infiltration coefficients derived from field investigations and regional reports; spatial heterogeneity in these parameters introduces uncertainty into recharge and exploitable-resource estimates. Third, the quasi-steady-state assumption neglects short-term changes in groundwater storage and may therefore be less representative in areas experiencing persistent groundwater-level decline. Finally, the 2020 water-use assessment provides a detailed reference-year diagnosis but does not explicitly simulate interannual hydrological variability or future climate trajectories.

These uncertainties were considered when translating the assessment into management recommendations. Consequently, the proposed measures are interpreted as priority directions and adaptive management options rather than deterministic engineering prescriptions. Measures involving infrastructure capacity, ecological-flow requirements, or future allocation targets require additional site-specific feasibility analysis before implementation. The framework therefore emphasizes monitoring, periodic reassessment, and adjustment of management targets as new hydrological, ecological, and socioeconomic information becomes available.

2.4. Integrated Assessment-to-Management Framework

Based on the water-balance assessment and sectoral water-use diagnosis, this study adopts a four-stage assessment-to-management framework for the Cherchen River Basin. The first stage, resource diagnosis, quantifies surface-water availability, groundwater resources, sectoral water consumption, and the overall degree of water-resource utilization. The second stage, pressure identification, distinguishes major climatic and anthropogenic pressures, including seasonal cryospheric runoff variability, agricultural water demand, groundwater dependence, conveyance and irrigation inefficiencies, and downstream ecological stress. The third stage, management prioritization, links each diagnosed pressure to corresponding management options: agricultural efficiency improvement for excessive irrigation demand; groundwater abstraction control and salinity monitoring for aquifer stress; evaluation of storage and conveyance infrastructure for seasonal supply–demand mismatch; and ecological-flow management for downstream ecosystems. The fourth stage, adaptive implementation, incorporates stakeholder responsibilities, monitoring indicators,

and periodic reassessment so that management measures can be adjusted in response to hydrological variability, climate change, socioeconomic development, and observed ecological responses. The structure and iterative logic of the proposed assessment-to-management framework, including the links among resource diagnosis, pressure identification, management prioritization, stakeholder implementation, and adaptive reassessment, are illustrated in Figure 2.

Table 2. Principal variables, parameters, assumptions, and data sources used in the groundwater-resource assessment.

Variable/ Parameter	Symbol	Adopted Value/Criterion	Unit	Role in Assessment	Source/ Assumption	Main Uncertainty
Groundwater evaluation area	—	45,504	km^2	Spatial domain of groundwater assessment	Groundwater-resource evaluation	Domain-definition uncertainty
Mountainous area	—	25,494.6	km^2	Groundwater evaluation subdivision	Regional survey	Spatial aggregation
Plain area	—	13,456.7	km^2	Area used in precipitation-recharge assessment	Regional survey	Spatial heterogeneity
Lower Sanwei River area	—	6552.7	km^2	Downstream groundwater evaluation zone	Regional survey	Boundary definition
Assessed aquifer depth	—	≤200	m	Defines shallow Quaternary pore-aquifer system	Groundwater survey	Vertical heterogeneity
Groundwater salinity criterion	—	≤2	$g\ L^{-1}$	Criterion for exploitable groundwater	Resource-evaluation criterion	Water-quality threshold
Mean annual precipitation	P	0.0257	$m\ yr^{-1}$	Precipitation-recharge calculation	Climatic observations	Temporal variability
Storm-flood catchment area	F	431.11	km^2	Used in $Q_{flood} = F \times A$	Catchment delineation	Runoff-depth uncertainty
Hydraulic conductivity	K	21.89	$m\ d^{-1}$	Lateral groundwater flow	Field tests/regional report	Strong spatial heterogeneity
Specific yield	μ/Sy	0.25	dimensionless	Groundwater-storage calculation	Field tests/regional report	Lithological variability
Transmissivity	T	930.89	$m^2\ d^{-1}$	Groundwater-flow calculation	Field tests/regional report	Aquifer heterogeneity
River infiltration coefficient	αr	0.30	dimensionless	River seepage recharge	Regional report	Spatial and seasonal variation
Canal infiltration coefficient	αc	0.15	dimensionless	Canal leakage recharge	Regional report	Canal condition
Irrigation infiltration coefficient	αi	0.20	dimensionless	Irrigation return recharge	Regional report	Irrigation method and soil variability
Groundwater storage change	$\mu F\Delta h/\Delta t$	Assumed ≈ 0 in equilibrium zones	$m^3\ yr^{-1}$	Balance closure	Quasi-steady-state assumption	May be invalid where water levels are changing

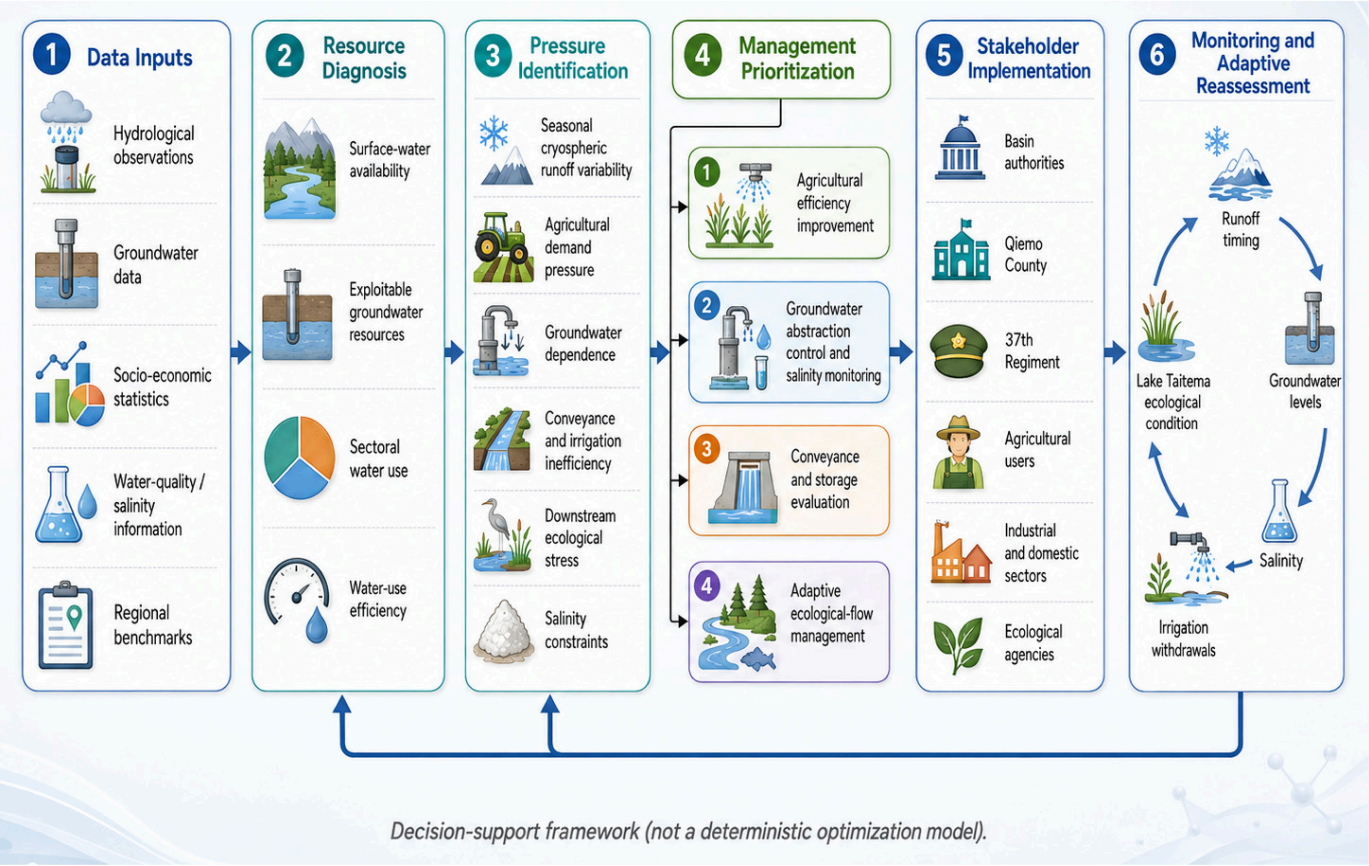

Figure 2. Integrated assessment-to-management framework for the Cherchen River Basin.

The principal stakeholders represented within this framework are basin-level water-management authorities, the Qiemo County and the 37th Regiment as distinct administrative water-use units, agricultural users, industrial and domestic water-supply sectors, and agencies responsible for desert-control and downstream ecological functions. The framework is therefore intended primarily as a decision-support structure for basin and local water managers rather than as a deterministic optimization model. Its application consists of diagnosing the dominant source of water stress, selecting the corresponding management intervention, monitoring its hydrological and socioeconomic consequences, and revising allocation rules when observed conditions depart from management targets.

3. Results

3.1. Water Supply Structure in the Cherchen River Basin

In 2020, the total water supply in the Cherchen River Basin reached 471.85 million m^3, comprising surface water (77.3%), groundwater (22.6%), and a minor contribution from other sources (0.1%). Socioeconomic activities accounted for 93.4% of total water use (440.67 million m^3), while the remaining 6.6% (31.18 million m^3) supported ecological functions, notably windbreak and sand fixation efforts by the Hedong Desert Control Station.

Water consumption in the socioeconomic sectors was heavily dominated by agriculture, which consumed 426.58 million m^3, accounting for 96.8% of total socioeconomic water use. The remaining water consumption was distributed across industrial (0.8%), domestic (0.7%), livestock (0.6%), and fisheries (1.2%) sectors. Agricultural water use was particularly high in the Qiemo County and the 37th Regiment, both of which exhibited irrigation intensities significantly above regional averages (Table 3).

Table 3. Water supply by administrative unit and water source in the Cherchen River Basin in 2020.

Administrative/ Water-Use Unit	Surface Water (million m^3)	Groundwater (million m^3)	Other Sources (million m^3)	Total (million m^3)	Surface Water (%)	Groundwater (%)	Other (%)
Qiemo County—socioeconomic uses	348.55	63.94	—	412.49	84.5	15.5	—
Hedong Desert Control Station—ecological use	—	30.63	0.55	31.18	—	98.2	1.8
Qiemo County subtotal	348.55	94.57	0.55	443.67	78.6	21.3	0.1
37th Regiment—socioeconomic uses	16.06	12.12	—	28.18	57.0	43.0	—
Total socioeconomic uses	364.61	76.06	—	440.67	82.7	17.3	—
CRB total	364.61	106.69	0.55	471.85	77.3	22.6	0.1

Note: "—" indicates no separately reported water supply from that source. Socioeconomic uses include agriculture, industry, domestic use, livestock, and fisheries. Ecological use refers primarily to windbreak and sand-fixation activities at the Hedong Desert Control Station. Percentages may not sum exactly to 100 because of rounding.

To avoid double counting, socioeconomic water-use categories were treated as mutually exclusive. Agricultural water use refers to irrigation water supplied to cropland and forestry, whereas direct water consumption for animal husbandry is reported separately under the livestock category. Fisheries' water use is likewise reported independently. Industrial water use represents freshwater intake excluding internal recycling within enterprises, while domestic water use comprises urban and rural residential and public water uses. Conveyance losses are incorporated within the corresponding gross withdrawal estimates and are not treated as an additional water-use sector.

According to statistics, the total current water usage in the Cherchen River Basin is 471.85 million m^3, of which 440.67 million m^3 is allocated to socioeconomic activities, and 31.18 million m^3 is used for windbreak and sand fixation at the Hedong Desert Control Station. Among socioeconomic water uses, agricultural irrigation accounts for 426.58 million m^3, representing 96.8% of total water use; industrial water use is 3.35 million m^3, or 0.8%; domestic water use totals 2.90 million m^3, contributing 0.7%; livestock water use is 2.48 million m^3, or 0.6%; and fisheries' water use amounts to 5.36 million m^3, making up 1.2%.

Details of socioeconomic water usage in the Cherchen River Basin, categorized by sector and administrative division, are provided in Table 4.

Table 4. The annual socioeconomic water consumption in the Cherchen River Basin.

Administrative Unit	Agriculture	Industry	Domestic	Livestock	Fisheries	Total
Qiemo County	398.99 (96.7%)	3.00 (0.7%)	2.75 (0.7%)	2.39 (0.6%)	5.36 (1.3%)	412.49
37th Regiment	27.59 (97.9%)	0.35 (1.2%)	0.15 (0.5%)	0.09 (0.3%)	—	28.18
CRB total	426.58 (96.8%)	3.35 (0.8%)	2.90 (0.7%)	2.48 (0.6%)	5.36 (1.2%)	440.67

Note: Water-use categories are mutually exclusive. Agricultural water use refers to irrigation supplied to cropland and forestry; direct animal-husbandry water consumption is reported separately under livestock. Fisheries', industrial, and domestic uses are also treated as independent categories. Conveyance losses are included within the corresponding gross withdrawals and are not treated as a separate water-use sector.

3.2. Water-Use Efficiency Assessment

3.2.1. Domestic Water Use

Domestic water consumption totaled 2.90 million m^3, of which 1.48 million m^3 was attributed to urban areas and 1.42 million m^3 to rural settlements. The basin has a population of approximately 62,500 (26,500 urban and 36,000 rural). Urban per capita water consumption was 167 L/person·day, below the Xinjiang average (193 L/person·day), while rural usage (102 L/person·day) closely matched the regional mean (100 L/person·day).

3.2.2. Industrial and Economic Efficiency

In 2020, the basin's GDP was 3.48 billion yuan, with an industrial added value of 251 million yuan. The total socioeconomic water use per 10,000 yuan of GDP was 1266 m^3, significantly higher than the Xinjiang average (450 m^3/10,000 yuan). Industrial water consumption per 10,000 yuan of added value was 133 m^3, which is approximately four times the provincial average (34 m^3/10,000 yuan), indicating low economic water-use efficiency.

3.2.3. Agricultural Water-Use Efficiency

Agricultural irrigation covered 647,200 mu (≈43,147 hectares) and used 426.58 million m^3 of water, equating to 659 m^3/mu. This rate exceeds both the Xinjiang-wide benchmark (558 m^3/mu) and the southern Xinjiang benchmark (616 m^3/mu), indicating comparatively high irrigation demand relative to these regional reference levels. The high-efficiency water-saving irrigation area totaled 266,000 mu, representing a coverage rate of 41.1%, below the Xinjiang-wide reference level of 59.3% (Table 5).

Table 5. Water-use efficiency indicators and regional benchmarks for the Cherchen River Basin in 2020.

Indicator	Unit	Qiemo County	37th Regiment	CRB	Regional Benchmark	Interpretation
Urban domestic water use	L person^{-1} d^{-1}	167	165	167	193 (Xinjiang)	Below regional mean
Rural domestic water use	L person^{-1} d^{-1}	102	102	102	100 (Xinjiang)	Similar to regional mean
Socioeconomic water use per GDP	m^3 per 10^4 yuan GDP	1241	1825	1266	450 (Xinjiang)	High water intensity
Industrial water use per industrial added value	m^3 per 10^4 yuan	133	140	133	34 (Xinjiang)	Low industrial water productivity
Agricultural irrigation application	m^3 mu^{-1}	660	640	659	616 (southern Xinjiang); 558 (Xinjiang)	Higher than regional benchmarks
High-efficiency irrigation coverage	% of irrigated area	—	—	41.1	59.3 (Xinjiang)	Below regional benchmark

Note: 1 mu = 666.7 m^2 = 0.0667 ha. Regional benchmark values are used for diagnostic comparison and should not be interpreted as mandatory management thresholds.

The Xinjiang and southern Xinjiang values are used here as regional management benchmarks rather than as hydrologically equivalent reference basins. The comparison is considered useful because the CRB is administratively located within Xinjiang and its irrigation systems operate within the same regional agricultural and water-management policy context. The southern Xinjiang benchmark provides a geographically closer reference with broadly comparable arid climatic and irrigation conditions, whereas the Xinjiang-wide benchmark provides a broader policy-level reference. Nevertheless, Xinjiang contains substantial climatic, hydrological, crop, and irrigation-system heterogeneity, and therefore

these benchmarks should not be interpreted as directly transferable estimates of technically achievable efficiency in the CRB. They are used only to identify the magnitude of potential improvement and to construct transparent demand-reduction scenarios.

3.3. Water-Resource Development and Utilization Levels

3.3.1. Surface Water Utilization

The total estimated surface-water availability in the CRB was 958.2 million m^3. With an actual extraction volume of 364.61 million m^3, the surface water development rate was 38%, representing moderate utilization. However, upstream areas exhibited underutilization due to limited infrastructure, while downstream zones experienced seasonal overextraction during peak agricultural periods.

3.3.2. Groundwater Utilization

Groundwater abstraction reached 106.69 million m^3 in 2020, equivalent to approximately 72% of the estimated exploitable groundwater resource of 148.2 million m^3. This high exploitation ratio indicates strong dependence on groundwater and leaves a relatively limited operational buffer for dry years or periods of reduced surface-water availability. The pressure is particularly important in the lower Sanwei River segment, where groundwater salinity exceeds 2 g L^{-1}. Because the exploitation ratio used here is not equivalent to the Water Exploitation Index Plus (WEI^+), no universal WEI^+ threshold is applied directly to this groundwater-specific indicator. Importantly, this utilization ratio alone does not demonstrate long-term aquifer depletion; establishing groundwater overexploitation would require a consistent temporal record of groundwater levels and storage changes.

3.3.3. Total Water Utilization

Total water supplied in 2020 was 471.85 million m^3 relative to an estimated available water-resource base of 1006.4 million m^3. This corresponds to an annual gross water-resource utilization ratio of approximately 47%. Because sectoral return flows were not explicitly quantified, this ratio is used only as an annual diagnostic indicator of development intensity and should not be interpreted as a formal WEI^+ value or as a universal sustainability threshold.

3.3.4. Temporal Trends in Water Utilization (2006–2020)

Long-term trends indicate:

- An 18% increase in surface water use, largely driven by the expansion of irrigated cropland from 512,000 mu in 2006 to 647,200 mu in 2020;
- A 62% surge in groundwater extraction, primarily due to reduced surface water reliability and limited regulation of groundwater development;
- An increase in overall water-resource utilization from 39% in 2006 to 47% in 2020, signaling a progressive intensification of water stress in the basin.

3.4. Key Drivers of Water Stress and Inefficiencies

3.4.1. Climatic and Hydrological Factors

- The basin is subject to extreme aridity, with an annual precipitation of only 25.7 mm and evaporation of 1526.2 mm.

3.4.2. Anthropogenic Factors

- Agricultural dominance, inefficient irrigation techniques (e.g., flood irrigation), and outdated infrastructure contribute to excessive water use;
- Weak enforcement of water extraction quotas and limited investment in modern irrigation technologies hinder sustainable water management;

- Industrial sectors demonstrate low water productivity, while domestic systems lack efficiency improvements and infrastructure upgrades.

3.5. Overall Water-Resource Utilization Ratio and Sustainability Implications

The overall water-resource utilization ratio was calculated as the ratio between total water supplied and the estimated available water resources:

$$WRUR = \frac{471.85}{1006.4} \times 100\% \approx 47\%$$

This indicator is used here as a basin-scale measure of the intensity of current water-resource development. It should not be interpreted as a formal WEI$^+$ calculation because return flows and the complete WEI$^+$ renewable-water-resource formulation were not explicitly quantified in the present dataset. The value nevertheless indicates that a substantial proportion of the assessed water-resource base is already committed to existing uses, while groundwater dependence and downstream ecological pressures further reduce management flexibility.

The annual utilization ratio does not capture seasonal water stress. A formal seasonal WEI$^+$ or equivalent scarcity index was not calculated because monthly sectoral abstraction and return-flow data were not consistently available for all water-use categories. Seasonal pressure is therefore interpreted separately from the pronounced intra-annual runoff distribution rather than being inferred from the annual ratio. Future monitoring should prioritize monthly abstraction and return-flow accounting to enable seasonal water-stress assessment.

3.6. Benchmark Scenarios and Policy Options for Adaptive Water Management

In light of these findings, the following strategies are proposed to ensure sustainable water resource management.

The evidence from this study makes it clear that incremental adjustments will not suffice; the Cherchen River Basin requires a systematic and forward-looking package of interventions that address infrastructure deficits, regulatory weaknesses, economic dependencies, and ecological neglect simultaneously.

Demand-side agricultural management should receive first priority because agriculture accounts for the overwhelming majority of socioeconomic water use. Rather than prescribing an unsupported technology-coverage target, the existing regional water-use benchmarks provide a transparent basis for evaluating potential savings. If mean irrigation applications across the existing 647,200 mu of irrigated land were reduced from the current 659 m^3/mu to the southern Xinjiang benchmark of 616 m^3/mu, gross annual irrigation demand would decrease by approximately 27.8 million m^3. Reaching the Xinjiang-wide benchmark of 558 m^3/mu would correspond to a reduction of approximately 65.4 million m^3, equivalent to about 6.5–15.3% of current agricultural water use. The assumptions and resulting reductions in gross agricultural water demand under the two regional benchmark scenarios are summarized in Table 6.

These values should be interpreted as benchmark scenarios rather than direct estimates of savings attributable solely to drip irrigation, because crop structure, conveyance losses, field application efficiency, and return flows were not separately modeled. Expansion of high-efficiency irrigation from the current 41.1% toward or beyond the regional benchmark of 59.3% should therefore be combined with canal rehabilitation, volumetric metering, irrigation scheduling, and monitoring of actual withdrawals.

The high dependence on groundwater also warrants precautionary management. Groundwater abstraction in 2020 represented approximately 72% of the estimated exploitable groundwater resource; this ratio does not by itself establish long-term aquifer

depletion, but it indicates limited flexibility for further expansion of abstraction. Strengthened groundwater-level and salinity monitoring, improved metering of withdrawals, and adaptive abstraction limits linked to observed aquifer responses should therefore be considered as management options, particularly in the lower Sanwei River area where groundwater salinity exceeds 2 g L^{-1}.

Table 6. Benchmark scenarios for reducing agricultural irrigation demand in the Cherchen River Basin.

Scenario	Irrigation Application (m^3 mu^{-1})	Reduction Relative to Current Use (m^3 mu^{-1})	Estimated Annual Agricultural Water Use (million m^3)	Gross Annual Reduction (million m^3)	Reduction from Current Agricultural Use (%)
Current CRB condition	659	—	426.58	—	—
Southern Xinjiang benchmark	616	43	398.75	27.83	6.5
Xinjiang benchmark	558	101	361.21	65.37	15.3

Note: Scenario calculations assume the current irrigated area of 647,200 mu remains unchanged. The estimated reductions represent gross withdrawal benchmarks and should not be interpreted as guaranteed basin-scale water savings. Actual savings depend on crop structure, conveyance efficiency, field application efficiency, irrigation scheduling, return flows, and possible changes in irrigated area.

Economic diversification represents an additional long-term policy option for reducing dependence on irrigation-intensive development. Potential alternatives may include less water-intensive sectors; however, the present study does not quantify their economic feasibility, employment effects, or basin-scale water savings. Economic diversification is therefore identified only as a strategic option requiring dedicated socioeconomic and cost–benefit analysis before implementation.

Ecological water allocation should also be incorporated explicitly into basin management. Because the present study does not derive an environmental-flow requirement from ecological response functions, lake-level targets, or habitat-based analysis, the previously suggested 15% allocation should be interpreted as a planning scenario rather than as a validated ecological threshold. In practice, ecological allocation should be adaptive to annual hydrological conditions, with allocation rules linked to runoff availability and monitored responses of Lake Taitema, riparian ecosystems, groundwater levels, and salinity. A site-specific environmental-flow assessment is therefore required before establishing a legally binding fixed percentage. To distinguish evidence directly derived from the present assessment from its management interpretation, the principal diagnostic findings, associated implications, proposed policy options, and their analytical limitations are synthesized in Table 7.

Table 7. Diagnostic findings, management implications, and corresponding policy options for the Cherchen River Basin.

Diagnostic Evidence	Interpretation	Policy Option	Evidence Status/Limitation
Agriculture accounts for 96.8% of socioeconomic water use	Agricultural demand dominates basin withdrawals	Irrigation efficiency, metering, canal rehabilitation	Benchmark savings quantified
Irrigation application = 659 m^3/mu	Higher than Xinjiang and southern Xinjiang benchmarks	Reduce irrigation application toward regional benchmarks	27.8–65.4 million m^3 gross benchmark reduction
Groundwater abstraction = 106.69 million m^3, 72% of exploitable groundwater resource	High groundwater dependence and limited buffer	Monitoring, metering, adaptive abstraction limits	Does not alone demonstrate long-term depletion

Table 7. *Cont.*

Diagnostic Evidence	Interpretation	Policy Option	Evidence Status/Limitation
Groundwater salinity >2 g L^{-1} in lower Sanwei zone	Water-quality constraint on usable groundwater	Salinity monitoring/protection zones	Site-specific monitoring required
Seasonal concentration of cryospheric runoff	Seasonal supply–demand mismatch	Improve regulation and evaluate storage/conveyance options	Storage effects not simulated
Lake Taitema is downstream ecological receptor	Ecological allocation must be considered	Adaptive environmental-flow management	Ecological-flow requirement not quantitatively derived
High industrial water intensity	Scope for non-agricultural efficiency gains	Industrial efficiency improvement	Economic impacts not modeled
Climate and hydrological uncertainty	Fixed thresholds may not remain appropriate	Monitoring and periodic reassessment	Future climate scenarios not simulated

4. Discussion

The central water-management problem identified in the Cherchen River Basin is not simply limited water availability, but a structural mismatch among the timing, location, and sectoral distribution of water supply and demand. The basin's strong dependence on glaciers and snowmelt is characteristic of cryosphere-dependent inland river systems, in which seasonal meltwater provides an important contribution to downstream water availability [23]. In the CRB, however, cryospheric runoff is concentrated seasonally, whereas agricultural and socioeconomic water demands impose sustained pressure on the system. Spatial and temporal mismatches between water-resource availability and socioeconomic demand have also been identified as an important constraint on sustainable water management in other water-limited regions [24]. Groundwater consequently functions as a buffer against variability in surface-water availability. However, the high proportion of exploitable groundwater already being abstracted indicates that this buffering function cannot be expanded indefinitely without reducing the basin's capacity to absorb future drought and runoff variability. Similar concerns regarding aquifer depletion and groundwater-quality deterioration have been reported in other intensively exploited aquifer systems in China and arid regions [25–27]. Therefore, surface water and groundwater should be managed conjunctively rather than as independent resources. The major interacting hydrological, climatic, agricultural, and groundwater constraints identified in the CRB are summarized in Figure 3.

The results further indicate that agricultural demand management provides the largest immediately identifiable opportunity for reducing water stress. The importance of irrigation modernization does not arise solely from the dominance of agriculture in the water-use structure, but also from the gap between current irrigation applications and regional benchmarks. The predominance of agricultural water consumption and the underutilization of water-saving irrigation technologies observed in the CRB are consistent with broader water–agriculture management challenges reported for arid regions of northwestern China and Central Asia [28,29]. In the present basin, benchmark calculations suggest that reducing mean irrigation application from 659 m^3/mu to 616–558 m^3/mu could lower gross annual agricultural demand by approximately 27.8–65.4 million m^3. These values do not represent guaranteed savings from drip irrigation alone; actual benefits will depend on crop composition, conveyance efficiency, irrigation scheduling, return flows, and possible expansion of the irrigated area. This distinction is important because improvements in field-scale efficiency do not necessarily translate one to one into basin-scale water savings unless total withdrawals are simultaneously controlled. Industrial water productivity should also remain part of the management response because the relatively high water consumption

per unit of industrial added value indicates that water-use efficiency improvements cannot be restricted to the agricultural sector alone [30].

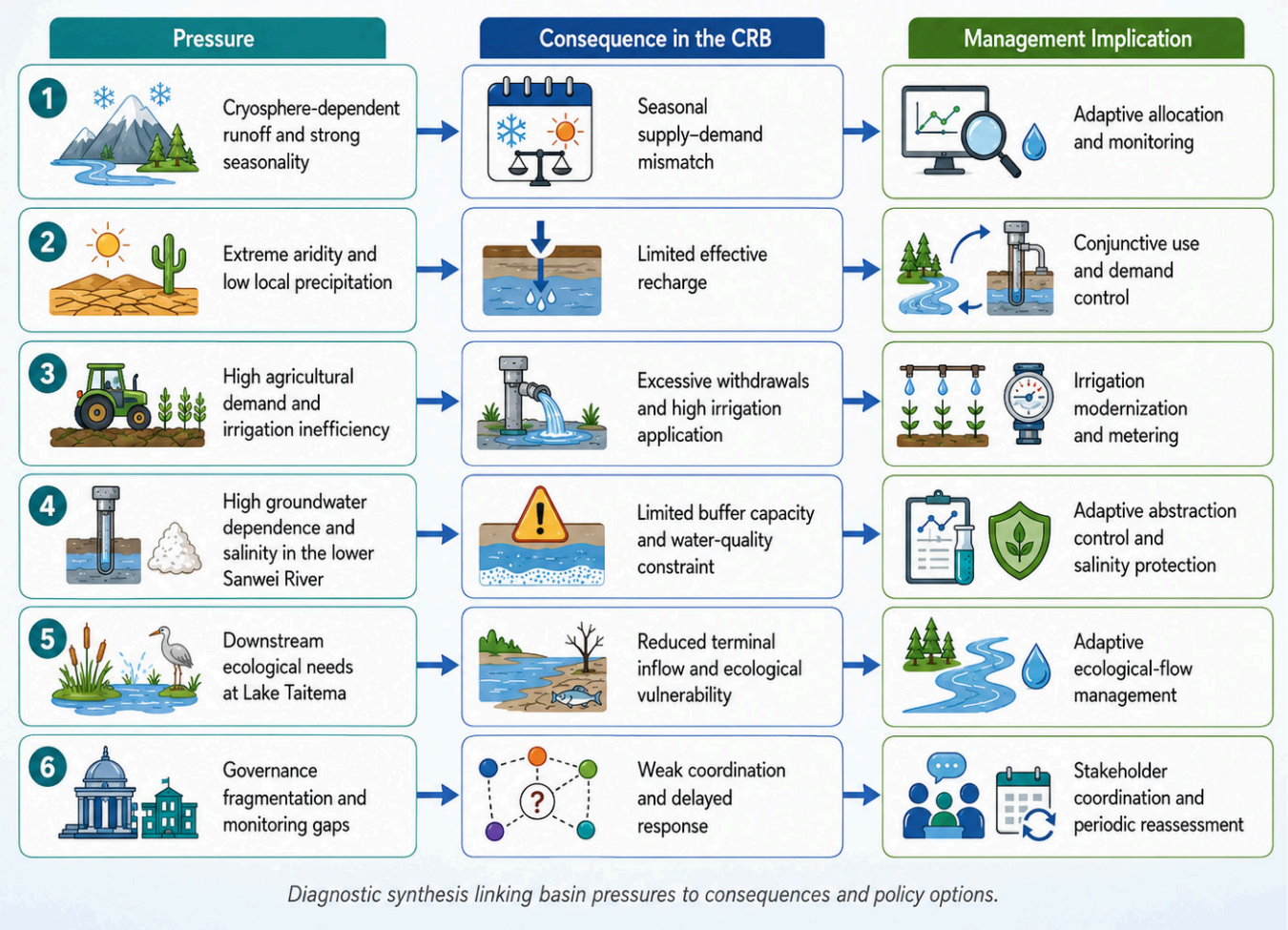

Figure 3. Major constraints on the sustainable use of water resources in the Cherchen River Basin.

A second implication concerns the balance between productive and ecological water uses. Lake Taitema represents a downstream ecological receptor of upstream allocation decisions, and reduced terminal inflow therefore provides an important indication of basin-wide water stress. Comparable degradation of terminal lake and wetland systems elsewhere in arid Central Asia illustrates the sensitivity of downstream ecosystems to changing upstream water availability and landscape conditions [31,32]. Nevertheless, the present analysis does not establish a quantitative ecological-flow requirement for Lake Taitema. A fixed runoff percentage should consequently not be interpreted as a universally valid ecological threshold. A more robust approach would link environmental allocations to hydrological-year type and observed ecological responses, including terminal-lake condition, riparian vegetation, groundwater depth, and salinity. Such an adaptive rule would be particularly important in a cryosphere-dependent basin where future runoff magnitude and seasonality are uncertain.

The intensity of current water-resource development further reduces this management flexibility. Although water exploitation indices such as WEI^{+} provide useful comparative tools for evaluating water stress in highly regulated basins [33], the overall utilization ratio calculated in the present study should not be interpreted as a formal WEI^{+} value because return flows and the complete WEI^{+} water-balance formulation were not explicitly quantified. It is more appropriately interpreted as a diagnostic indicator showing that a

substantial fraction of the assessed water-resource base is already committed to existing uses. When this overall utilization pressure is considered together with intensive groundwater abstraction, downstream ecological requirements, and the dominance of agricultural consumption, the basin has relatively little flexibility to accommodate additional demand without efficiency improvements or reallocation.

Climate change strengthens the need for an adaptive rather than fixed management approach. The present study identifies warming and increasing uncertainty in cryospheric runoff, but it does not explicitly simulate future glacier evolution or climate scenarios. Future runoff changes therefore cannot be quantitatively attributed or projected from the current analysis. The management implications should instead be interpreted in terms of robustness: reducing avoidable irrigation demand, limiting chronic groundwater dependence, improving monitoring, maintaining flexible ecological allocations, and evaluating storage options against changing seasonal runoff are measures that remain relevant under a range of future hydroclimatic conditions. This interpretation is consistent with adaptive water-management approaches that emphasize iterative adjustment of management strategies as environmental conditions and available information change [34,35]. Management thresholds should therefore be periodically reassessed rather than treated as permanent values.

The analysis also highlights that implementation is fundamentally institutional as well as hydrological. Fragmented responsibilities, limited information sharing, and weak coordination can constrain integrated water resource management, as similarly reported in other major Chinese river-basin governance contexts [36,37]. The proposed framework therefore links diagnosis, intervention, responsibility, and monitoring. Basin-level water-management authorities should coordinate overall allocation, groundwater regulation, and monitoring; the Qiemo County and the 37th Regiment should implement administrative extraction and irrigation controls; agricultural, industrial, and domestic users should undertake sector-specific efficiency improvements; and agencies responsible for ecological management should monitor downstream environmental responses. Adaptive and participatory water governance is particularly important where hydrological uncertainty and competing sectoral demands require management decisions to be revised over time [38,39]. Because uncertainty remains in groundwater parameters, spatial heterogeneity, return flows, and future climate forcing, the framework should therefore be used as an iterative decision-support process rather than as a fixed allocation prescription. Its broader transferability lies in this diagnostic-to-adaptive-management structure rather than in transferring individual CRB thresholds directly to other basins.

5. Conclusions

This study addressed three questions concerning the structure, pressures, and management implications of water resources in the Cherchen River Basin. First, the 2020 assessment showed that total water supply was 471.85 million m^3, with surface water providing 77.3% and groundwater 22.6%, while socioeconomic water use was strongly dominated by agriculture (96.8%). Groundwater abstraction reached 106.69 million m^3, equivalent to approximately 72% of the estimated exploitable groundwater resource, indicating substantial groundwater dependence but not, by itself, demonstrating long-term aquifer depletion. These results demonstrate that the basin's current water-use structure combines strong dependence on seasonally variable surface water with substantial reliance on groundwater buffering.

Second, the integrated assessment identified the main pressures as the seasonal concentration of cryosphere-derived runoff, high agricultural water demand, irrigation and conveyance inefficiencies, groundwater dependence, and downstream ecological and water-quality constraints. Agricultural demand represents the largest directly manageable pressure. Benchmark calculations indicate that reducing mean irrigation application from 659 m^3/mu toward the southern Xinjiang and Xinjiang-wide reference levels of 616 and 558 m^3/mu, respectively, could reduce gross agricultural demand by approximately 27.8–65.4 million m^3 yr^{-1}. These values are benchmark scenarios rather than guaranteed basin-scale savings because crop structure, return flows, conveyance efficiency, and total withdrawals were not separately modeled.

Third, these diagnostic findings were translated into an adaptive assessment-to-management framework comprising resource diagnosis, pressure identification, management prioritization, and adaptive implementation. The framework links sector-specific management options with stakeholder responsibilities, monitoring indicators, and periodic reassessment. Agricultural efficiency improvement and conveyance modernization should receive priority, while groundwater abstraction control, salinity monitoring, adaptive ecological-flow allocation, and evaluation of storage options should be considered according to observed hydrological and ecological conditions.

The resulting framework consists of four linked stages: resource diagnosis, pressure identification, management prioritization, and adaptive implementation. Basin water authorities, local administrative units including the Qiemo County and the 37th Regiment, sectoral water users, and ecological-management agencies occupy different implementation roles within these stages. Monitoring and periodic reassessment provide the feedback required to revise allocation decisions as conditions change. Because uncertainties remain in hydrogeological parameters, spatial representation, return flows, and future climate forcing, the proposed framework should be interpreted as a decision-support structure rather than a deterministic management prescription. Its broader relevance to other cryosphere-dependent endorheic basins lies in the integration of water-balance diagnosis with sector-specific interventions, explicit stakeholder responsibilities, and adaptive management under uncertainty.

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References

1. Priyan, K. Issues and challenges of groundwater and surface water management in semi-arid regions. In *Groundwater Resources Development and Planning in the Semi-Arid Region*; Springer: Cham, Switzerland, 2021; pp. 1–17.
2. Li, Z.; Feng, Q.; Wang, Q.J.; Yong, S.; Li, J.; Li, Y.; Wang, Y. Quantitative evaluation on the influence from cryosphere meltwater on runoff in an inland river basin of China. *Glob. Planet. Change* **2016**, *143*, 189–195. [CrossRef]
3. Li, J.; Zhou, Y.; Zhou, J.; Sun, Y.; Zeng, Y.; Ding, Q. Hydrogeochemical evidence for fluoride sources and enrichment in desert groundwater: A case study of Cherchen River Basin, northwestern China. *J. Contam. Hydrol.* **2023**, *259*, 104270. [CrossRef]
4. Zerbe, S. Global land-use development trends: Traditional cultural landscapes under threat. In *Restoration of Multifunctional Cultural Landscapes: Merging Tradition and Innovation for a Sustainable Future*; Springer: Cham, Switzerland, 2022; pp. 129–199.
5. Abbas, M.; Zhao, L.; Wang, Y. Perspective impact on water environment and hydrological regime owing to climate change: A review. *Hydrology* **2022**, *9*, 203. [CrossRef]
6. Pepin, N.; Bradley, R.S.; Diaz, H.F.; Baraer, M.; Caceres, E.B.; Forsythe, N.; Fowler, H.; Greenwood, G.; Hashmi, M.Z.; Liu, X.D.; et al. Elevation-dependent warming in mountain regions of the world. *Nat. Clim. Change* **2015**, *5*, 424–430. [CrossRef]
7. Shao, Z.; Wu, F.; Li, F.; Zhao, Y.; Xu, X. System dynamics model for evaluating socio-economic impacts of different water diversion quantity from transboundary river basins: A case study of Xinjiang. *Int. J. Environ. Res. Public Health* **2020**, *17*, 9091. [CrossRef]
8. El Kenawy, A.M. Hydroclimatic extremes in arid and semi-arid regions: Status, challenges, and future outlook. In *Hydroclimatic Extremes in the Middle East and North Africa*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 1–22.
9. Drenkhan, F.; Buytaert, W.; Mackay, J.D.; Barrand, N.E.; Hannah, D.M.; Huggel, C. Looking beyond glaciers to understand mountain water security. *Nat. Sustain.* **2023**, *6*, 130–138. [CrossRef]
10. Shamsudduha, M.; Panda, D.K. Spatio-temporal changes in terrestrial water storage in the Himalayan river basins and risks to water security in the region: A review. *Int. J. Disaster Risk Reduct.* **2019**, *35*, 101068. [CrossRef]
11. Cao, S.; He, Z.; Wang, S.; Niu, J. Decoupling analysis of water consumption and economic growth in tourism in arid areas: Case of xinjiang, China. *Sustainability* **2023**, *15*, 10379. [CrossRef]
12. Guan, C.; Zhu, X.; Heerink, N.; Ma, X.; Shi, X. Why do farmers stop using collective drip irrigation technology? Evidence from rural Xinjiang, China. *Agric. Water Manag.* **2024**, *302*, 108969. [CrossRef]
13. Liu, B.; Zhang, L.; Wang, W.; Sun, C.; Dong, S.; Wang, Z. Development of a conceptual regional industrial water use efficiency model driven by economic development level. *J. Hydrol. Reg. Stud.* **2024**, *55*, 101926. [CrossRef]
14. Zeitoun, M.; Goulden, M.; Tickner, D. Current and future challenges facing transboundary river basin management. *Wiley Interdiscip. Rev. Clim. Change* **2013**, *4*, 331–349. [CrossRef]
15. Chartres, C.; Noble, A. Sustainable intensification: Overcoming land and water constraints on food production. *Food Secur.* **2015**, *7*, 235. [CrossRef]
16. Khorrami, M.; Malekmohammadi, B. Effects of excessive water extraction on groundwater ecosystem services: Vulnerability assessments using biophysical approaches. *Sci. Total Environ.* **2021**, *799*, 149304. [CrossRef]
17. Granata, F.; Di Nunno, F. Pathways for hydrological resilience: Strategies for adaptation in a changing climate. *Earth Syst. Environ.* **2026**, *10*, 203–231. [CrossRef]
18. Xu, Z.; Wu, B.; Liu, K.; Gao, F.; He, B.; Abdul, W.; Aili, A.; Han, F. Hydrochemical and isotopic signatures revealing surface-groundwater dynamics: An empirical evidence from the Cherchen River Basin. *iScience* **2026**, *29*, 116614. [CrossRef]
19. Mei, J.; Yong, B.; Corzo, G.; Hong, Y.; Sun, R.; Tao, X.; Wang, J.; Duan, Q. Diagnosing cryospheric runoff dynamics: A distributed differentiable hydrological model with global transfer learning. *Water Resour. Res.* **2026**, *62*, E2026WR044148. [CrossRef]
20. Su, F.; Pritchard, H.D.; Yao, T.; Huang, J.; Ou, T.; Meng, F.; Sun, H.; Li, Y.; Xu, B.; Zhu, M.; et al. Contrasting fate of western Third Pole's water resources under 21st century climate change. *Earth's Future* **2022**, *10*, E2022EF002776. [CrossRef]
21. Li, C.; Gao, X.; Liu, Y.; Wang, Y. Impact of anthropogenic activities on the enrichment of fluoride and salinity in groundwater in the Yuncheng Basin constrained by Cl/Br ratio, $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$ and $\delta^{7}Li$ isotopes. *J. Hydrol.* **2019**, *579*, 124211. [CrossRef]
22. Chen, C.; Hu, Z.; Liu, T.; Chen, X.; Kazhigulovich, K.A.; Yimamaidi, D.; Guo, W.; Han, Y. Analyzing the synergistic relationship of FWEE-SDGs in the inland river basins using bi-level fuzzy multi-objective optimization: A case study of the Aral Sea Basin. *Environ. Dev. Sustain.* **2026**, 1–26. [CrossRef]
23. Zhang, F.; Qaiser, F.-U.-R.; Zeng, C.; Pant, R.R.; Wang, G.; Zhang, H.; Chen, D. Meltwater hydrochemistry at four glacial catchments in the headwater of Indus River. *Environ. Sci. Pollut. Res.* **2019**, *26*, 23645–23660. [CrossRef]
24. Song, S.; Fang, L.; Yang, J.; Zhou, R.; Bai, G.; Qiu, Y. The spatial-temporal matching characteristics of water resources and socio-economic development factors: A case study of Guangdong Province. *Water* **2024**, *16*, 362. [CrossRef]
25. Yang, X.; Qin, Q.; Yésou, H.; Ledauphin, T.; Koehl, M.; Grussenmeyer, P.; Zhu, Z. Monthly estimation of the surface water extent in France at a 10-m resolution using Sentinel-2 data. *Remote Sens. Environ.* **2020**, *244*, 111803. [CrossRef]
26. Du, J.; Laghari, Y.; Wei, Y.-C.; Wu, L.; He, A.-L.; Liu, G.-Y.; Yang, H.-H.; Guo, Z.-Y.; Leghari, S.J. Groundwater depletion and degradation in the North China Plain: Challenges and mitigation options. *Water* **2024**, *16*, 354. [CrossRef]

27. Du, H. China's groundwater situation in 2011–2020: Dynamic evolution, Influencing Factors, and sustainable development. *Heliyon* **2024**, *10*, e34097. [CrossRef]
28. Schulz, S.; Re, V.; Kebede, S.; Abdalla, O.; Wang, W.; Simmons, C.; Michelsen, N. Preface: Hydrogeology of arid environments. *Hydrogeol. J.* **2024**, *32*, 1–8. [CrossRef]
29. Tang, X.; Huang, Y.; Pan, X.; Liu, T.; Ling, Y.; Peng, J. Managing the water-agriculture-environment-energy nexus: Trade-offs and synergies in an arid area of Northwest China. *Agric. Water Manag.* **2024**, *295*, 108776. [CrossRef]
30. Chen, X.; Cui, X.; Sun, L.; Yu, Y.; Zhang, H.; Liu, T.; Luo, G.; Hu, Z.; Huang, Y.; Malik, I. Dryland social-ecological systems in Central Asia. In *Dryland Social-Ecological Systems in Changing Environments*; Springer: Singapore, 2024; pp. 203–241.
31. Jain, S.; Srivastava, A.; Khadke, L.; Chatterjee, U.; Elbeltagi, A. Global-scale water security and desertification management amidst climate change. *Environ. Sci. Pollut. Res.* **2024**, *31*, 58720–58744. [CrossRef]
32. Tan, D.; Hu, F.; Thieriot, H.; McGregor, D. *Towards a Water & Energy Secure China*; China Water Risk: Hong Kong, China, 2015.
33. Sondermann, M.N.; de Oliveira, R.P. Using the WEI+ index to evaluate water scarcity at highly regulated river basins with conjunctive uses of surface and groundwater resources. *Sci. Total Environ.* **2022**, *836*, 155754. [CrossRef]
34. Zan, C.; Liu, T.; Huang, Y.; Bao, A.; Yan, Y.; Ling, Y.; Wang, Z.; Duan, Y. Spatial and temporal variation and driving factors of wetland in the Amu Darya River Delta, Central Asia. *Ecol. Indic.* **2022**, *139*, 108898. [CrossRef]
35. Yan, W.; Ma, X.; Liu, Y.; Qian, K.; Yang, X.; Li, J.; Wang, Y. Ecological assessment of terminal lake basins in central Asia under changing landscape patterns. *Remote Sens.* **2022**, *14*, 4842. [CrossRef]
36. Wang, J.; Liu, N. Research on Environmental Legal Challenges in Trans-boundary Water Resource Management of the Yellow River Basin. *J. Soc. Sci. Humanit. Lit.* **2024**, *7*, 76–82. [CrossRef]
37. Chen, Y.; Yan, Y.; Zhu, T. Water market development in the Yellow River Basin: Challenges and opportunities. *Water* **2024**, *16*, 894. [CrossRef]
38. Pahl-Wostl, C. Adaptive and sustainable water management: From improved conceptual foundations to transformative change. In *Global Water Resources*; Routledge: London, UK, 2021; pp. 175–193.
39. Thomas, E.A.; Kathuni, S.; Wilson, D.; Muragijimana, C.; Sharpe, T.; Kaberia, D.; Macharia, D.; Kebede, A.; Birhane, P. The drought resilience impact platform (DRIP): Improving water security through actionable water management insights. *Front. Clim.* **2020**, *2*, 6. [CrossRef]

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