

ADAPTIVE STRATEGIES FOR WATER SCARCITY MANAGEMENT IN GOLESTAN PROVINCE: PATHWAYS TOWARD SUSTAINABLE AGRICULTURAL RESILIENCE UNDER CLIMATE CHANGE

STRATEGIES D'ADAPTATION POUR LA GESTION DE LA PENURIE D'EAU DANS LA PROVINCE DU GOLESTAN : VOIES VERS UNE RESISTANCE AGRICOLE DURABLE FACE AU CHANGEMENT CLIMATIQUE

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ABSTRACT

Golestan Province, positioned strategically along the southern coast of the Caspian Sea, is intrinsically vulnerable to compounding environmental pressures, primarily stemming from climate change-induced hydrological volatility and unsustainable historical water usage patterns. The province's complex geology and topography, coupled with significant agricultural dependence, place immense strain on both surface and, critically, **groundwater resources**. This paper underscores the imperative for implementing a comprehensive, multi-sectoral adaptation strategy, as formalized in the **Operational Plan for Water Scarcity Adaptation in Golestan Province**. The necessity is underscored by observed trends, including erratic river flow regimes and mounting pressure on aquifers supplying major urban centers. The context demands a move beyond reactive measures toward a codified, measurable framework for water security, especially given the high reliance on **groundwater reserves** in cities like Kordkuy and Minudasht, where unsustainable abstraction poses risks to water quality and long-term yield stability. The methodology employed in this operational plan is built upon a rigorous, evidence-based assessment that integrates **completed remedial actions** with **future structural and non-structural development programs**.

Phase I: Remedial Action & Loss Mitigation (Period: 1399-1400): The initial focus was on immediate tactical improvements led by the Rural Water and Wastewater Company. These actions targeted both **Apparent Losses** (e.g., unauthorized connections, inaccurate metering) and **Real Losses** (e.g., leakage from aged infrastructure). Specific interventions included the replacement of faulty domestic meters, installation of smart meters, and significant pipeline rehabilitation efforts. For example, planned savings from these initial loss-reduction strategies in the Behrshahr-Bandargaz zone alone were projected at **1.4 MCM** (Million Cubic Meters). Furthermore, comprehensive management strategies, including the purchase and installation of new low-flow fixtures and pressure-regulating valves, were initiated to control consumption patterns across the provincial network.

Phase II: Proactive Structural & Non-Structural Development (Period: 1399-1405): The long-term strategy centers on quantifiable groundwater conservation through a **Total Proposed Groundwater Saving target of 84.326 MCM**. This target is structurally divided: **51.176 MCM** is expected from structural measures (e.g., physical infrastructure development), while **17.97 MCM** is assigned to non-structural methods, primarily involving the substitution of surface water use where feasible. The distribution of these savings across key hydrological zones (e.g., Gorgan targeted for **48.9 MCM** of savings) demonstrates a localized implementation strategy. A core component of this phase involves strict adherence to **seven key prerequisites**, emphasizing economic scrutiny through **Cost-Benefit Analysis (CBA)**, ensuring all investments yield measurable efficacy. This systematic evaluation ensures that adaptation efforts are not only ecologically necessary but also fiscally sustainable.

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The successful implementation of this structured, dual-phase methodology is anticipated to deliver significant, measurable improvements in Golestan's water security profile by the end of the Seventh Development Plan period (1405/2026). The immediate impact will be the stabilization of vulnerable aquifers through the **71.376 MCM** conservation target, directly mitigating the risks of quality degradation and over-pumping associated with high dependency on underground sources. On the supply side, the integrated urban loss-reduction programs will enhance the efficiency of existing infrastructure, reducing the need for costly emergency supply projects. In conclusion, this operational plan offers a validated, **metric-driven roadmap** that successfully marries immediate utility management reforms with long-term systemic development goals. It stands as a practical case study demonstrating how **Integrated Water Resources Management (IWRM)** principles can be translated into actionable, regionally specific programs to bolster resilience against inevitable future water scarcity scenarios.

Keywords: Water Scarcity Adaptation, Agricultural Resilience, Golestan Province Water Governance, Watershed Management, Urban Water Stress, Network Loss Management, Climate Change.

RESUME

La province du Golestan, située stratégiquement le long de la côte sud de la mer Caspienne, est intrinsèquement vulnérable à des pressions environnementales complexes, découlant principalement de la volatilité hydrologique induite par le changement climatique et des modèles historiques d'utilisation de l'eau non durables. La complexité de la géologie et de la topographie de la province, associées à une dépendance agricole importante, exercent une pression immense sur les ressources en eau de surface et, surtout, sur les **ressources en eaux souterraines**. Ce document souligne l'impératif de la mise en œuvre d'une stratégie d'adaptation globale et multisectorielle, telle que formalisée dans le **Plan opérationnel pour l'adaptation à la pénurie d'eau dans la province du Golestan**. La nécessité est mise en évidence par les tendances observées, y compris les régimes irréguliers de débit d'une rivière et la pression croissante sur les aquifères qui alimentent les grands centres urbains. Le contexte exige de passer des mesures réactives à l'adoption d'un cadre codifié et mesurable pour la sécurité de l'eau, en particulier compte tenu de la forte dépendance de réserves d'eaux souterraines dans des villes telles que Kordkuy et Minudasht, où le prélèvement non durable menacent la qualité de l'eau et la stabilité du rendement à long terme. La méthodologie adoptée dans ce plan opérationnel porte sur une évaluation rigoureuse, fondée sur des données probantes, qui intègre les mesures correctives déjà réalisées aux programmes futurs de développement structurels et non structurels.

Phase I : Mesures correctives et atténuation des pertes (période : 1399-1400) : L'accent a d'abord été mis sur les améliorations tactiques immédiates menées par la Société des eaux et des eaux usées en milieu rural. Ces actions ciblaient à la fois les **pertes apparentes** (par exemple, connexions non autorisées, relevés de compteurs imprécis) et les **pertes réelles** (par exemple, fuites provenant d'infrastructures vieillissantes). Les interventions spécifiques comprenaient le remplacement des compteurs domestiques défectueux, l'installation de compteurs intelligents et d'importants efforts de réhabilitation des pipelines. Par exemple, les économies prévues grâce à ces stratégies initiales de réduction des pertes dans la seule zone Behrshahr-Bandargaz ont été projetées à **1,4 MCM** (millions de mètres cubes). En outre, des stratégies de gestion globales, y compris l'achat et l'installation de nouveaux équipements à faible débit et de vannes de régulation de pression, ont été lancées pour maîtriser les habitudes de consommation dans l'ensemble du réseau provincial.

Phase II : Développement structurel et non structurel proactif (période : 1399-1405) : La stratégie à long terme porte sur la conservation quantifiable des eaux souterraines grâce à un **objectif global proposé d'économie d'eau de l'ordre de 84,326 MCM**. Cet objectif est divisé de manière structurelle : **51,176 MCM** proviendront des mesures structurelles (par exemple, le développement des infrastructures physiques), tandis que **17,97 MCM** seront obtenus grâce à des méthodes non structurelles, impliquant principalement la substitution de l'utilisation des eaux de surface lorsque cela est possible. La répartition de ces économies entre les zones hydrologiques clés (par exemple, Gorgan vise l'économie de l'ordre de **48,9 MCM**) démontre une stratégie de mise en œuvre localisée. Un élément central de cette phase implique le respect strict de **sept conditions essentielles**, mettant l'accent sur l'examen économique par une **analyse coûts-avantages (CBA)**, garantissant que tous les

investissements produisent une efficacité mesurable. Cette évaluation systématique assure que les efforts d'adaptation ne sont pas seulement nécessaires sur le plan écologique, mais reste aussi viable sur le plan financier.

La mise en œuvre réussie de cette méthodologie structurée en double phase devrait permettre d'apporter des améliorations significatives et mesurables au profil de sécurité de l'eau du Golestan d'ici la fin de la période du septième plan de développement (1405/2026). L'impact immédiat sera la stabilisation des aquifères vulnérables grâce à l'objectif de conservation de **71,376 MCM**, atténuant directement les risques de dégradation de la qualité et de surexploitation associés à une forte dépendance de sources souterraines. Du côté de l'offre, les programmes intégrés de réduction des pertes urbaines amélioreront l'efficacité des infrastructures existantes, réduisant ainsi le besoin de projets coûteux d'approvisionnement d'urgence. En conclusion, ce plan opérationnel propose une feuille de route validée, basée sur des indicateurs, qui associe avec succès des réformes immédiates de gestion des services publics à des objectifs de développement systémique à long terme. Il s'agit d'une étude de cas pratique démontrant la manière dont les principes de la **Gestion intégrée des ressources en eau (GIRE)** peuvent être traduits en programmes concrets et spécifiques aux régions afin de renforcer la résistance face à des scénarios futurs inévitables de pénurie d'eau.

Mots-clés : Adaptation à la pénurie d'eau; Résistance agricole; Gouvernance de l'eau dans la province du Golestan; Gestion des bassins versants; Stress hydrique urbain; Gestion des pertes du réseau; Changement climatique.

1. INTRODUCTION

Water scarcity has emerged as one of the most critical environmental and socio-economic challenges in arid and semi-arid regions worldwide, particularly under the accelerating impacts of climate change. (Ward, 2022). Iran is among the countries facing severe water stress due to prolonged droughts, increasing water demand, unsustainable groundwater abstraction, and inefficient water management practices. In recent decades, declining precipitation patterns, rising temperatures, and increasing variability in hydrological regimes have intensified pressure on both surface and groundwater resources across the country (Ciampittiello et al., 2024).

Golestan Province, located in northeastern Iran along the southern coast of the Caspian Sea, represents a highly vulnerable region in terms of water security. Despite its relatively favorable climatic conditions compared to central Iran, the province has experienced increasing water shortages resulting from rapid agricultural expansion, population growth, urbanization, and overexploitation of groundwater aquifers. Agriculture remains the dominant water-consuming sector in the province, placing considerable stress on available water resources and threatening long-term environmental sustainability.

The growing imbalance between water supply and demand has resulted in declining groundwater levels, deterioration of water quality, increased competition among sectors, and heightened vulnerability of rural and urban communities (Rosa, 2022). In response to these challenges, the Government of Iran initiated the National Water Scarcity Adaptation Program to establish coordinated and measurable strategies for sustainable water management at both national and provincial scales.

Within this framework, Golestan Province developed a comprehensive operational adaptation plan aimed at reducing water withdrawals, improving water productivity, enhancing groundwater sustainability, and strengthening resilience against future climate-related risks. The program integrates structural and non-structural measures across agricultural, urban, industrial, and watershed management sectors.

The present study aims to evaluate the adaptation strategies implemented in Golestan Province and to analyze their contribution to regional water resilience and sustainable agricultural development. Particular emphasis is placed on quantifiable water-saving targets, groundwater conservation measures, demand management strategies, and integrated water resources management (IWRM) approaches adopted within the provincial adaptation framework.

2. STUDY AREA AND WATER SCARCITY CHALLENGES

Golestan Province is located in northeastern Iran along the southeastern coastline of the Caspian Sea. The province covers diverse climatic and topographic conditions ranging from humid coastal plains to semi-arid mountainous and steppe regions. Due to this geographical diversity, the province contains complex hydrological systems that include rivers, groundwater aquifers, agricultural plains, and forested watersheds.



Figure 1. Location and major hydrological zones of Golestan Province

Agriculture represents the dominant economic activity in the province and accounts for the largest share of water consumption. Major agricultural products include wheat, rice, cotton, oilseeds, horticultural crops, and livestock-related activities. However, increasing agricultural water demand combined with climate variability has intensified pressure on available water resources.

During recent decades, several critical challenges have emerged in the province, including declining groundwater levels, seasonal water shortages, overexploitation of aquifers, unauthorized groundwater abstraction, deterioration of irrigation efficiency, and increasing urban water demand (Allen *et al.*, 1998). The situation has become particularly severe in groundwater-dependent regions such as Gorgan, Kordkuy, Minudasht, and Maraveh Tappeh.

According to the provincial water scarcity adaptation program, the first phase of adaptation measures aims to achieve a total water-saving target of approximately 141.59 million cubic meters (MCM) by 2026. Of this amount, 122.64 MCM is associated with groundwater conservation, while 18.95 MCM is related to surface water management measures. Additionally, watershed management and aquifer recharge programs are expected to contribute approximately 105.2 MCM in aquifer recovery and recharge effectiveness.

The adaptation framework recognizes that sustainable water management in Golestan cannot rely solely on supply-side infrastructure development. Instead, integrated demand management, agricultural efficiency improvement, groundwater governance, public participation, and watershed rehabilitation are considered essential pillars for long-term resilience.

3. METHODOLOGY

The present study is based on the operational framework of the Water Scarcity Adaptation Program developed for Golestan Province under the national adaptation strategy of Iran. The methodology combines quantitative water-saving targets with sectoral implementation plans and integrated governance mechanisms.

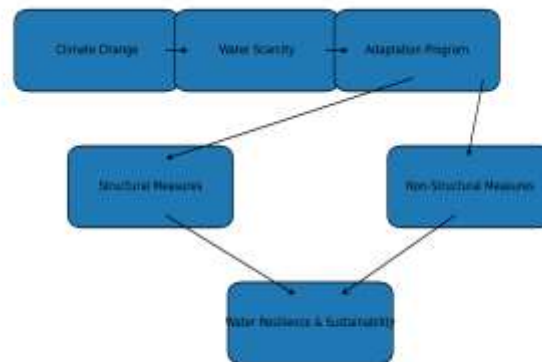


Figure 2. Conceptual framework of the Golestan water scarcity adaptation program

The adaptation framework was developed through extensive inter-agency cooperation involving regional water authorities, agricultural organizations, urban water utilities, environmental agencies, watershed management institutions, and academic experts. More than 2570 person-hours of expert-level interdisciplinary discussions and technical assessments were conducted during the preparation of the program.

The methodological structure of the program consists of two major components:

3.1 Structural Measures

Structural measures focused primarily on physical interventions aimed at reducing water losses and improving water-use efficiency. These measures included:

- modernization of irrigation systems,
- rehabilitation of water distribution networks,
- installation of smart meters,
- replacement of defective water meters,
- groundwater recharge projects,
- construction of wastewater treatment and reuse systems,
- watershed management and flood control projects.

Agricultural structural programs included the development of modern irrigation systems across 20,000 hectares and rehabilitation of irrigation infrastructure in dam command areas.

3.2 Non-Structural Measures

Non-structural measures focused on governance improvement, demand management, institutional coordination, and behavioral adaptation strategies. These included:

- groundwater abstraction control,
- regulation of illegal wells,
- modification of groundwater withdrawal permits,
- establishment of water user associations,
- cropping pattern adjustment,
- reduction of rice cultivation in water-stressed areas,
- public awareness and cultural programs.

One of the major non-structural strategies involved reducing groundwater abstraction through legal and monitoring mechanisms, including the installation of more than 14,000 smart meters on agricultural wells. The overall methodological approach follows Integrated Water Resources Management (IWRM) principles by combining engineering, institutional, environmental, and socio-economic dimensions within a unified adaptation framework (Meran *et al.*, 2020).

4. RESULTS AND DISCUSSION

The implementation of the adaptation program demonstrated significant potential for improving water security and groundwater sustainability in Golestan Province. The total projected groundwater saving within the first implementation phase was estimated at 122.64 MCM, while surface water conservation measures contributed an additional 18.95 MCM. Agricultural measures represented the largest contribution to water conservation, accounting for approximately 117.82 MCM of groundwater savings.

Table 1. Water-saving targets under the Golestan adaptation program (MCM) (MOE, 2019)

Sector	Groundwater Saving	Surface Water Saving	Total
Agriculture	117.82	18.95	136.77
Domestic Water Supply	2.00	-	2.00
Industry	2.82	-	2.82
Total	122.64	18.95	141.59

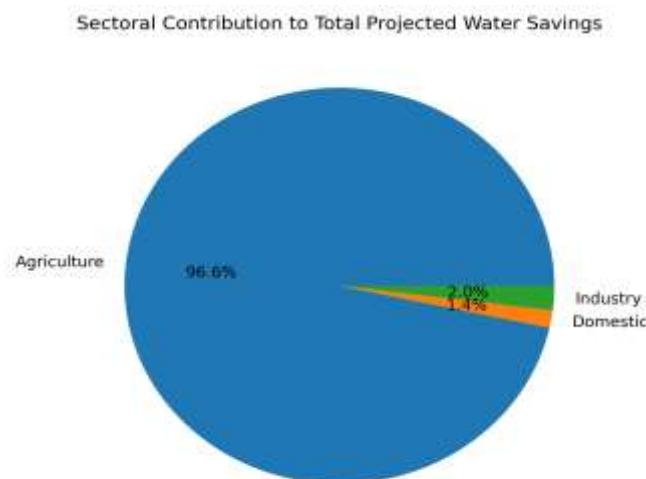


Figure 3. Sectoral contribution to total projected water savings

Among the study areas, Gorgan exhibited the highest groundwater conservation target with approximately 113.3 MCM of projected savings, indicating the strategic importance of this aquifer system for regional water security.

The agricultural sector adaptation measures included modernization of irrigation systems, greenhouse expansion, canal rehabilitation, and reduction of water-intensive rice cultivation (Martinez-Santos *et al.*, 2014). The rice dry-cultivation strategy alone was expected to save approximately 34.6 MCM of groundwater resources.

Urban water management measures also played a significant role in the adaptation strategy (Zhao and Boll, 2022). Leakage reduction, illegal connection control, defective meter replacement, and water distribution rehabilitation collectively improved urban water efficiency. Approximately 2 MCM of groundwater savings were projected through urban and rural water utility programs.

Industrial adaptation measures focused mainly on wastewater treatment and water reuse systems within industrial zones. The reuse strategy was estimated to reduce groundwater abstraction by approximately 2.82 MCM.

Watershed management and aquifer recharge projects constituted another critical component of the adaptation framework (Bouwer, 2002). These measures were projected to generate approximately 105.2 MCM of recharge effectiveness through flood spreading, soil conservation, and watershed rehabilitation programs.

The results demonstrate that successful adaptation to water scarcity requires integrated implementation across multiple sectors rather than isolated engineering interventions. The combination of agricultural efficiency improvement, groundwater governance, urban demand management, and watershed restoration provides a comprehensive pathway toward long-term regional resilience.

5. POLICY IMPLICATIONS

The Golestan adaptation program provides an important practical example of regional-scale climate adaptation planning under water-stressed conditions. The results indicate that sustainable water governance requires coordinated institutional cooperation and measurable implementation targets (Bhave et al., 2014).

One of the major strengths of the program is its integration of engineering, agricultural, environmental, and governance-based approaches within a unified operational framework. The experience of Golestan Province demonstrates that groundwater sustainability cannot be achieved solely through supply augmentation projects; instead, long-term resilience depends heavily on demand management and behavioral adaptation.

Table 2. Groundwater conservation targets across major aquifer zones

Study Area	Groundwater Saving (MCM)	Aquifer Stabilization Year
Behrshahr–Bandargaz	2.70	1401
Gorgan Plain	113.30	1400
Maraveh Tappeh	1.60	1400
Dashli Borun–Incheh	0.20	Illegal abstraction control
Total	117.82	—

The adaptation framework also highlights the importance of localized planning. Different hydrological zones required distinct adaptation measures depending on groundwater dependency, agricultural intensity, and infrastructure conditions (Billib et al., 2009).

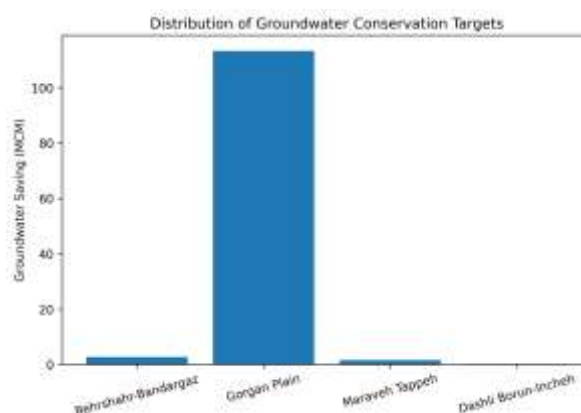


Figure 4. Distribution of groundwater conservation targets among study areas

The lessons learned from Golestan Province may provide a transferable framework for other semi-arid regions facing increasing climate-related water stress.

Table 3. Major agricultural adaptation measures and projected water savings (MOE, 2019)

Adaptation Measure	Operational Scale	Groundwater Saving (MCM)
Modern irrigation systems	20,000 ha	27.05
Reservoir irrigation modernization	3,000 ha	6.00
Greenhouse development	720 ha	4.20
Dry cultivation of rice	4,000 ha	34.60
Total	—	65.85

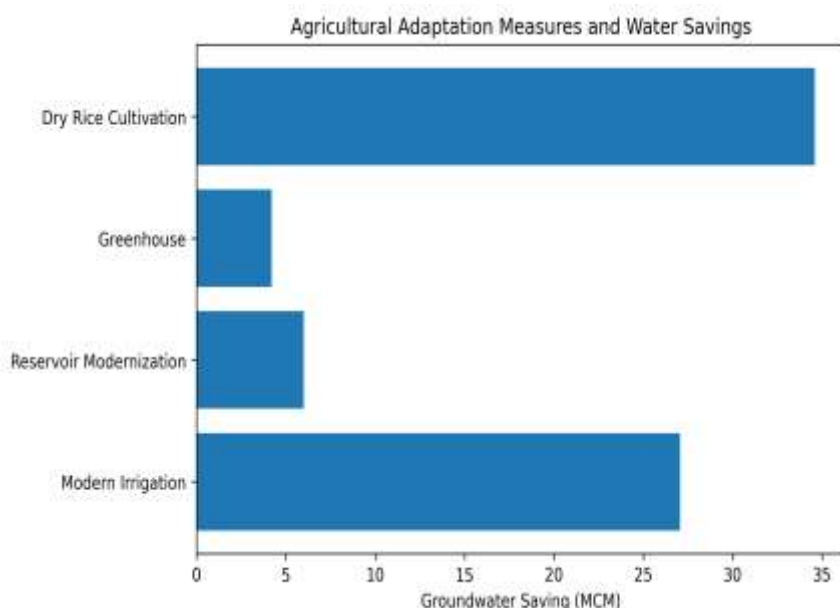


Figure 5. Groundwater savings associated with agricultural adaptation measures

Table 4. Urban and rural water demand management measures (MOE, 2019)

Measure	Operational Scale	Water Saving (MCM)
Replacement of faulty meters	132,000 units	1.25
Distribution network rehabilitation	270 km	0.50
Leakage detection	1,200 km	1.00
Illegal connection control	2,500 cases	0.35
Total	—	2.00

Table 5. Watershed management and aquifer recharge effectiveness (MOE, 2019)

Program	Operational Area (ha)	Recharge Effectiveness (MCM)
Atrak watershed management	9,500	7.90
Soil and watershed conservation	3,500	5.40
Flood control watershed projects	27,700	19.40
Comprehensive watershed program	75,600	45.20
Total	—	105.20

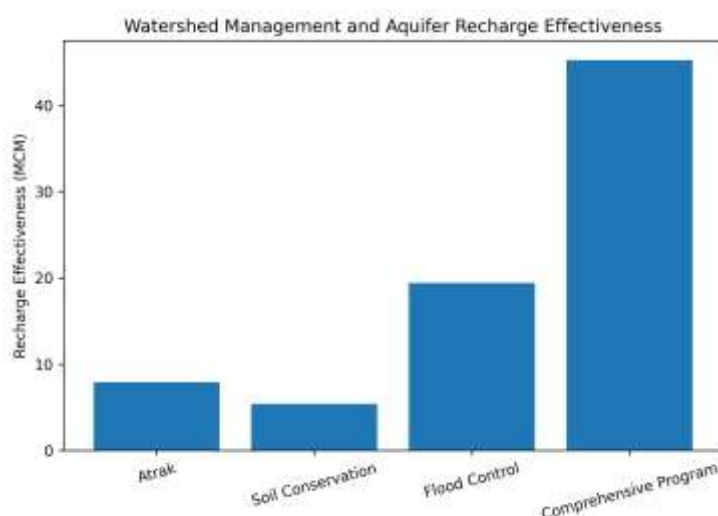


Figure 6. Watershed Management and Aquifer Recharge Effectiveness

6. CONCLUSION

This study evaluated the integrated water scarcity adaptation strategies developed for Golestan Province under the national adaptation framework of Iran. The results demonstrated that the implementation of combined structural and non-structural measures can significantly improve regional water resilience and groundwater sustainability (Fard *et al.*, 2018).

The adaptation program established measurable water-saving targets exceeding 141 MCM while simultaneously strengthening aquifer recharge, irrigation efficiency, urban water management, and institutional coordination mechanisms.

Agricultural water management represented the most influential sector within the adaptation framework, emphasizing the critical role of irrigation modernization, cropping pattern adjustment, and groundwater abstraction control.

Overall, the Golestan experience illustrates that integrated adaptation planning based on IWRM principles can provide an effective pathway toward sustainable water management under increasing climate change pressures.

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