Deliverable Phase 2 – Climate risk assessment

AGROSHIELD

Turkey, Marmara / Marmara Municipalities Union

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Document Information

Deliverable Title	Phase 2 – Climate risk assessment
Brief Description	This report presents the second-phase Climate Risk Assessment (CRA) of the AGROSHIELD project, which deepens the preliminary Phase 1 assessment of agricultural drought risk in four boroughs of the Southern Marmara region of Türkiye — Gönen (Balıkesir), Gemlik and İznik (Bursa), and Karamürsel (Kocaeli) — using local and national datasets, high-resolution spatial analysis, and socio-economic impact assessment. Applying the CLIMAAX CRA framework (Hazard × Exposure × Vulnerability), the report produces borough-level drought hazard characterisations from MGM station records, crop-specific yield loss projections under RCP 4.5 and RCP 8.5 across three future time horizons (2021–2049, 2050–2074, 2075–2100), and an integrated composite agricultural drought risk layer at ~1 km resolution.
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Table of contents

List of figures

List of tables

Abbreviations and acronyms

Abbreviation / acronym	Description
CAAP	Community Adaptation Action Plan
CAAPs	Community Adaptation Action Plans (plural)
CDI	Combined Drought Indicator (Copernicus EDO)
CHELSA	Climatologies at High Resolution for the Earth's Land Surface Areas
CINEA	European Climate, Infrastructure and Environment Executive Agency
CLIMAAX	CLIMate risk Assessment and Xchange (EU Horizon Europe project)
CLC	CORINE Land Cover
CNRM-CM5.1	Centre National de Recherches Météorologiques Coupled Model 5.1
CORINE	Coordination of Information on the Environment (land cover dataset)
CRA	Climate Risk Assessment
DJF	December–January–February (meteorological winter)
DMP	Drought Management Plan
DSİ	Devlet Su İşleri (Turkish State Hydraulic Works)
ECMWF	European Centre for Medium-Range Weather Forecasts
EDO	European Drought Observatory (Copernicus)
EEA	European Environment Agency
EPSG	European Petroleum Survey Group (coordinate reference system registry)
ERA5	Fifth generation ECMWF reanalysis dataset
ET_0	Reference evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAO-33	FAO Irrigation and Drainage Paper No. 33 (Doorenbos & Kassam, 1979)
FAO-56	FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998)
GCM	General Circulation Model

GDP	Gross Domestic Product
GIS	Geographic Information System
GeoTIFF	Georeferenced Tagged Image File Format
HadGEM2-ES	Hadley Centre Global Environment Model version 2 – Earth System
IBBS	İstatistiki Bölge Birimleri Sınıflaması (NUTS equivalent for Türkiye)
IDEMA	IDEMA Consultancy
IPCC	Intergovernmental Panel on Climate Change
JJA	June–July–August (meteorological summer)
KPI	Key Performance Indicator
MAM	March–April–May (meteorological spring)
MGM	Meteoroloji Genel Müdürlüğü (Turkish State Meteorological Service)
MMU	Marmara Municipalities Union
MPI-ESM-MR	Max Planck Institute Earth System Model – Medium Resolution
NDVI	Normalised Difference Vegetation Index
OLS	Ordinary Least Squares (regression)
PDSI	Palmer Drought Severity Index
PNG	Portable Network Graphics (image format)
PU	Public (dissemination level)
RCP	Representative Concentration Pathway
RCP 4.5	Representative Concentration Pathway 4.5 (moderate emissions scenario)
RCP 8.5	Representative Concentration Pathway 8.5 (high-emissions scenario)
RMSE	Root Mean Square Error
RTMAF-GDWM	Republic of Türkiye Ministry of Agriculture and Forestry – General Directorate of Water Management
scPDSI	Self-Calibrating Palmer Drought Severity Index
SEGE	Sosyo-Ekonomik Gelişmişlik Endeksi (Socio-Economic Development Index)
SON	September–October–November (meteorological autumn)
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation-Evapotranspiration Index
SSP	Shared Socioeconomic Pathway
TAGEM	Tarımsal Araştırmalar ve Politikalar Genel Müdürlüğü (General Directorate of Agricultural Research and Policies)
TAMP	Türkiye Afet Müdahale Planı (Türkiye Disaster Response Plan)
TARSİM	Tarım Sigortaları Havuzu (Turkish Agricultural Insurance Pool)
TÜİK	Türkiye İstatistik Kurumu (Turkish Statistical Institute)
UNDP	United Nations Development Programme
WEI	Water Exploitation Index
WMO	World Meteorological Organization

Executive Summary

This deliverable presents the second-phase Climate Risk Assessment (CRA) of the AGROSHIELD project, addressing agricultural drought risk in four boroughs of the Southern Marmara region of Türkiye — Gönen (Balıkesir), Gemlik and İznik (Bursa) and Karamürsel (Kocaeli). Agriculture is central to these boroughs' economies and to national food supply, yet the region faces a drying climate. The assessment was developed to move beyond the preliminary, EU-data-based picture of Deliverable 1 and to give local decision-makers a spatially explicit, locally grounded understanding of where agricultural drought risk is concentrated, how it will evolve, and where adaptation should be prioritised.

Following the CLIMAAX CRA framework, the assessment deepened all four risk determinants — hazard, exposure, vulnerability and risk — using local and national data (the Turkish State Meteorological Service, ERA5 reanalysis, CORINE land cover, the Marmara Basin Drought Management Plan and TÜİK statistics) and resolving the analysis from the city scale to a ~1 km grid. Future conditions were projected with the HadGEM2-ES model under RCP 4.5 and RCP 8.5 for three horizons (near-term 2021–2049, mid-century 2050–2074 and long-term 2075–2100). Per-crop yield loss was quantified with the FAO-33 method using locally calibrated coefficients for nine crops, and the three layers were integrated into a composite agricultural drought risk.

The hazard is projected to intensify markedly: agricultural drought frequency rises from 16–18% today to 41–54% by the late century under RCP 8.5, with the growing-season water deficit deepening from episodic to near-permanent. The principal finding emerges from the integration of vulnerability: risk is governed as much by the sector's capacity to cope as by the severity of the hazard. İznik carries the most severe hazard yet the lowest integrated risk, because its sector is currently the least vulnerable, whereas the Gulf boroughs (Gemlik, Karamürsel) — with a milder hazard but very high vulnerability from inter-sectoral water competition — carry the highest risk. The upper-bound agricultural revenue at risk approaches 1.57 billion TL, about 13% of the four-borough agricultural economy, by the late century under RCP 8.5, with olive the single largest exposure. The risk is assessed as moderate today and substantial by the late century, requiring more adaptation action than is currently in place; the highest priority falls on the Gulf boroughs, with Gönen strategically important as a national rice basin and İznik a preventive priority.

The assessment delivers a borough-resolved evidence base — sixty georeferenced risk layers and a full CRA report — that converts a recognised but diffuse concern into a targeted, prioritised picture of agricultural drought risk. Its findings now pass to Phase 3, where they will be validated with farmers, producers, cooperatives and government departments and translated into Community Adaptation Action Plans. The key message for decision-makers is that managing agricultural drought in Southern Marmara will depend not only on the climate hazard but on strengthening the coping capacity of the most vulnerable farming systems, above all in the water-stressed Gulf sub-basin.

1 Introduction

1.1 Background

The Southern Marmara Basin occupies a transitional zone between the temperate climate of northwestern Türkiye and the increasingly arid conditions characteristic of the Mediterranean Basin. The basin encompasses some of the country's most productive agricultural landscapes, including the provinces of Bursa and Balıkesir, which together host three of the four target boroughs of the AGROSHIELD project: İznik, Gemlik, and Gönen. The fourth, Karamürsel, is located in Kocaeli province on the southeastern shore of the Marmara Sea. Each borough has a distinct agricultural identity shaped by its sub-basin location, soil characteristics, and water availability.

İznik is situated within the İznik Lake sub-basin and is known for its production of high-value perennial crops, particularly olives and fruit trees including cherries. The borough's agricultural economy depends significantly on Lake İznik as a water source and on the fertile soils of the surrounding plain. Despite a currently low drought vulnerability index, recent projections indicate the sub-basin faces a sharply rising risk in the near term (2021–2049), with the agricultural drought vulnerability rating escalating from Low to High before moderating somewhat toward the end of the century (RTMAF-GDWM, 2023 - Republic of Türkiye Ministry of Agriculture and Forestry, General Directorate of Water Management — Marmara Basin Drought Management Plan, 2023). This trajectory makes İznik a priority for early adaptation planning, as the perennial crops underpinning its agricultural economy require multi-year investment and cannot be rapidly adjusted in response to deteriorating conditions.

Gemlik straddles both the İznik Lake and Körfez (Gulf) sub-basins and is nationally recognized as a centre of olive production. Gemlik-type olives are among Türkiye's most commercially significant olive varieties, and the borough's identity is closely tied to this perennial crop. The Körfez sub-basin, which also encompasses Karamürsel, is characterized by extreme competition for water between agriculture, industrial users, and a large and growing urban population — conditions that have already driven the sub-basin's agricultural drought vulnerability to a Very High rating under current conditions (RTMAF-GDWM, 2023).

Karamürsel is an agricultural and horticultural borough embedded within the heavily industrialized Gulf of İzmit corridor. Farming here operates under persistent structural pressure from competing water users, with the Water Use Index (WEI) for the Körfez sub-basin among the highest in the entire Marmara Basin and projected to exceed critical stress thresholds by the end of the century (RTMAF-GDWM, 2023). The agricultural sector relies almost entirely on open canal irrigation systems, which significantly reduces adaptive flexibility in the face of water scarcity and limits the sector's ability to respond to increasingly variable precipitation.

Gönen is located in the Gönen Çayı (Gönen Stream) sub-basin in Balıkesir province and is one of Türkiye's most important rice-producing areas. In addition to paddy rice, the borough produces maize, sunflower, and wheat, as well as tomatoes and watermelon. Gönen's agricultural system is highly water-intensive and structurally exposed to drought. Over the 1980–2021 reference period, the Gönen Çayı sub-basin recorded the highest number of drought months of the three focal sub-basins across multiple drought indices — including 74 months under SPI-3, 93 months under SPEI-9, and 101 months under scPDSI — underscoring the chronic and multi-dimensional nature of the drought hazard in this area (RTMAF-GDWM, 2023).

The broader Marmara Basin is under intensifying climate pressure. According to the regional climate projections underpinning the Marmara Basin Drought Management Plan (RTMAF-GDWM, 2023), the basin is transitioning toward hotter and drier conditions, with average temperatures rising and total precipitation declining in a pattern consistent with the wider Mediterranean climate shift. Temperature trend analyses for MGM stations across the basin confirm statistically significant warming trends at 95% confidence at 11 of 15 stations, including Station 17674 at Gönen (Mann-Kendall $z = 3.24$, $p = 0.00$, 1967–2020) (RTMAF-GDWM, 2023). The basin's total usable water potential currently stands at approximately 4,893.74 hm^3, a figure already under stress from growing urban, industrial, and agricultural demand. Climate projections under the MPI RCP 8.5 scenario indicate significant declines in both surface water potential and groundwater recharge by the end of the 21st century. National-scale drought projections independently corroborate this trajectory, indicating that drought intensity across the Marmara region will increase progressively over the medium and long term, with the rate of increase accelerating under high-emission conditions (UNDP, 2023).

Within this regional context, the four target boroughs represent a cross-section of agricultural drought exposure that is both representative and strategically important. Gönen and Karamürsel anchor the high-risk end of the vulnerability spectrum due to their water-intensive crop systems, inadequate irrigation infrastructure, and limited socio-economic adaptive capacity. İznik and Gemlik, while currently at lower risk levels, face emerging hazards that threaten the long-term viability of their perennial economies. Across all four boroughs, the gap between the scale of existing regional assessments and the resolution needed for effective local adaptation planning remains significant — a gap the AGROSHIELD project is specifically designed to close.

1.2 Main objectives of the project

The AGROSHIELD project — Agricultural Risk Assessment and Resilience Strategies against Drought in the Southern Marmara Basin — is a climate risk assessment initiative funded under the EU Horizon Europe programme through the CLIMAAX project. Its overarching goal is to strengthen the agricultural resilience of the Southern Marmara Basin by producing a high-resolution, borough-level climate risk assessment for agricultural drought and translating that evidence into policy-ready adaptation tools.

The project is structured across three progressive phases. Phase 1 established a standardized baseline assessment using the CLIMAAX Agricultural Drought Workflow and EU-level datasets, producing drought hazard characterizations and crop-specific yield loss and revenue loss projections for the four target boroughs under medium (RCP 4.5) and pessimistic (RCP 8.5) climate scenarios to the period 2056–2060. This second phase — the subject of the present deliverable — advances that foundation in four substantive ways: it grounds the hazard analysis in locally-observed station data and nationally-authoritative drought indices; it extends and deepens the yield loss analysis to true borough resolution across three future time horizons; it translates projected crop losses into their socio-economic implications for farming communities; and it prepares the evidential and institutional groundwork for the participatory Phase 3. Phase 3 will translate these refined findings into co-produced Community Adaptation Action Plans (CAAPs) developed through participatory workshops with borough-level authorities, farmers, agricultural cooperatives, and other local stakeholders.

The specific objectives of Phase 2 are as follows.

Objective 1 — Regionalize the drought hazard analysis using local and national data. Phase 1 relied on EU-scale climate datasets available through the CLIMAAX toolbox. Phase 2 replaces these with station-level meteorological data from the Turkish State Meteorological Service (MGM) to produce borough-level Standardized Precipitation Index (SPI) and Standardized Precipitation-Evapotranspiration Index (SPEI) time series spanning several decades. These original computations are complemented by scPDSI, hydrological drought indices, irrigation water demand projections, and Water Use Index trajectories drawn from the Marmara Basin Drought Management Plan (Marmara DMP, 2023) — the authoritative national reference for the basin. National-scale drought projections from the UNDP drought vulnerability report (UNDP, 2023) provide an independent corroborating frame at the regional level. Throughout, the scenario framework remains consistent with Phase 1: RCP 4.5 as the moderate emissions pathway and RCP 8.5 as the high-emissions reference.

Objective 2 — Extend and deepen the crop yield loss analysis. Phase 1 produced yield loss and revenue loss projections at city level for a single medium-term time slice (2056–2060). Phase 2 builds directly on those outputs by applying the FAO-33 yield response framework — using the locally-calibrated crop coefficient tables developed in Phase 1 — to produce borough-level yield loss projections across three time horizons: near-term (2021–2049), mid-century (2050–2074), and long-term (2075–2100), under both RCP 4.5 and RCP 8.5. Projections cover the nine locally significant crops — paddy rice, maize, tomato, watermelon, olive, fig, cherry, peach and walnut — each assessed in every borough where it is cultivated according to TÜİK production records, extending the four-crop-per-borough selection of Phase 1. Paddy rice is specific to Gönen; olive and the orchard crops (cherry, peach, fig, walnut) dominate Gemlik, İznik and Karamürsel; and tomato is a major annual crop in Gönen, İznik and Karamürsel. These outputs provide the first borough-resolution, multi-horizon crop impact assessment for the Southern Marmara Basin, directly advancing the evidence base beyond the Phase 1 baseline. Yield loss projections are accompanied by spatial maps and summary tables enabling direct comparison across boroughs, crops, scenarios, and time periods.

Objective 3 — Translate crop losses into socio-economic implications. Physical yield loss figures are necessary but insufficient for policy action. Phase 2 therefore translates the crop impact results into a structured socio-economic assessment covering agricultural revenue at risk per borough, estimated from local production area and price statistics (TÜİK), together with a qualitative characterization of the differential vulnerability of small-scale versus larger farming enterprises, in which smallholders are identified as the most exposed and least able to cope. A fuller quantification of the farming population and agricultural workforce exposed, and a TARSİM-based analysis of agricultural insurance coverage gaps, are identified as priorities for the Phase 3 stakeholder and adaptation stage. This socio-economic layer provides the bridge between physical drought risk and its consequences for rural livelihoods, food security, and community resilience, and directly informs the prioritisation of adaptation measures in Phase 3.

The use of the CLIMAAX Handbook and CRA framework in Phase 2 brings specific benefits beyond methodological consistency. It ensures that locally derived findings are structured in a form comparable with climate risk assessments across European regions, enabling methodological exchange within the CLIMAAX community of practice. It also provides a transparent, replicable framework that borough-level authorities can apply independently in future adaptation planning cycles — building lasting institutional capacity rather than producing a one-time study.

Taken together, the Phase 2 outputs are designed to give the four borough municipalities the empirical foundation they need to move from awareness of drought risk to evidence-based, locally-owned adaptation action — at a resolution that reflects the real differences between their landscapes, economies, and communities.

1.3 Project Team

Prof. Dr. Binnaz Zeynep Zaimoğlu — Team Leader (Çukurova University, Department of Environmental Engineering). Prof. Zaimoğlu holds a Bachelor's, Master's, and Ph.D. in Agricultural Structures and Irrigation from Çukurova University, Faculty of Agriculture. She joined the Faculty of Engineering and Architecture at Çukurova University as Assistant Professor in 2000, was promoted to Associate Professor in 2006, and attained the rank of Full Professor in 2013. Her post-doctoral research, conducted at Cornell University (2006–2007), focused on watershed management, soil contamination, and hydrological modelling. Between 2013 and 2014 she was a visiting researcher at West Virginia University, working on climate change modelling in the College of Natural Sciences. She has led and contributed to numerous EU and United Nations projects at the nexus of climate change and agriculture, and as of 2025 serves as the United Nations Expert on Climate Change and Agricultural Security for Türkiye. She provides scientific oversight and methodological guidance for the AGROSHIELD assessment.

M. Yavuz Sucu, Ph.D. — Lead Expert (Çukurova University). Dr. Sucu is a specialist in agricultural water management and irrigation engineering at Çukurova University. His expertise supports the hydrological and water-balance dimensions of the AGROSHIELD assessment.

Büşra İnce — Institutional Coordinator (Marmara Municipalities Union). Ms. İnce serves as the institutional focal point for AGROSHIELD within the Marmara Municipalities Union (MMU), coordinating communications with the four target borough municipalities, managing deliverable obligations toward the CLIMAAX programme, and ensuring alignment between the technical outputs and the Union's policy and planning priorities.

Çağkan Korur — Reporting Associate Mr. Korur is an international development and sustainability professional with over ten years of experience in climate resilience, programme management, and policy advisory roles within United Nations agencies, bilateral donors, and multilateral development institutions. He holds a Bachelor's degree in Political Science and Public Administration from Bilkent University and has contributed to climate and agriculture programmes in Türkiye and across multiple countries. Relevant to AGROSHIELD, he has managed the SCALA programme at UNDP — a joint UNDP–FAO initiative supporting NDC and NAP translation in agriculture across twelve countries — and serves as Project Manager of the Belmont Forum–funded CLIMB project on climate-induced migration. At IDEMA, he leads a portfolio of EU- and UN-funded public-policy and sustainability initiatives. Within AGROSHIELD, he is responsible for report development, stakeholder coordination, and the translation of technical findings into deliverable outputs.

1.4 Outline of the document's structure

This deliverable is organised in three main parts. Section 1 introduces the project background, objectives, team and the structure of the document. Section 2 contains the Climate Risk Assessment itself: it sets out the scoping of the assessment (2.1), the exploration and screening of risks and the choice of climate scenarios (2.2), and the regionalised risk analysis (2.3), which forms the analytical core — the hazard, exposure, vulnerability and risk layers for agricultural drought, together with their socio-economic implications and the additional local-data analyses. The findings are then evaluated in the Key Risk Assessment (2.4), where severity, urgency, resilience capacity and risk priority are assessed for each borough, before the monitoring-and-evaluation reflections (2.5) and the Phase 3 work plan (2.6). Section 3 presents the conclusions, and the remaining sections cover the progress evaluation (4), the supporting documentation and data (5) and the references (6).

2 Climate Risk Assessment — Phase 2

2.1 Scoping

2.1.1 Objectives

Phase 2 of the AGROSHIELD Climate Risk Assessment builds directly on the baseline established in Phase 1, where the CLIMAAX Agricultural Drought Workflow was applied using EU-scale datasets to produce drought hazard characterizations and crop-specific yield loss and revenue loss projections for the four target boroughs of İznik, Gemlik, Karamürsel, and Gönen. The foundational scoping decisions of Phase 1 — the identification of agricultural drought as the primary hazard, the borough-level geographic focus, and the RCP 4.5 and RCP 8.5 scenario framework — remain valid and are carried forward without modification. What changes in Phase 2 is the depth, resolution, and data foundation of every component of the analysis.

The overarching objective of Phase 2 is to advance the AGROSHIELD CRA from a standardized EU-scale baseline toward a locally grounded, borough-specific assessment that integrates original meteorological analysis, extended crop yield loss projections, and a structured socio-economic impact evaluation. The expected outcome is a coherent set of quantitative indicators, maps, and summary statistics that characterize drought hazard, crop impact, and socio-economic vulnerability at the borough level — outputs that directly inform adaptation planning by the four target municipalities. Phase 2 pursues four specific objectives toward this end.

How Phase 2 outcomes feed into policy and decision-making

The Phase 2 findings are designed to feed into four specific governance contexts. At the borough level, the locally-computed drought indices, borough-resolution yield loss projections, and socio-economic impact estimates will give İznik, Gemlik, Karamürsel, and Gönen municipalities empirical evidence at the resolution needed to integrate agricultural drought risk into local adaptation plans, land-use policies, and water management decisions — a resolution that neither the Marmara DMP nor the Phase 1 assessment provides directly. At the provincial level, the findings reinforce and localize the sub-basin vulnerability classifications of the Marmara DMP, providing Bursa, Kocaeli, and Balıkesir provincial agricultural directorates with borough-scale crop impact detail that the plan's sub-basin framing cannot supply. At the national level, the AGROSHIELD methodology demonstrates a replicable approach for borough-level CRA that other river basins in Türkiye facing similar resolution gaps could adopt. At the European level, the structured outputs — produced within the CLIMAAX framework — contribute to the harmonized evidence base for climate risk assessment across EU and EU-adjacent regions.

Limitations and boundaries — Phase 2

Phase 2 operates within a set of constraints that were partly inherited from Phase 1 and partly specific to this phase. These are acknowledged transparently below, along with the approaches taken to address them.

Challenge	Description	Mitigation approach
Spatial resolution of CLIMAAX toolbox	The CLIMAAX toolbox operates at city level; borough boundaries are smaller than the tool's native resolution. This limitation was identified in Phase 1 and carries forward for the CLIMAAX workflow outputs.	Phase 2 original computations (SPI, SPEI, yield loss) are calculated directly at the MGM station and borough level. Borough boundary shapefiles are used for all map production, restoring spatial specificity for the Phase 2 outputs.
Yield loss modelling constraints	The FAO-33 yield response framework provides a well-established but simplified representation of crop-water relationships. It does not capture heat stress, pest and disease interactions, or farmer adaptive behavior, which may influence real-world yield outcomes.	Results are presented as indicative projections rather than precise forecasts. Uncertainty is communicated explicitly in all yield loss tables. The framework is consistent with Phase 1 methodology, enabling direct comparison.
Atmospheric pressure data gap for Karamürsel	The MGM dataset does not include atmospheric pressure records for Karamürsel station, limiting the completeness of the meteorological characterization for that borough.	Pressure data from the nearest available MGM station is used as a proxy where required. This limitation is flagged in the relevant data tables.
Stakeholder engagement at preparatory stage	Active participatory engagement with farmers, producer groups, and local communities is planned for Phase 3. Phase 2 engagement is limited to institutional coordination with borough municipalities and national agency data exchange.	Phase 2 documents the stakeholder map and risk ownership structure comprehensively, ensuring Phase 3 engagement is grounded in a clear understanding of actors, priorities, and responsibilities.
Sub-basin vs. borough unit mismatch	The Marmara DMP presents vulnerability and hydrological data at sub-basin level. The three focal sub-basins — Gönen Çayı, Körfez, and İznik Gölü — each contain areas beyond the target boroughs.	Sub-basin findings are attributed to the relevant boroughs with explicit acknowledgement of the spatial unit mismatch. Borough-level MGM station analysis provides the finer-resolution grounding that partially compensates for this limitation.

2.1.2 Context

How climate hazards, impacts, and risks have been assessed and managed in the region until now?

Climate hazard assessment in the Marmara Basin has developed substantially in recent years, most significantly through the completion of the Marmara Basin Drought Management Plan (Marmara DMP, 2023), prepared by the General Directorate of Water Management of the Republic of Türkiye Ministry of Agriculture and Forestry. This is the most comprehensive basin-scale drought assessment produced for the region to date. It applies internationally recognized drought indices — including SPI, SPEI, and the Palmer Drought Severity Index (PDSI) — to characterize the historical drought record across the basin's sub-basins, and produces future projections of hydrological drought severity, irrigation water demand, and sectoral vulnerability under RCP 4.5 and RCP 8.5 scenarios across three-time horizons to 2100. The Plan's sectoral vulnerability analysis is structured around the standard Exposure-Sensitivity-Adaptive Capacity framework, identifying the agricultural sector as the most exposed and the Körfez sub-basin as the most vulnerable due to extreme inter-sectoral water competition.

Prior to the Marmara DMP, drought risk management in the region relied primarily on national frameworks. The National Drought Management Strategy Document and Action Plan (2017–2023) provided the overarching legal and institutional basis for drought response, while the Türkiye Agricultural Drought Combat Strategy and Action Plan defined sector-specific measures. Monitoring was carried out by MGM through its national meteorological observation network and periodic drought bulletins based on SPI and PDSI indices. However, these assessments operated at regional or basin scale, without the borough-level resolution needed to support local adaptation planning in places like İznik, Gemlik, Karamürsel, or Gönen.

The AGROSHIELD Phase 1 assessment was the first application of a standardized European climate risk assessment framework (CLIMAAX) to these four boroughs. It produced a hazard characterization using EU-level datasets and the CLIMAAX Agricultural Drought Workflow and delivered crop-specific yield loss and revenue loss projections at city level for 2056–2060. Phase 2 advances this by grounding the assessment in local MGM station data and integrating it with the sub-basin evidence base of the Marmara DMP — moving from a standardized baseline to a locally-calibrated assessment.

The problem the project addresses and its place in the wider system

The core problem AGROSHIELD addresses is the resolution gap between existing drought risk assessments and the scale at which local adaptation decisions are made. The Marmara Basin is simultaneously one of Türkiye's most economically productive and most climatically stressed regions. It hosts Istanbul and the Kocaeli industrial corridor — accounting for a substantial share of national GDP — alongside significant agricultural areas in Bursa, Balıkesir, and Kocaeli provinces that are central to national food supply. The basin's total usable water potential stands at approximately 4,893.74 hm^3, a figure already under pressure from growing urban, industrial, and agricultural demand, with climate projections indicating further reductions in water availability over the coming decades (Marmara DMP, 2023).

Within this system, borough-level municipalities occupy a structurally under-resourced position. National and provincial-scale assessments frame the problem at a level too coarse for municipal decision-making, while the administrative and financial capacity to conduct independent risk assessments at borough level is absent in most rural municipalities. The result is that the boroughs most directly affected by agricultural drought — those where farming defines both the economy and the social fabric — are the least equipped with the evidence they need to plan adaptive responses. AGROSHIELD directly addresses this governance gap by delivering borough-specific analysis that municipal authorities can integrate into local adaptation plans, land-use decisions, and water management strategies.

The problem is also embedded in a broader socio-economic trajectory. The Marmara Basin's rapid population growth — with the Körfez sub-basin alone projected to exceed 15 million people by 2100 (Marmara DMP, 2023) — is systematically intensifying competition for water between agricultural, industrial, and domestic users. As urban and industrial demand grows, the agricultural sector faces declining water allocations even before the effects of climate change are accounted for. For water-intensive farming systems like Gönen's paddy rice production and Karamürsel's horticulture, this represents an existential structural challenge that drought risk assessment must account for alongside climate projections.

Governance context

The governance of climate risk and drought management in the Marmara Region operates across three institutional levels, as established in Phase 1 and carried forward without material change into Phase 2.

At the national level, the primary statutory authority rests with the Ministry of Agriculture and Forestry, which leads drought management through its General Directorate of Water Management and General Directorate of Agricultural Research and Policies (TAGEM). The Water Management Coordination Board and Agricultural Drought Management Coordination Board coordinate inter-institutional policy. The Türkiye Disaster Response Plan (TAMP) classifies drought as a slow-onset natural disaster and mandates integrated provincial response planning. The Climate Change Mitigation Strategy and Action Plan (2024–2030) and Türkiye's Water Efficiency Strategy and Action Plan (2023–2033) — which sets targets of 60% irrigation efficiency by 2030 and 65% by 2060 — provide the strategic framework within which all sub-national assessments must be positioned.

At the basin level, the Basin Management Board coordinates the implementation and monitoring of the Marmara DMP and associated plans, and is responsible for ensuring that sub-basin-level findings are integrated into provincial water allocation and drought response processes.

At the provincial and local level, Provincial Water Management Coordination Boards and Agricultural Drought Provincial Crisis Centres prepare and implement emergency action plans. District Directorates of Agriculture (İlçe Tarım ve Orman Müdürlükleri) are the primary institutional interface with farming communities and are responsible for implementing support measures, coordinating with TARSİM for agricultural insurance, and disseminating early warning information. Borough municipalities — the four target institutions of AGROSHIELD — sit at the base of this governance hierarchy with responsibility for local spatial planning, but limited formal mandate or capacity for independent drought risk assessment. AGROSHIELD directly strengthens their position in this hierarchy by providing the analytical foundation for meaningful participation in drought governance processes.

Sectors affected by climate change in the region

The sectors most relevant to AGROSHIELD, and how they are affected by agricultural drought, are as follows. This builds on the sectoral analysis presented in Phase 1.

Agriculture is the primary sector of concern and the focus of the AGROSHIELD assessment. As established in Phase 1 and confirmed by the Marmara DMP, declining precipitation, rising temperatures, and increasing evapotranspiration are reducing crop water availability during critical growth periods, suppressing yields, increasing irrigation demand, and threatening the economic viability of water-intensive farming systems. The perennial crops of İznik and Gemlik — olives, cherries, walnuts, and figs — face particular long-term risk because they cannot be rapidly switched in response to deteriorating conditions; a failed olive harvest in one year reflects multiple years of accumulated water stress. The paddy rice system of Gönen is among the most water-intensive agricultural systems in the country and is structurally exposed to both reduced Gönen Stream flow and increased inter-seasonal drought frequency.

Water resources are directly implicated in every dimension of the agricultural impact. DSİ-managed irrigation infrastructure — primarily open canal systems in all four boroughs — loses substantial water to evaporation and seepage, reducing effective delivery at a time when demand is rising. The Marmara DMP projects that the Körfez sub-basin's Water Use Index will rise from 0.49 under current conditions to 1.20 by 2075–2099, reaching a critical threshold at which total demand is projected to exceed available supply (Marmara DMP, 2023). This trajectory makes inter-sectoral water allocation — between agriculture, industry, and domestic use — one of the defining governance challenges of the coming decades for Karamürsel and Gemlik.

Industry and urban development act as indirect but powerful external pressures on agricultural water access in the Körfez sub-basin. The concentration of heavy industry along the Gulf of İzmit corridor, combined with the population growth trajectory, means that agriculture competes for water with users that have greater economic and political weight. This structural disadvantage of the agricultural sector is a core vulnerability driver that physical drought indices alone cannot capture — it is why the socio-economic dimensions of Phase 2 matter.

Rural livelihoods and food security represent the social dimension of the sectoral picture. Agricultural income in the four target boroughs supports not only farming households directly but the broader rural service economy. Yield losses translate into income shocks that deepen rural poverty and can trigger outmigration — a trend already visible in parts of the Southern Marmara Basin.

External influences on the problem

Phase 2 takes place within the same external framework identified in Phase 1, which has not materially changed. The National Drought Management Strategy, the Agricultural Drought Combat Strategy, and the Eleventh Development Plan collectively provide the national policy context within which the AGROSHIELD findings will be positioned and disseminated. The Marmara DMP itself is the most significant external influence on Phase 2 — it is the document that AGROSHIELD's local analysis is designed to complement and localise, and its sub-basin vulnerability classifications and future projections provide the primary reference frame for contextualising borough-level findings.

At the international level, the CLIMAAX programme framework connects AGROSHIELD to a community of comparable regional climate risk assessments across Europe and EU-adjacent regions, providing methodological comparability and enabling knowledge exchange. The EU Mission on Adaptation to Climate Change, to which Türkiye is aligned through its candidacy process, reinforces the importance of sub-national, evidence-based adaptation planning of the kind AGROSHIELD delivers.

Possible adaptation interventions

The priority adaptation interventions identified in Phase 1 and the Marmara DMP remain valid for Phase 2. They can be grouped into three categories relevant to the four target boroughs. First, irrigation infrastructure modernisation: the transition from open canal systems to pressurised drip and sprinkler systems is the single highest-impact physical intervention available in all four boroughs, directly reducing both water losses and crop water stress. Türkiye's Water Efficiency Strategy targets 60% irrigation efficiency by 2030. Second, agronomic adaptation: promotion of drought-resistant crop varieties, optimisation of planting calendars, and where economically viable, crop diversification away from the most water-intensive systems (particularly paddy rice in Gönen). Third, institutional and financial measures: expansion of agricultural insurance coverage through TARSİM, strengthening of early warning systems at the borough level, and integration of drought risk evidence into municipal land-use planning. Phase 2 provides the locally-specific yield loss and socio-economic evidence that makes these interventions prioritisable and financially justifiable at the borough scale.

2.1.3 Participation and risk ownership

Agricultural drought risk in the Southern Marmara Basin sits within a multi-level governance structure that distributes risk ownership across national, regional, and individual actors. At the national level, the Ministry of Agriculture and Forestry holds primary statutory responsibility for the identification, assessment, and mitigation of agricultural drought risk, exercised through the General Directorate of Water Management (which produced the Marmara Basin Drought Management Plan) and the General Directorate of Agricultural Research and Policies (TAGEM). The Turkish State Meteorological Service (MGM) provides the national monitoring and early-warning infrastructure, while the State Hydraulic Works (DSİ) manages the irrigation infrastructure on which all four boroughs depend. The overarching legal and institutional framework is the Drought Management Strategy and Action Plan (2017–2023) and the Türkiye Agricultural Drought Combat Strategy, both of which define the roles and escalation procedures for drought response.

At the regional and local level, the Marmara Municipalities Union (MMU) acts as the institutional lead for the AGROSHIELD project and coordinates with the four borough municipalities. Provincial Directorates of Agriculture in Bursa, Balıkesir, and Kocaeli implement national policy at sub-basin level and provide data to both the national authorities and the project team. District Directorates of Agriculture (İlçe Tarım ve Orman Müdürlükleri) in each of the four target boroughs are the primary interface with farming communities, responsible for disseminating early-warning information, coordinating support measures, and liaising with TARsİM for agricultural insurance. Cooperatives play a parallel representation function, aggregating the interests of farming communities and channeling them into local policy processes.

At the individual level, the primary risk-bearing actors are farmers themselves — particularly small-scale and subsistence producers who lack the financial buffers and adaptive capacity of larger agricultural enterprises. Small-scale farmers in all four boroughs have the highest exposure to yield and revenue loss from agricultural drought and the lowest capacity to self-insure or rapidly adopt alternative crops or irrigation technology. This differential is most acute in the Gulf sub-basin boroughs (Gemlik, Karamürsel), where inter-sectoral water competition amplifies the vulnerability of the farming sector relative to industrial and domestic users.

Formal risk tolerance thresholds are not explicitly defined at the borough level. The Marmara DMP's sub-basin vulnerability ratings provide the closest proxy: a 'Very High' rating for the Körfez sub-basin signals that the current level of risk is already at or beyond what the agricultural sector can absorb without institutional support. The escalation from 'Low' to 'High' projected for the İznik Gölü sub-basin within the near-term window (2021–2049) suggests that preventive action is required before risk reaches an intolerable level.

2.1.4 Application of principles

Social justice, equity, and inclusivity were embedded in the assessment design by ensuring that the analysis distinguishes between actors with different capacities to cope with drought. The revenue-at-risk and socio-economic impact assessment (Section 2.3.1) distinguishes qualitatively between small-scale and larger farming enterprises in their exposure and capacity to cope, and the vulnerability ratings drawn from the Marmara DMP are structured around the Exposure–Sensitivity–Adaptive Capacity framework, which captures differential social outcomes. The choice of four target boroughs — each with a distinct agricultural profile and socio-economic baseline — ensures that the analysis does not flatten important differences in vulnerability across the region.

2.1.5 Stakeholder engagement

Structured stakeholder engagement — in the form of workshops, surveys, or co-design sessions with farmers, cooperatives, and government agencies — has not yet taken place in Phase 2. By the design of the AGROSHIELD project, the first two phases are primarily analytical: Phase 1 produced the preliminary baseline assessment and Phase 2 delivers the regionalized, locally-grounded CRA. The participatory phase, in which findings are validated with and communicated to stakeholders and Community Adaptation Action Plans (CAAPs) are co-produced, is scheduled for Phase 3.

Phase 2 has nonetheless engaged with public institutions in a data-collection capacity. The Turkish State Meteorological Service (MGM) provided the station-level monthly precipitation and temperature records that form the empirical backbone of the hazard assessment for all four boroughs. The Marmara Basin Drought Management Plan (2023), produced by the General Directorate of Water Management (RTMAF-GDWM), was the principal authoritative source for sub-basin vulnerability ratings, hydrological drought indices, and irrigation water demand projections. Provincial and District Directorates of Agriculture were consulted informally to verify crop area and production data against TÜİK statistics. These data-exchange interactions, while not constituting formal stakeholder engagement in the CLIMAAX sense, represent the first institutional touchpoints of the AGROSHIELD project with the government agencies that will be central participants in Phase 3.

Phase 3 stakeholder engagement is planned as a series of structured workshops at the borough level, involving four principal groups: (i) farmers and small-scale agricultural producers from each of the four boroughs; (ii) agricultural cooperatives, which serve as the organized voice of the farming communities; (iii) District and Provincial Directorates of Agriculture, which hold both formal responsibility for agricultural policy implementation and direct relationships with the farming sector; and (iv) the borough municipalities themselves, which will be the primary institutional actors responsible for incorporating the AGROSHIELD findings into local adaptation plans. In these workshops, the Phase 2 risk findings will be presented, ground-truthed against local knowledge, and used as the evidential basis for co-producing CAAPs. The feedback from this engagement will be reflected in subsequent deliverables.

2.2 Risk Exploration

2.2.1 Screen risks (selection of main hazards)

The risk screening conducted in Phase 1 identified agricultural drought as the primary and most critical climate hazard for the four target boroughs of the Southern Marmara Basin. This determination was grounded in the region's high agricultural dependency, the historically documented frequency and severity of drought events, and the direct linkage between precipitation deficits and crop yield losses in all four borough contexts. The Phase 1 screening also identified heatwaves, soil degradation and desertification, heavy rainfall, and wildfires as secondary hazards with compounding interactions with agricultural drought, though these were not selected for dedicated workflow analysis in Phase 1.

Phase 2 does not revise this hazard selection. Agricultural drought remains the primary focus of the AGROSHIELD CRA. However, three developments since Phase 1 reinforce and sharpen the evidence base for this selection.

First, the sub-basin drought index analysis contained in the Marmara Basin Drought Management Plan (Marmara DMP, 2023) provides a substantially richer empirical picture of drought occurrence than was available at the Phase 1 screening stage. Over the 1980–2021 reference period, the Gönen Çayı sub-basin recorded 74 drought months under SPI-3, 93 under SPEI-9, and 101 under scPDSI — the highest figures across all three focal sub-basins and indicative of chronic, multi-index drought exposure rather than episodic events. The Körfez sub-basin, covering Karamürsel and Gemlik, shows the highest current agricultural vulnerability rating (Very High) driven by inter-sectoral water competition, while the İznik Gölü sub-basin is projected to escalate from Low to High vulnerability within the near-term period (2021–2049) (Marmara DMP, 2023). These findings provide nationally authoritative quantitative confirmation of the Phase 1 screening judgment.

Second, basin-wide temperature trend analysis confirms statistically significant warming at 11 of 15 MGM stations across the Marmara Basin, with the Gönen station (No. 17674) showing a Mann-Kendall trend coefficient of $z = 3.24$ ($p = 0.00$) over the 1967–2020 record (Marmara DMP, 2023). Rising temperatures directly amplify agricultural drought severity by increasing evapotranspiration demand independently of precipitation. This temperature signal, absent from the Phase 1 screening evidence base, strengthens the case for agricultural drought as the dominant and worsening hazard.

Third, national-scale projections from the UNDP drought vulnerability assessment for Türkiye (UNDP, 2023) corroborate these sub-basin findings at the regional level, indicating progressive intensification of drought conditions across northwest Türkiye — the climate zone within which the four target boroughs fall — under both moderate and high-emission trajectories. The UNDP assessment uses a different modelling framework from the primary Turkish national datasets (MPI-ESM-MR under SSP scenarios rather than RCP), but its directional findings are consistent with the Marmara DMP projections.

Regarding secondary hazards: heatwaves are incorporated in Phase 2 as an amplifying factor within the agricultural drought analysis — specifically through their contribution to elevated evapotranspiration and crop heat stress — rather than as a standalone workflow. Soil degradation and desertification are addressed qualitatively within the vulnerability discussion.

The current situation across the four boroughs remains as characterized in Phase 1: all four face significant agricultural drought exposure, with Gönen and Karamürsel at the high-risk end of the spectrum due to water-intensive crop systems and structural irrigation constraints, and İznik and Gemlik facing growing medium-term risk to their perennial orchard economies. Phase 2 deepens this characterization through original station-level analysis and borough-resolution crop impact projections.

2.2.2 Choose Scenario

Phase 2 maintains the two-scenario framework established in Phase 1: RCP 4.5, representing a moderate emissions pathway with active mitigation, and RCP 8.5, representing a high-emissions business-as-usual trajectory. This choice is carried forward for three reasons. First, it ensures direct comparability between Phase 1 and Phase 2 outputs, including the yield loss projections that explicitly build on Phase 1 baselines. Second, RCP 4.5 and RCP 8.5 are the scenarios used in the primary Turkish national datasets underpinning this phase — specifically the climate model runs embedded in the Marmara DMP (MPI-ESM-MR, HadGEM2-ES, and CNRM-CM5.1 under RCP 4.5 and 8.5) — ensuring methodological consistency with the authoritative national reference.

Third, both scenarios remain widely understood and practically relevant to Turkish municipal decision-makers, for whom the RCP framework is more familiar than the newer SSP combinations.

Where national-scale projections using SSP-based scenarios (UNDP, 2023) are cited in Phase 2, they are used as corroborating evidence for directional trends rather than as primary scenario drivers, and their different modelling framework is explicitly noted.

The key climate change assumptions underlying both scenarios, consistent with Phase 1, are: continued warming trends leading to intensified evapotranspiration demand; reduced total precipitation with increased seasonal variability, particularly during critical summer growing periods; increased frequency and severity of extreme drought episodes; and compounding effects from heatwaves on crop water requirements and yield stability.

Temporal scope

Phase 2 is based on three time series:

The **near-term horizon (2021–2049)** corresponds to the first major planning cycle for current agricultural infrastructure and irrigation investment decisions. For perennial crops such as olives and fruit trees, which dominate İznik and Gemlik, investment decisions made now will still be bearing fruit in this period. The near-term is also the horizon over which the Marmara DMP identifies the most pronounced shift in sub-basin vulnerability — particularly for the İznik Gölü sub-basin, whose agricultural vulnerability rating is projected to escalate from Low to High.

The **mid-century horizon (2050–2074)** represents the period of most acute divergence between RCP 4.5 and RCP 8.5, making it the most analytically informative window for understanding the consequences of mitigation choices. The Marmara DMP projects that Körfez sub-basin WEI will reach 0.77 by 2050–2074 — approaching critical water stress thresholds — under current demand growth trends.

The **long-term horizon (2075–2100)** captures the structural transformation of the regional climate system and is most relevant for land-use planning, water resource infrastructure with long design lives, and the viability of crop types that define each borough's agricultural identity. Körfez WEI is projected to exceed 1.0 by this period — indicating demand exceeding sustainable supply — and Gönen Çayı faces progressively increasing hydrological drought frequency (Marmara DMP, 2023).

Socio-economic scenario assumptions

Phase 2 expands the socio-economic dimension of the scenario framework relative to Phase 1, which treated it largely qualitatively. The following assumptions are applied consistently across all time horizons and both climate scenarios:

Population growth in the Körfez sub-basin — which encompasses both Karamürsel and part of Gemlik's water catchment — is projected to be substantial, rising from approximately 5.1 million (2022) to 7.4 million (2050) and 15.0 million (2100) (Marmara DMP, 2023). This growth intensifies inter-sectoral competition for water between agriculture, industry, and municipal use, reducing the share available for irrigation even under unchanged climate conditions.

Agricultural land use in all four boroughs is assumed to remain broadly stable in crop composition through the near term, reflecting the structural inertia of perennial agriculture (İznik, Gemlik) and the established rice-growing economy of Gönen. Significant crop mix shifts are considered possible under mid- and long-term scenarios if drought losses render current crop selections economically unviable — this is discussed qualitatively in the socio-economic assessment.

Food prices and farm income are assumed to face increasing volatility under both scenarios, with more pronounced effects under RCP 8.5, driven by regional and national production losses from drought. The implications for smallholder income stability are addressed in the socio-economic impact section.

Irrigation infrastructure is assumed to remain broadly at current coverage in the absence of active policy intervention, consistent with the Marmara DMP's baseline trajectory. Scenarios do not assume autonomous adaptation — improvements to irrigation efficiency or crop switching are treated as adaptation options rather than baseline assumptions, preserving the risk assessment's integrity as a picture of outcomes under current trajectories.

2.3 Regionalized Risk Analysis

Phase 2 of the AGROSHIELD Climate Risk Assessment advances from the standardised EU-scale baseline established in Phase 1 to a locally-grounded, borough-resolution analysis built on Turkish national meteorological data and the authoritative regional drought management planning literature. The core methodological departure from Phase 1 is the replacement of EU-level gridded datasets with station-level observations from the Turkish State Meteorological Service (MGM), enabling direct, place-specific drought characterisation for each target borough. This approach is complemented by systematic integration of the *Marmara Basin Drought Management Plan* (RTMAF-GDWM, 2023) — the Marmara DMP — which provides nationally-authoritative sub-basin drought indices, future water stress projections, and sectoral vulnerability assessments.

A key methodological feature of Phase 2 is the ERA5 reanalysis gap-filling procedure applied to three of the four target stations (Gemlik, İznik, and Karamürsel), which addresses multi-year breaks in the MGM station record created by the MANUEL–OMGİ network transition. The complete calibration methodology and confidence levels are documented in Table 2-4 and the data limitations section below.

Table 2-1: *Data Overview — Workflow #1: Agricultural Drought (Phase 2)*

Hazard data	Vulnerability data	Exposure data	Impact metrics / Risk output
MGM monthly precipitation: Gönen (17674), Gemlik (17663), İznik (17661), Karamürsel (18412). MANUEL + OMGİ networks merged. ERA5 reanalysis gap-filling applied for Gemlik, İznik, and Karamürsel (see note).	Agricultural drought vulnerability ratings, current and projected 2025–2099 (Marmara DMP, 2023)	Agricultural land area by borough; crop-specific sown area (TÜİK)	SPI-3, SPI-6, SPI-12 per borough; drought episode frequency and severity; Mann-Kendall trend statistics
MANUEL gauge records: Gönen 1967–2012; Gemlik 1965–1992; İznik 1969–2001; Karamürsel 1983–1992	Water Exploitation Index (WEI) by sub-basin, three future periods to 2099 (Marmara DMP, 2023)	Irrigation-dependent cropland area; rural population dependent on agricultural income	Drought frequency heatmap (decade × borough); gap-filling calibration statistics

OMGİ automatic station records: all four stations 2005–2025 (Karamürsel from 2013)	Irrigation infrastructure type; adaptive capacity indicators (Marmara DMP, 2023)	Population projections by sub-basin (Marmara DMP, 2023)	Climatological comparison: historical vs. recent period (2000–2025)
ERA5 reanalysis gap-fill: Gemlik 157 months (1992–2005), İznik 62 months (2002–2004), Karamürsel 157+97 months (1992–2013)	Sub-basin drought indices: SPI-3, SPEI-9, scPDSI 1980–2021 (Marmara DMP, Vol. 3)		Calibrated ERA5 gap-fill series; source-labelled data workbook
MGM monthly temperature (mean/max/min), all four stations; ERA5 back-extension of short records to full SPI period (R^2 0.976–0.995)	Socio-economic development index (SEGE) by province		SPEI-3, SPEI-9 (original computation); Hargreaves ET_0; growing-season water balance

Note: *Yellow cells indicate ERA5-filled or reanalysis-reconstructed records. ★ = ERA5 reanalysis gap-fill applied. ★★ = ERA5 + neighbour-station regression (layered). All filled values source-labelled in the supporting data workbook.*

2.3.1 Agricultural Drought — Fine-Tuning to Local Context

2.3.1.1 Hazard Assessment

Methodological approach

The Phase 2 hazard assessment characterises agricultural drought at borough resolution using three complementary analytical strands. The first is an original computation of the Standardized Precipitation Index (SPI) at three accumulation scales — SPI-3, SPI-6, and SPI-12 — from MGM station records for each of the four target boroughs, following McKee et al. (1993) and the WMO SPI User Guide (2012). SPI-3 captures short-term growing-season soil moisture deficits; SPI-6 reflects medium-term water availability and reservoir recharge; SPI-12 integrates the annual precipitation balance linked to hydrological drought and multi-year crop impacts. Drought thresholds follow the WMO classification: −1.0 (moderate), −1.5 (severe), −2.0 (extreme).

The second strand is a Mann-Kendall non-parametric trend test on annual and seasonal precipitation totals at each station, enabling direct comparison with basin-scale findings from the Marmara DMP. The third strand integrates sub-basin drought index data, Water Exploitation Index (WEI) projections, and agricultural vulnerability ratings from the Marmara DMP, situating the borough-level analysis within its broader hydrological context.

Prior to SPI calculation, multi-year gaps in the Gemlik, İznik, and Karamürsel station records were addressed through ERA5 reanalysis gap-filling. ECMWF ERA5 monthly mean total precipitation (0.25° resolution, 1990–2005) was extracted at the nearest grid point to each station (Gemlik: 14.2 km; İznik: 8.5 km; Karamürsel: 13.9 km) and calibrated against the overlapping MGM record by ordinary least squares regression. For Karamürsel, a second-stage neighbour-station regression (using filled Gemlik and İznik series as predictors) was applied for the 2006–2013 period not covered by ERA5. Full calibration statistics are reported in Table 2-4. SPI values derived from gap-filled months are flagged throughout with ★ (ERA5) or ★★ (layered regression).

Precipitation climatology and baseline conditions

Mean annual precipitation varies substantially across the four target boroughs. Long-term means over the full merged record are approximately 669 mm at Gönen (1967–2025), 590 mm at Gemlik (1965–2025, ★), 490 mm at İznik (1969–2025, ★), and 620 mm at Karamürsel (1983–2025,

★★). İznik records the lowest mean annual precipitation, consistent with its sheltered position in the İznik Lake basin. Precipitation at all four boroughs follows a strongly seasonal Mediterranean-temperate pattern: peak rainfall in November–March, with July–August means below 20 mm at all stations. This seasonal distribution creates a structural mismatch between natural precipitation timing and peak crop water demand — Gönen's paddy rice and maize require intensive irrigation through July–August precisely when precipitation is at its annual minimum.

A comparison of mean monthly precipitation between the historical period (pre-2000) and recent period (2000–2025) reveals no statistically significant shift in annual totals at Gönen, Gemlik, or İznik — consistent with the Mann-Kendall results in Table 2-2. The absence of a monotonic drying trend does not diminish the evidence for increasing drought risk: as the SPI analysis below demonstrates, the most recent decade shows a dramatic clustering of drought conditions not captured by long-term mean statistics.

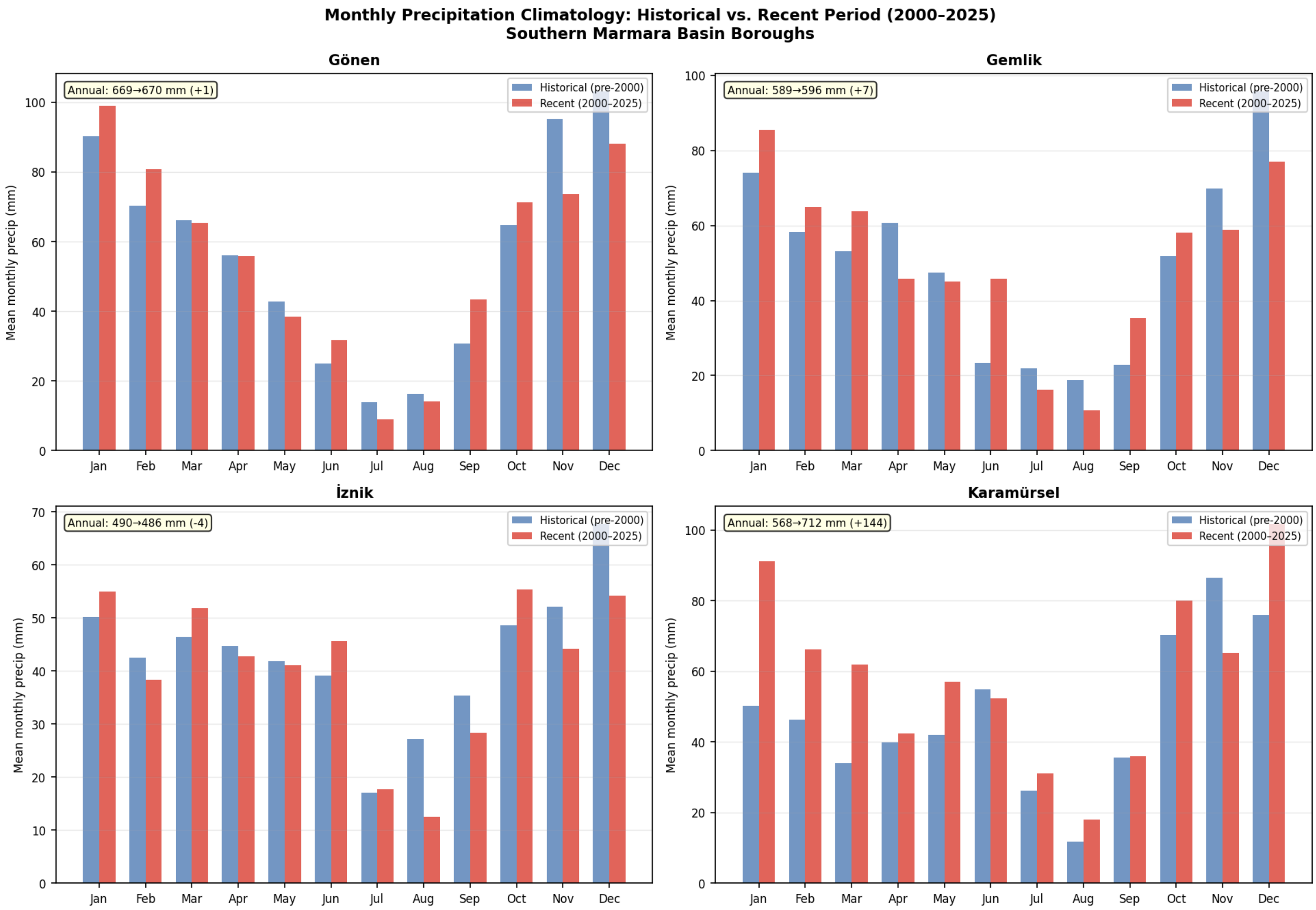

Figure 2-1: Monthly Precipitation Climatology: Historical (pre-2000) vs. Recent Period (2000–2025). Red bars indicate the recent period. ★ ERA5 gap-fill applied for Gemlik, İznik; ★★ layered gap-fill for Karamürsel.

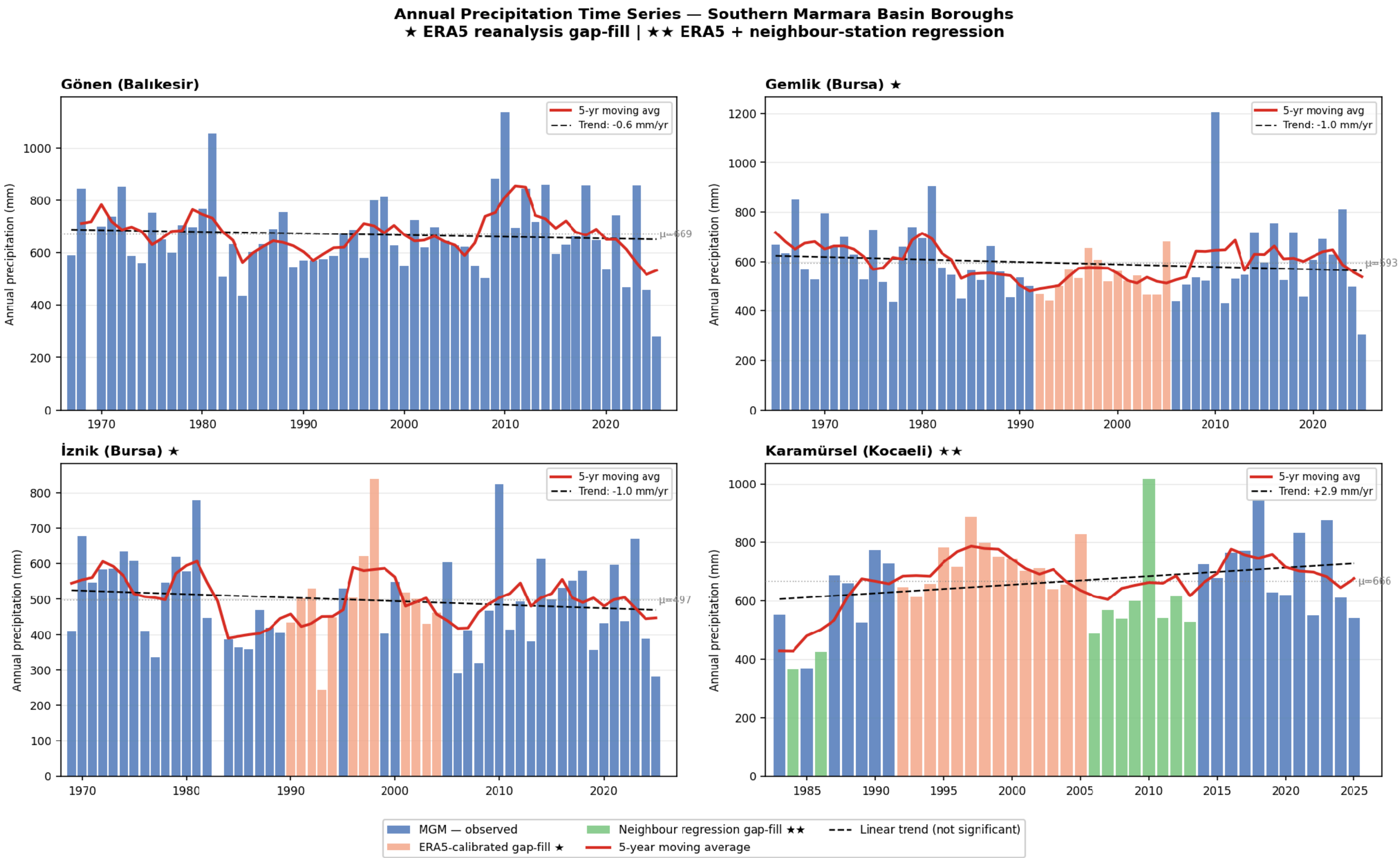

Figure 2-2: *Annual Precipitation Time Series. Blue bars = MGM observed; orange bars = ERA5 calibrated gap-fill (★); green bars = neighbour-station regression gap-fill (★★). Dashed line = linear trend (not significant); red line = 5-year moving average. μ = long-term mean.*

Table 2-2: *Mann-Kendall Trend Test Results — Annual and Seasonal Precipitation*

Borough	Season	Z-stat	p-value	Sen slope (mm/yr)	Trend
Gönen	Annual	−0.456	0.648	−0.38	No significant trend
	Winter (DJF)	0.295	0.768	0.19	No significant trend
	Spring (MAM)	−0.436	0.663	−0.16	No significant trend
	Summer (JJA)	−1.060	0.289	−0.34	No significant trend
	Autumn (SON)	−0.751	0.453	−0.58	No significant trend
Gemlik ★	Annual	−0.605	0.545	−1.17	No significant trend
	Winter (DJF)	−1.137	0.256	−1.07	No significant trend

	Spring (MAM)	−0.664	0.507	−0.46	No significant trend
	Summer (JJA)	0.454	0.650	0.21	No significant trend
	Autumn (SON)	−0.210	0.834	−0.25	No significant trend
İznik ★	Annual	−0.520	0.603	−0.64	No significant trend
	Winter (DJF)	−0.892	0.373	−0.44	No significant trend
	Spring (MAM)	−0.926	0.355	−0.44	No significant trend
	Summer (JJA)	−0.385	0.700	−0.23	No significant trend
	Autumn (SON)	0.333	0.739	0.18	No significant trend
Karamürsel ★★	Annual	1.523	0.128	11.82	No significant trend
	Winter (DJF)	2.876	0.004	5.50	★ Significant increase ($p < 0.01$)
	Spring (MAM)	1.805	0.071	4.12	Marginal increase ($p < 0.10$)
	Summer (JJA)	−0.338	0.735	−0.66	No significant trend
	Autumn (SON)	0.000	1.000	0.50	No significant trend

Note: *★ significant at $p < 0.01$. Karamürsel winter result likely reflects inter-station location differences between MANUEL (1855) and OMGİ (18412) stations rather than a genuine trend; interpret with caution. ★ ERA5 gap-fill | ★★ layered gap-fill.*

Two baseline features frame the rest of the hazard assessment. Precipitation is spatially uneven and strongly seasonal — İznik is the driest borough (≈490 mm yr^{-1}) and all four receive under 20 mm in mid-summer, so the rainfall minimum coincides with peak crop-water demand. Yet the long-term record shows no statistically significant trend in annual or seasonal precipitation across Gönen, Gemlik, and İznik (the lone exception, Karamürsel's winter increase, most plausibly reflects the inter-station difference noted above). The series is therefore essentially stationary: the intensifying drought documented below is driven not by declining rainfall but by warming-driven evaporative demand and a clustering of dry episodes in the most recent decade — examined next, beginning with the SPI analysis.

Historical drought characterisation: SPI analysis

The SPI analysis at three accumulation scales reveals consistent and significant drought hazard across all four boroughs, with important spatial and temporal differences that are agronomically consequential. Figures 3, 4, and 5 present the SPI time series; Table 2-3 summarises the key episode statistics.

Following ERA5 gap-filling, the most striking result is the elevation of İznik to the highest drought frequency of the four boroughs at 19.2% of SPI-12 months (★), followed by Karamürsel at 15.2%

(★★), Gemlik at 14.8% (★), and Gönen at 11.6%. Previously invisible episodes now visible in the filled series include: in İznik, an April 1985–January 1987 episode (21 months, peak SPI-12 = −1.89) and a July 1993–October 1994 episode (15 months, peak = −2.48); in Gemlik, an October 1993–October 1994 episode (12 months, peak = −1.66) and a February 2007–November 2008 episode (10 months, peak = −2.14); and in Karamürsel, the main episode is revised from 44 to 38 months (May 1984–July 1987, peak = −3.09), with a January–August 2008 episode (8 months, peak = −1.53) and a January 2014–August 2015 episode (8 months, peak = −2.48) also newly resolved.

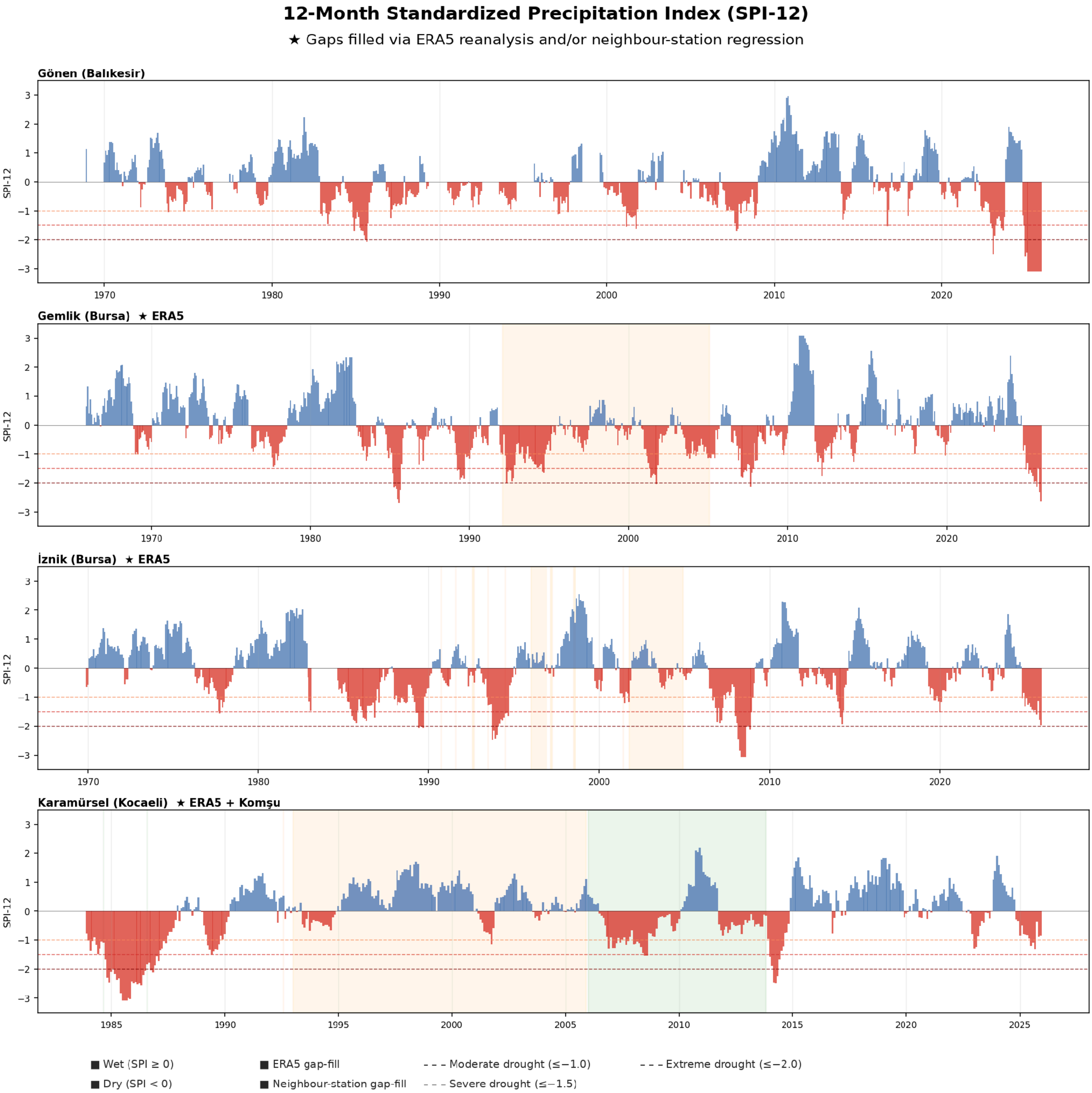

Figure 2-3: *12-Month Standardized Precipitation Index (SPI-12) for all four boroughs. Orange shading = ERA5 gap-fill period (★); green shading = neighbour-station regression period (★★). Blue bars = above normal; red bars = below normal.*

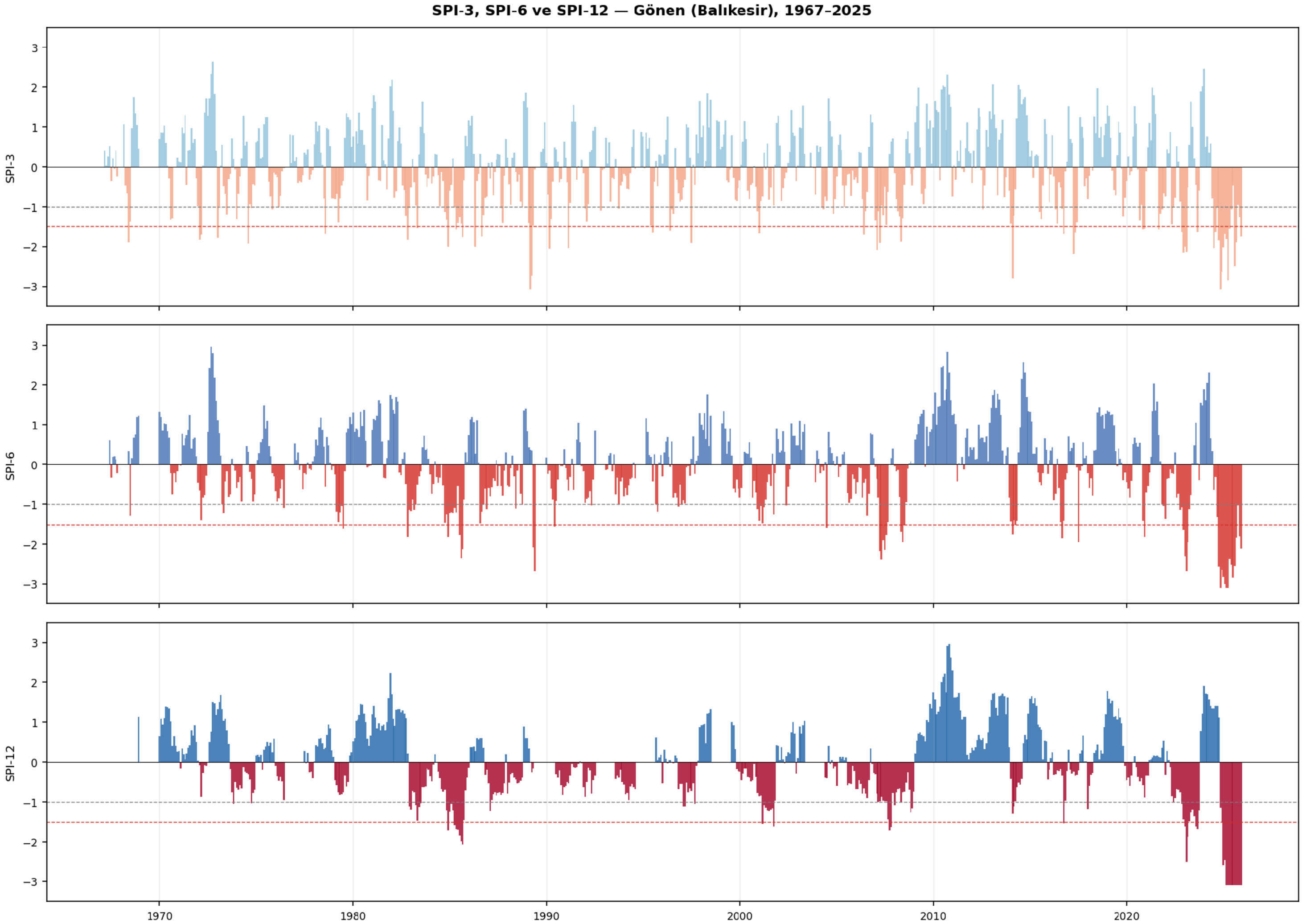

Figure 2-4: *SPI-3, SPI-6, and SPI-12 at Gönen (1967–2025), illustrating how short-term and sustained drought signals coincide or diverge. No gap-filling applied at Gönen.*

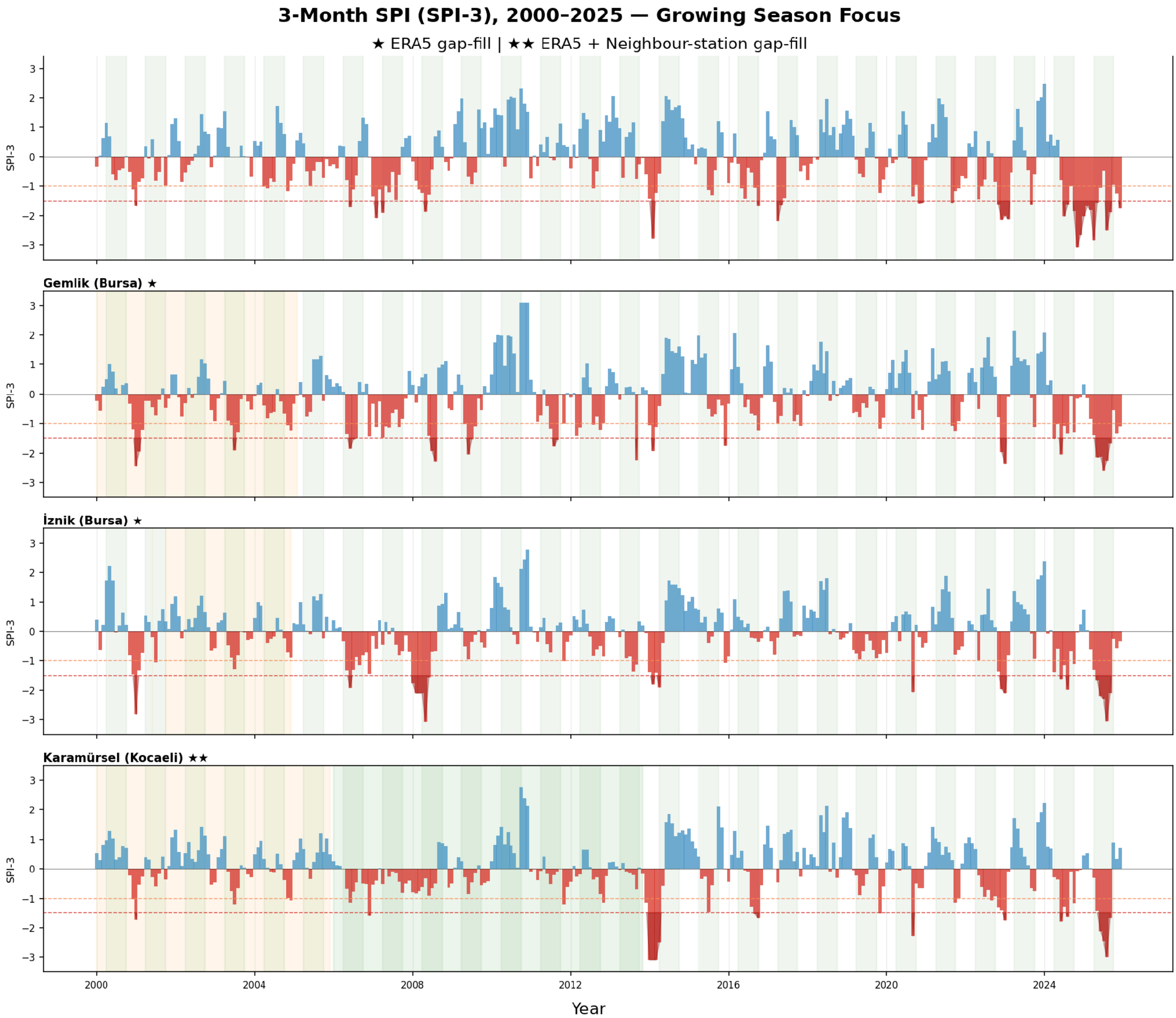

Figure 2-5: 3-Month SPI (SPI-3), 2000–2025. Green shading = growing season (April–September). Dark red fill = severe drought (SPI-3 ≤ −1.5) during the growing season.

Read together, the three SPI views give a consistent picture of the historical hazard. The SPI-12 series (Figure 2-3) show recurrent multi-year droughts in every borough, but at differing frequencies once the records are completed: İznik is the most drought-prone (19.2% of months below −1.0), followed by Karamürsel (15.2%), Gemlik (14.8%), and Gönen (11.6%). The multi-scale view at Gönen (Figure 2-4) shows how these signals are layered — sustained SPI-12 droughts are punctuated by sharper SPI-3 deficits that sometimes coincide with them in deep events and sometimes appear as short shocks within otherwise normal years. Figure 2-5 makes the agronomic consequence explicit: many of the severe short-term (SPI-3) droughts since 2000 fall within the April–September growing season, when crop water demand peaks, and they concentrate in the most recent years. The hazard is therefore not only recurrent but strikes when crops are most exposed — a pattern set out episode by episode in Table 2-3.

Table 2-3: Drought Episode Statistics — SPI-12 (Threshold: SPI ≤ −1.0)

Borough	Record (SPI-12)	Episodes ≤−1.0	Severe ≤−1.5	Drought freq. (%)	Min SPI-12	Most extreme / notable episodes
Gönen	1968–2025 (601 months)	19	9	11.6%	−3.09 (Mar 2025)	Nov 2024–Dec 2025 (14 months, ongoing)
Gemlik ★	1965–2025 (721 months)	30	11	14.8%	−2.70 (Aug 1985)	Oct 1993–Oct 1994 (12 months); Jan–Dec 2025 (12 months)
İznik ★	1969–2025 (655 months)	18	13	19.2%	−3.09 (May 2008)	Apr 1985–Jan 1987 (21 months); Jul 1993–Oct 1994 (15 months)
Karamürsel ★★	1983–2025 (505 months)	12	3	15.2%	−3.09 (Jul 1985)	May 1984–Jul 1987 (38 months); Jan–Aug 2008 (8 months)

Note: *★ Gemlik and İznik: ERA5 reanalysis gap-fill (R^2 = 0.47 and 0.38 respectively). ★★ Karamürsel: ERA5 Stage 1 (R^2 = 0.51) + neighbour-station regression Stage 2 ($R^2 \approx$ 0.51); interpret with lower confidence. Drought frequencies on filled series: Gönen 11.6% — Gemlik 14.8% ★ — Karamürsel 15.2% ★★ — İznik 19.2% ★. All gap-filled values source-labelled in supporting data workbook.*

The decadal analysis (Figure 6) illustrates the temporal pattern of drought frequency shifts most clearly at Gönen, where the 2020s already register 38% of months as drought conditions — the highest decadal value in the 58-year record. For İznik (ERA5-filled), the 1980s register 39% drought frequency, reflecting the newly revealed 1985–1987 episode. For Karamürsel (layered fill), the 1980s register 66%, largely driven by the 38-month main episode; this figure should be treated with caution given the lower-confidence gap-filling method. All four boroughs show elevated drought frequency in the 2020s.

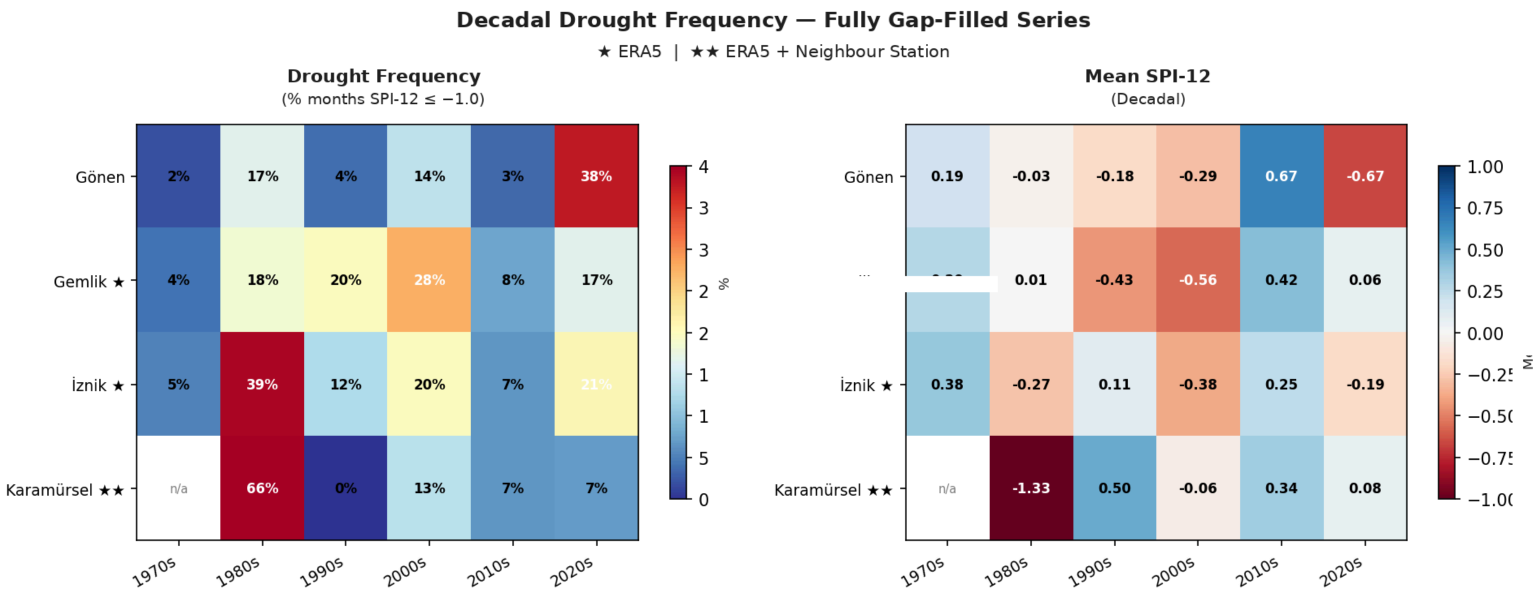

Figure 2-6: Decadal drought frequency (% months SPI-12 ≤ −1.0) and mean SPI-12 by borough. ★ ERA5 gap-fill | ★★ layered. n/a = insufficient data (<12 months in decade).

ERA5 gap-filling calibration

Several of the decadal frequencies in Figure 2-6 — and the İznik, Gemlik, and Karamürsel SPI series more broadly — rest on ERA5-reconstructed precipitation, so the reliability of that gap-filling is documented in Table 2-4. The calibration is only moderate (R^2 of 0.38–0.51), which is why every filled value carries an ★/★★ flag and the layered Karamürsel series is interpreted with particular caution.

Table 2-4: *ERA5 Reanalysis Gap-Filling: Calibration Statistics*

Borough	Gap-fill method	Calibration period	n (months)	R^2	Slope	RMSE (mm)	Confidence
Gönen	No gap-filling required (MGM MANUEL + OMGİ continuous)	—	—	—	—	—	High
Gemlik ★	ERA5 reanalysis (ECMWF, 0.25°)	1990-01–1992-12	35	0.472	0.574	23.8	Moderate
İznik ★	ERA5 reanalysis (ECMWF, 0.25°)	1990-01–2005-12	130	0.383	0.584	25.6	Moderate
Karamürsel ★★ (Stage 1)	ERA5 reanalysis (1992–2005)	1990-01–1992-12	35	0.506	0.750	26.6	Moderate
Karamürsel ★★ (Stage 2)	Neighbour regression: Gemlik + İznik average (2006–2013)	1983-01–1992-12	~110	~0.51	~0.83	—	Lower

Note: *ERA5 systematically overestimates point-gauge monthly precipitation in the eastern Mediterranean; the slope coefficient (~0.57–0.75) reflects this correction. Karamürsel Stage 2 uses the ERA5-filled Gemlik and İznik series as predictors, introducing layered uncertainty that limits confidence in 2006–2013 SPI values.*

Cross-validation with the Marmara DMP

A critical methodological strength of Phase 2 is the cross-validation between the station-level SPI results and the sub-basin drought index findings of the Marmara DMP. Over 1980–2021, the DMP documents that the Gönen Çayı sub-basin recorded the highest drought month counts of the three focal sub-basins across all five indices: 74 months under SPI-3, 93 under SPEI-9, and 101 under scPDSI — giving it a normalised Exposure Index of 0.894 (vs. 0.180 for Körfez and 0.171 for İznik Gölü). The major drought episodes identified at basin scale — most notably 1989–1990 and 2019–2021 — are directly visible in the station-level SPI time series for all four boroughs, providing methodological confidence in the station analysis and cross-validation of the ERA5 gap-fill approach.

Temperature trends and the evapotranspiration dimension

The SPI analysis captures precipitation deficit but not the full picture of agricultural drought hazard. Rising temperatures increase potential evapotranspiration (ET_0), reducing effective soil moisture availability even when precipitation is unchanged. The Marmara DMP confirms statistically significant warming at 11 of 15 MGM stations across the basin; the Gönen station shows a Mann-Kendall coefficient of $z = 3.24$ ($p < 0.01$, 1967–2020). This temperature amplification is quantified in the analysis that follows, through SPEI-3 and SPEI-9 time series and growing-season ET_0 water balance tables.

Reference evapotranspiration (ET_0)

Reference evapotranspiration was estimated at monthly resolution using the Hargreaves–Samani equation, which requires only mean, maximum, and minimum air temperature and is consistent with the temperature-based approach adopted in the Marmara DMP. MGM observational temperature records were obtained for all four stations but, unlike the precipitation series, the temperature archives are comparatively short — beginning in 2004 at Gemlik and İznik and only in 2013 at Karamürsel. To compute SPEI over the same period as SPI, the temperature series were back-extended to the start of each precipitation record using ECMWF ERA5 2-metre temperature, calibrated against the observed record through month-specific linear regression. The calibration is markedly stronger than that achieved for precipitation: ERA5 reproduces observed monthly mean temperature with R^2 of 0.976–0.995 across the four stations — compared with 0.38–0.51 for precipitation gap-filling — reflecting the high reliability of reanalysis temperature relative to reanalysis precipitation. For the back-extended period the diurnal temperature range required by the Hargreaves equation was represented by each station's observed monthly climatological range. Resulting mean annual ET_0 ranges from approximately 1,002 mm at coastal Gemlik to 1,173 mm at inland İznik, consistent with regional estimates for the eastern Marmara.

SPEI computation

The Standardized Precipitation–Evapotranspiration Index was computed from the monthly climatic water balance (precipitation minus ET_0), with a log-logistic distribution fitted to each calendar month following Vicente-Serrano et al. (2010) and standardized to a normal distribution. SPEI was calculated at 3- and 9-month accumulation scales over each borough's full record, matching the SPI reference period. For a minority of calendar months exhibiting strongly negative summer water balances, where the log-logistic fit was numerically unstable, an empirical (rank-based) standardization was substituted; this affected an appreciable share of months only at Karamürsel's 9-month scale, where the shorter record (from 1983) constrains distributional fitting.

Temperature amplification of drought

SPEI tracks SPI closely at all four boroughs (correlation 0.956–0.978), confirming that precipitation remains the dominant driver of drought variability. Incorporating evaporative demand, however, systematically increases the diagnosed drought frequency. As Table 2-6 shows, the proportion of months classified as drought (index ≤ -1) rises by 1.8 to 4.5 percentage points when ET_0 is included, with the largest increases at Karamürsel (11.1% to 15.6%) and İznik (13.7% to 17.2%). Figure 2-7 illustrates this at the monthly scale: SPEI follows the SPI trajectory but deepens below it during dry phases, the gap representing the additional desiccation imposed by atmospheric demand that a precipitation-only index cannot capture.

Table 2-6: SPI-3 vs. SPEI-3 — Drought Frequency and Severity Comparison (matched months, full record).

Borough	n	r (SPI,SPEI)	Drought % SPI-3	Drought % SPEI-3	Δ pts	Severe % SPI-3	Severe % SPEI-3
Gönen	671	0.962	16.2	18.0	+1.8	7.5	7.9
Gemlik	730	0.978	15.1	17.7	+2.6	6.3	7.7
İznik	673	0.960	13.7	17.2	+3.6	7.4	8.0
Karamürsel	514	0.956	11.1	15.6	+4.5	6.0	7.4

Note: Drought = index ≤ -1.0; severe = index ≤ -1.5. Δ pts = percentage-point increase in drought frequency under SPEI. r = Pearson correlation between SPI-3 and SPEI-3.

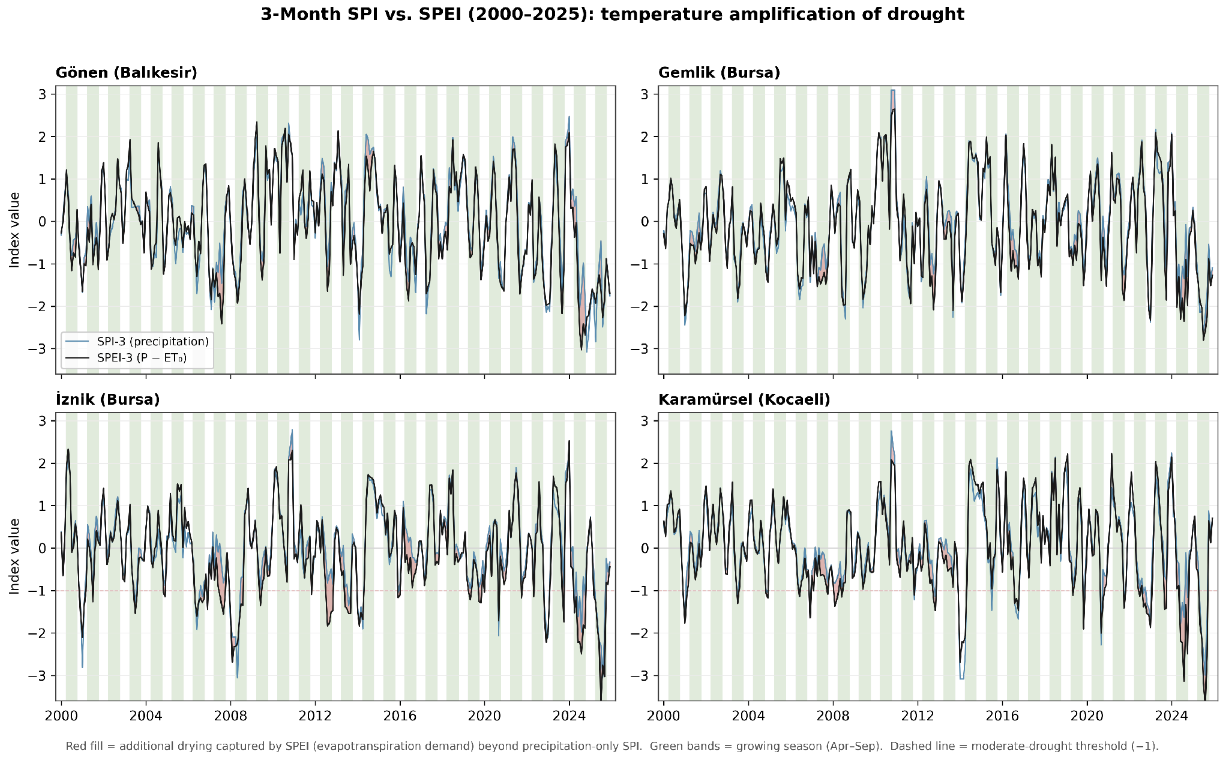

Figure 2-7: 3-Month SPI vs. SPEI (2000–2025), all four boroughs. Blue line = SPI-3 (precipitation only); black line = SPEI-3 (precipitation − ET_0). Red fill marks the additional drying captured by SPEI beyond precipitation-only SPI. Green bands = growing season (April–September); dashed line = moderate-drought threshold (−1).

The most policy-relevant result emerges from the temporal structure of this divergence (Figure 2-8). The decadal mean difference between SPEI-3 and SPI-3 shifts from positive in the cooler decades of the 1970s–1990s — when SPEI ran marginally wetter than SPI — to increasingly negative from the 2000s onward, reaching −0.17 to −0.22 standardized units in the 2020s across all four boroughs. This monotonic, spatially consistent shift is the signature of warming-enhanced evaporative demand: for an unchanged amount of rainfall, rising temperature now renders the water balance materially more negative than precipitation alone would indicate. In agronomic terms, the drought hazard documented by the SPI analysis is, in the current decade, an underestimate.

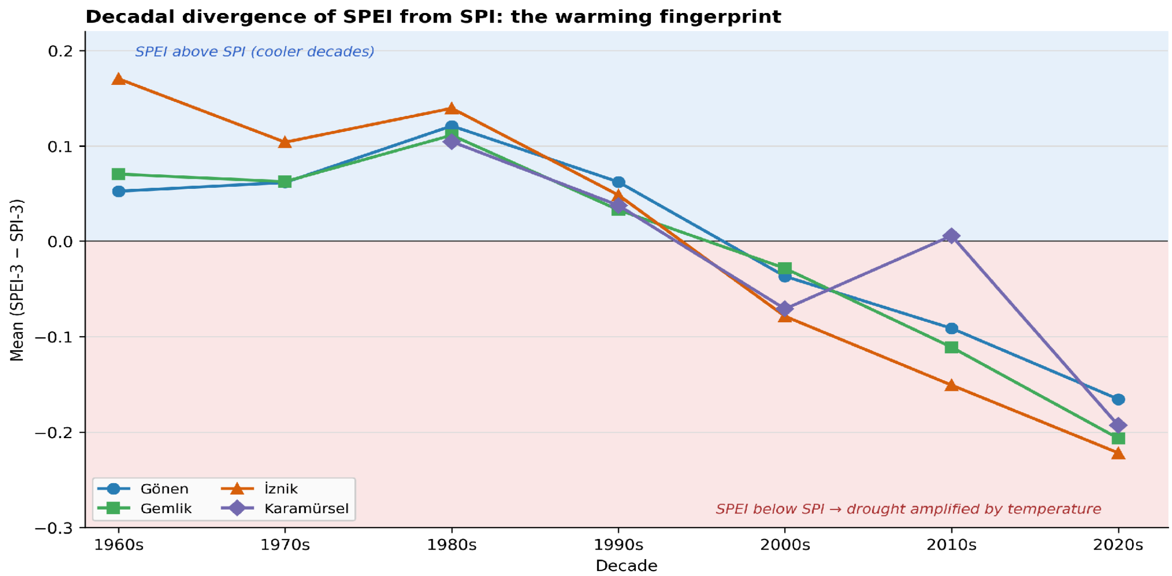

Figure 2-8: Decadal divergence of SPEI-3 from SPI-3 by borough (full record). Positive values indicate SPEI wetter than SPI; negative values indicate temperature-driven amplification of drought. The consistent shift toward negative values from the 2000s onward is the fingerprint of warming-enhanced evaporative demand. (Karamürsel's 2010s value reflects its shorter record.)

Growing-season water balance

The agronomic significance of evaporative demand is most acute during the April–September growing season, when crop water requirements peak. Table 2-7 quantifies the seasonal balance: across the four boroughs, growing-season precipitation (187–245 mm) meets only a fraction of reference evapotranspiration (761–897 mm), leaving a structural deficit of 554–703 mm that must be met by irrigation, stored soil moisture, or groundwater. The deficit is largest at the inland boroughs of İznik (−703 mm) and Gönen (−695 mm) and somewhat smaller at coastal Gemlik and Karamürsel. Critically, the deficit has widened in the recent period (2000–2025) relative to the pre-2000 baseline by 22–49 mm, most strongly at İznik and Gemlik — a direct measure of intensifying irrigation dependence under a warming climate, and a key input to the exposure and vulnerability analysis that follows.

Table 2-7: Growing-Season (April–September) Water Balance by Borough (mean, mm).

Borough	Mean P (mm)	Mean ET_0 (mm)	Balance (mm)	Balance <2000	Balance 2000–25	Change (mm)
Gönen	187	882	−695	−684	−707	−22
Gemlik	208	761	−554	−533	−581	−48
İznik	195	897	−703	−680	−729	−49
Karamürsel	245	804	−559	−536	−574	−38

Note: Balance = precipitation − ET_0. "Change" compares the 2000–2025 mean balance with the pre-2000 baseline; a more negative value indicates a widening seasonal deficit.

Caveats

These SPEI results should be read alongside two caveats recorded in the supporting methodology log. First, for the pre-record period the temperature series are reanalysis-based reconstructions rather than direct observations; although the calibration is strong, uncertainty is higher before 1979 (Gemlik, İznik). Second, Karamürsel's shorter record (from 1983) makes its SPEI — particularly at the 9-month scale — the least constrained of the four, and its results are interpreted accordingly.

Future water stress: Water Exploitation Index projections

The Körfez sub-basin (Karamürsel/Gemlik) WEI is projected to reach 0.49 by 2021–2049 — already exceeding the EEA severe stress threshold of 0.40 — rising to 0.77 by 2050–2074 and exceeding 1.0 (demand surpassing total available supply) by 2075–2099, driven by population growth from 5.1 million (2022) to 15.0 million (2100). For İznik (WEI 0.18–0.25) and Gönen (WEI 0.04–0.05), hazard remains primarily meteorological rather than structural.

Projected future drought hazard under climate change

To extend the hazard characterisation beyond the observed record, monthly climate projections from the HadGEM2-ES global model were obtained from MGM for RCP 4.5 and RCP 8.5, spanning a 1971–2000 reference period and a 2015–2098 future period at the grid cells nearest each borough. HadGEM2-ES was selected because it is one of the global climate models underpinning the Marmara Basin Drought Management Plan and was provided by MGM as monthly RCP 4.5 and RCP 8.5 fields at the grid cells nearest each borough, keeping Phase 2 methodologically consistent with the authoritative national reference and directly comparable with Phase 1. Being a comparatively climate-sensitive Earth-system model, it also yields a precautionary high-warming envelope well suited to stress-testing agricultural adaptation, and its trajectory is corroborated at the national scale by the UNDP projections.

Because raw GCM output carries systematic biases at the station scale, the projections were applied through the delta-change (change-factor) method: the model's projected change between each future window and its own reference period — additive for temperature, multiplicative for precipitation, computed separately for each calendar month — was imposed on the observed station series. Future reference evapotranspiration and SPEI were then recomputed from the series and evaluated against the historical (1965–2025) reference distribution, so that projected values express how drought-prone each future climate is relative to the observed baseline. Three windows were examined — 2021–2049, 2050–2074, and 2075–2100 — under both scenarios.

The projected signal is dominated by warming rather than by precipitation change. Mean annual temperature rises by approximately 2.0–2.1°C by the 2030s under both scenarios, diverging thereafter to +3.0–3.1°C (RCP 4.5) and +5.0–5.1°C (RCP 8.5) by the end of the century. Projected precipitation change, by contrast, is small and directionally mixed across boroughs and windows (−11% to +16%), consistent with the low model agreement on Mediterranean precipitation. Reference evapotranspiration responds directly to the warming, rising from about +6% in the near term to +16% (−roughly 160–190 mm yr^{-1}) by the late century under RCP 8.5.

This warming-driven increase in atmospheric demand translates into a steep rise in drought frequency (Figure 2-9, Table 2-8). Against the historical baseline — in which roughly 16–18% of months qualify as drought (SPEI-3 ≤ −1) — the drought share rises to 25–41% even in the near term (2021–2049) and reaches 41–54% by 2075–2100 under RCP 8.5. Conditions that were exceptional in the twentieth-century record thus become the prevailing state in the late-century high-emissions scenario, with İznik (54%) and Gemlik (51%) the most severely affected. The two scenarios track closely through mid-century and diverge sharply thereafter, underlining the value of emissions restraint for the second half of the century.

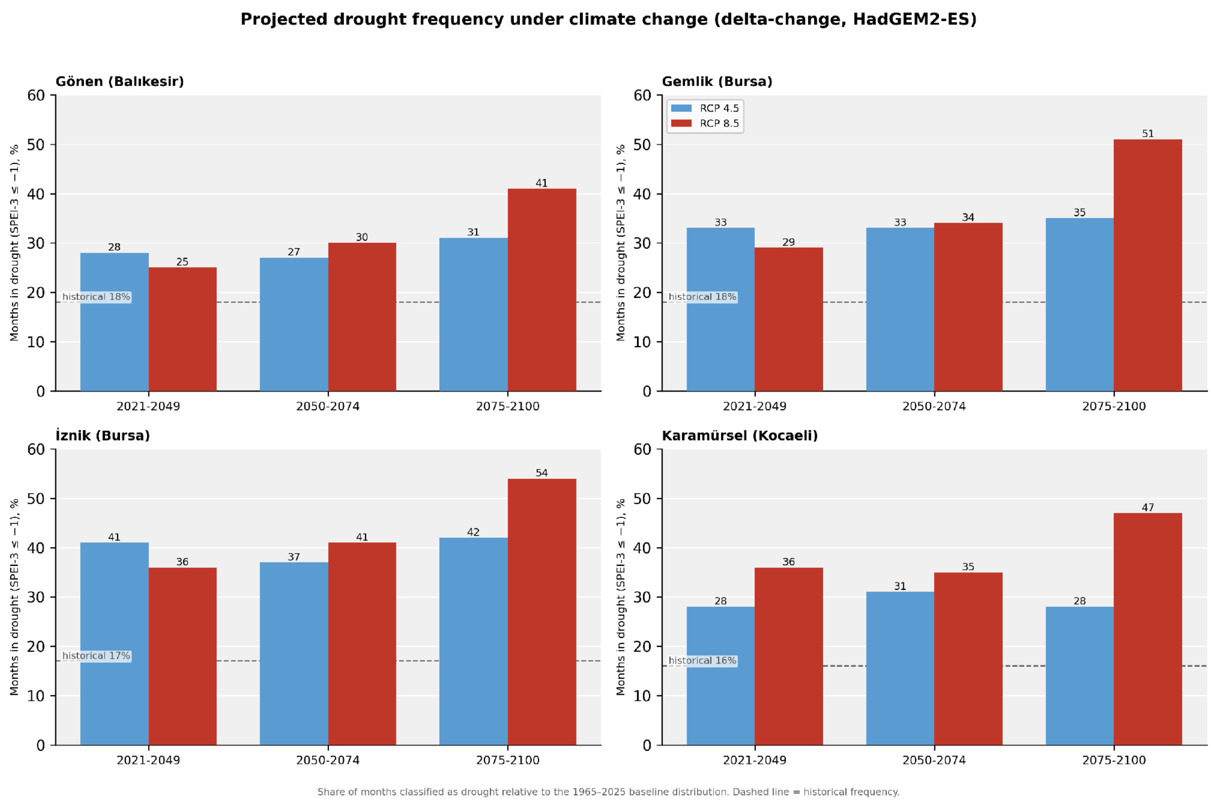

Figure 2-9: Projected drought frequency (share of months with SPEI-3 ≤ −1, evaluated against the 1965–2025 baseline distribution) for each borough, by future window and scenario. Dashed line = historical frequency.

Table 2-8: Future Climate Projection Summary by Borough (HadGEM2-ES, delta-change).

Borough	Scenario	Period	ΔT (°C)	ET_0 (mm)	Drought (%)	GS deficit (mm)
Gönen	**Historical**	**1965–2025**	**—**	**1156**	**18**	**−695**
	RCP 4.5	2021–2049	+2.0	1218	28	−756
	RCP 4.5	2050–2074	+2.5	1234	27	−722
	RCP 4.5	2075–2100	+3.0	1253	31	−762
	RCP 8.5	2021–2049	+2.2	1221	25	−731
	RCP 8.5	2050–2074	+3.5	1271	30	−727
	RCP 8.5	2075–2100	+5.0	1332	41	−839
Gemlik	**Historical**	**1965–2025**	**—**	**1002**	**18**	**−554**
	RCP 4.5	2021–2049	+2.1	1066	33	−626
	RCP 4.5	2050–2074	+2.6	1079	33	−633
	RCP 4.5	2075–2100	+3.1	1093	35	−636
	RCP 8.5	2021–2049	+2.3	1070	29	−601
	RCP 8.5	2050–2074	+3.6	1114	34	−607
	RCP 8.5	2075–2100	+5.1	1166	51	−703
İznik	**Historical**	**1965–2025**	**—**	**1173**	**17**	**−703**
	RCP 4.5	2021–2049	+2.1	1248	41	−799
	RCP 4.5	2050–2074	+2.6	1264	37	−788
	RCP 4.5	2075–2100	+3.1	1281	42	−809
	RCP 8.5	2021–2049	+2.3	1253	36	−773
	RCP 8.5	2050–2074	+3.6	1302	41	−796
	RCP 8.5	2075–2100	+5.1	1363	54	−874
Karamürsel	**Historical**	**1965–2025**	**—**	**1047**	**16**	**−559**
	RCP 4.5	2021–2049	+2.1	1110	28	−617
	RCP 4.5	2050–2074	+2.6	1125	31	−624
	RCP 4.5	2075–2100	+3.1	1137	28	−599
	RCP 8.5	2021–2049	+2.3	1120	36	−623
	RCP 8.5	2050–2074	+3.5	1158	35	−620
	RCP 8.5	2075–2100	+5.0	1216	47	−705

Note: ΔT = change in mean annual temperature vs. 1971–2000 model reference. ET_0 and drought frequency recomputed from delta-perturbed observed series; drought = SPEI-3 ≤ −1 against the historical distribution. GS deficit = April–September water balance (precipitation − ET_0). Full detail (including precipitation change and severe-drought frequency) in the supporting workbook.

The agronomic consequence is a deepening growing-season water deficit (Figure 2-10). The April–September balance — already a structural deficit of 554–703 mm in the observed period — widens by a further 60–80 mm in the near term and by 145–170 mm by the late century under RCP

8.5, reaching deficits of roughly −700 to −875 mm. Because this widening is driven by evaporative demand rather than rainfall, it falls squarely on the growing season, when crop water requirements and irrigation withdrawals peak — directly intensifying the irrigation dependence quantified above.

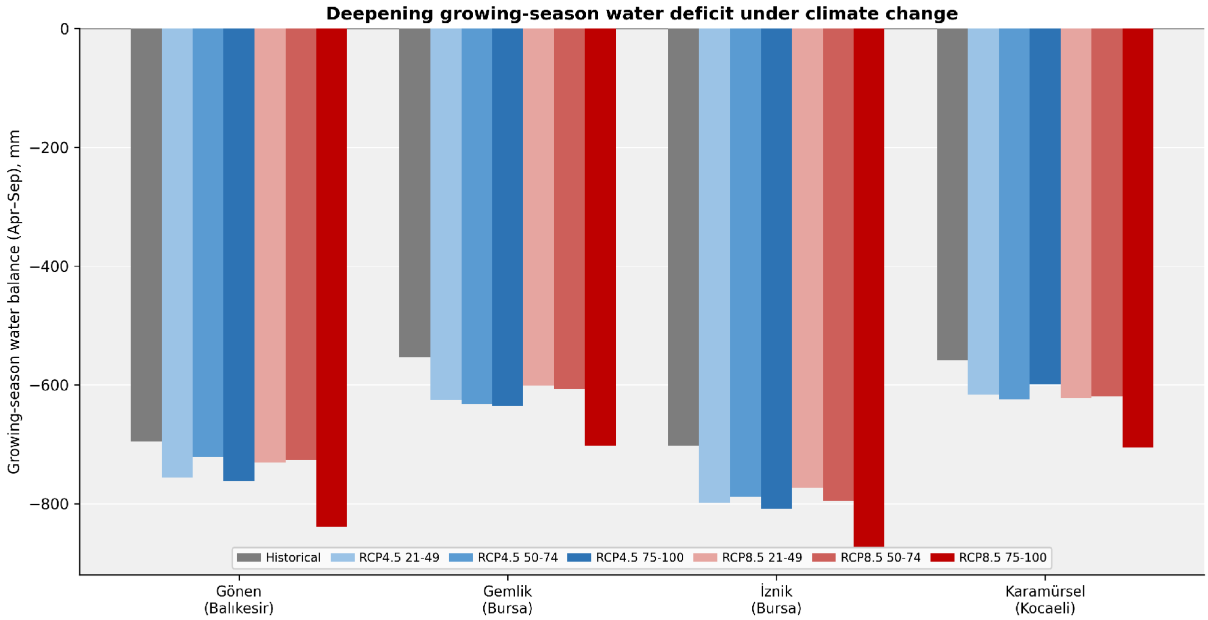

Figure 2-10: Growing-season (April–September) water balance by borough — historical and projected — across future windows and scenarios. More negative values indicate a wider seasonal deficit.

These station-level projections reinforce, at the agricultural scale, the basin-scale water-stress trajectory documented by the Marmara DMP's WEI projections above: both indicate a structural tightening of the water balance in the eastern Marmara through the century. They also supply the climate inputs for the yield-loss and socio-economic analysis in the following objective, where the projected growing-season deficits are translated into crop-specific impacts.

Three caveats apply. First, the projections derive from a single model realisation (HadGEM2-ES), which is comparatively sensitive and may sit toward the upper end of the warming range; the results should be read as a plausible high-warming trajectory rather than a multi-model central estimate, and are corroborated at the national scale by the UNDP climate projections. Second, the Karamürsel projection is taken from the nearest available grid cell, which corresponds to the Kocaeli station some 37 km to the east; because climate-change deltas vary smoothly in space this has limited effect, but the Karamürsel figures carry marginally higher uncertainty. Third, the delta-change method preserves observed variability while shifting the mean climate, and therefore does not capture potential changes in the variability or sequencing of wet and dry spells.

Spatial downscaling: 1 km gridded hazard mapping

The borough-level projections summarised in Table 2-8 and mapped in Figures 2-9 and 2-10 characterise the hazard as a single value per borough. To resolve sub-borough spatial variation — the explicit objective of advancing beyond the standardised CLIMAAX toolbox — the projected hazard was downscaled to an approximately 1 km grid. The procedure follows a gridded delta-change logic: the within-borough spatial texture of the growing-season (April–September) water balance is derived from the CHELSA V2.1 high-resolution climatology (1981–2010), from which reference evapotranspiration is computed using the Hargreaves method. Each borough's grid is then anchored so that its spatial mean reproduces exactly the borough-level projection value reported in Table 2-8 for the corresponding scenario and period.

Two properties of this approach are made explicit for transparency. First, the change signal between scenarios and periods is applied uniformly within each borough; all sub-borough spatial variability originates from the high-resolution baseline climatology rather than from the projection itself. Second, because the absolute level of each map is fixed to the borough projection, the maps are spatially explicit renderings of the Table 2-8 values and remain fully consistent with the borough-level analysis — they add spatial detail without altering any previously reported quantity.

Figures 2-11 to 2-17 present the growing-season water deficit (P − ET_0, mm) — the spatially resolved counterpart of Figure 2-10 — for the historical baseline and the six scenario–period combinations. A common colour scale is used across all seven panels so that change is directly comparable.

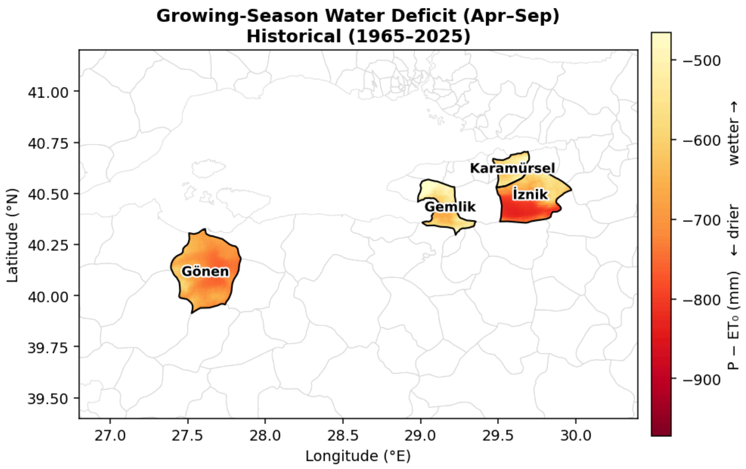

Figure 2-11: Growing-season (April–September) water deficit, P − ET_0 (mm), at ~1 km resolution — Historical baseline (1965–2025). More negative values (darker red) indicate a larger structural water deficit.

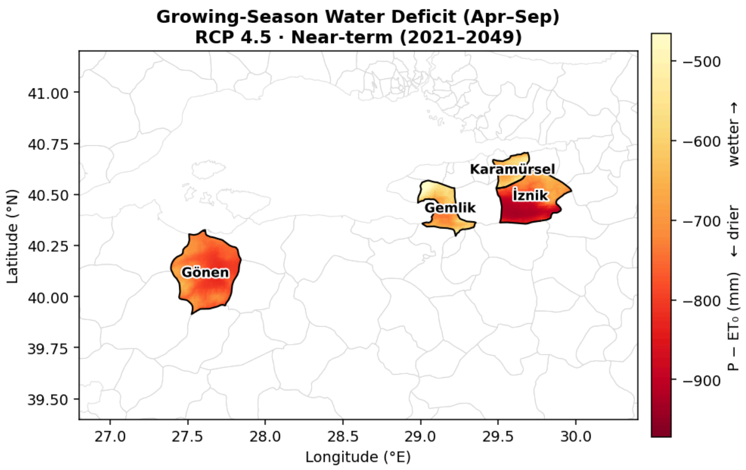

Figure 2-12: Growing-season water deficit, P − ET_0 (mm), ~1 km — RCP 4.5, near-term (2021–2049).

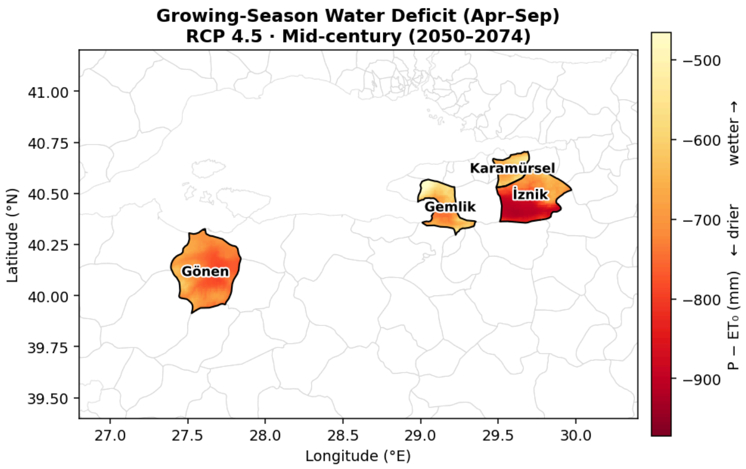

Figure 2-13: Growing-season water deficit, $P - ET_0$ (mm), ~1 km — RCP 4.5, mid-century (2050–2074).

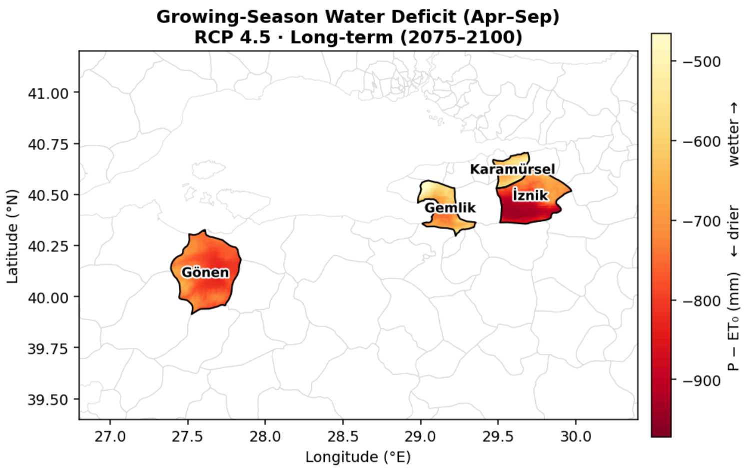

Figure 2-14: Growing-season water deficit, $P - ET_0$ (mm), ~1 km — RCP 4.5, long-term (2075–2100).

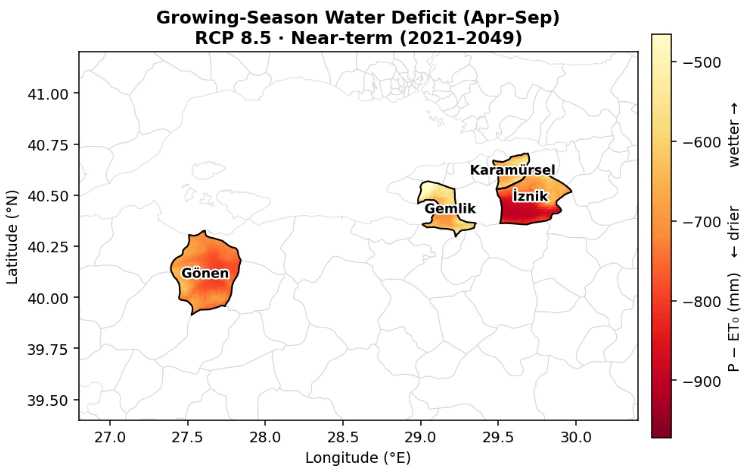

Figure 2-15: Growing-season water deficit, $P - ET_0$ (mm), ~1 km — RCP 8.5, near-term (2021–2049).

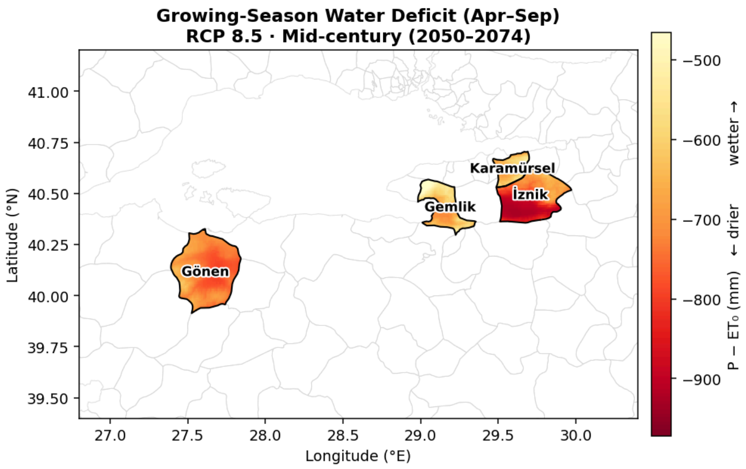

Figure 2-16: Growing-season water deficit, P − ET_0 (mm), ~1 km — RCP 8.5, mid-century (2050–2074).

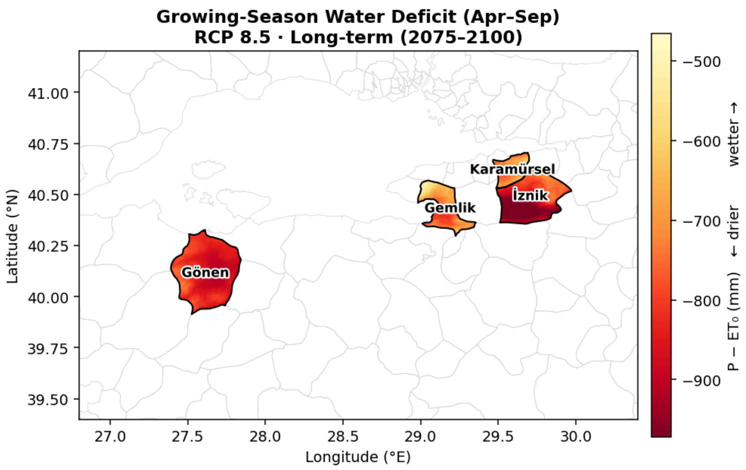

Figure 2-17: Growing-season water deficit, P − ET_0 (mm), ~1 km — RCP 8.5, long-term (2075–2100).

Figures 2-18 to 2-24 present the agricultural drought frequency (%) — the spatially resolved counterpart of Figure 2-9 — for the same baseline and scenario–period combinations, again on a common colour scale.

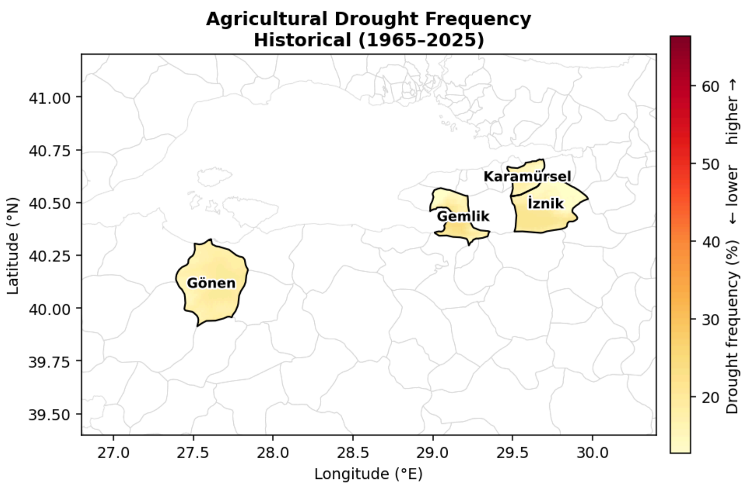

Figure 2-18: Agricultural drought frequency (%) at ~1 km resolution — Historical baseline (1965–2025). Darker tones indicate a higher share of months in drought.

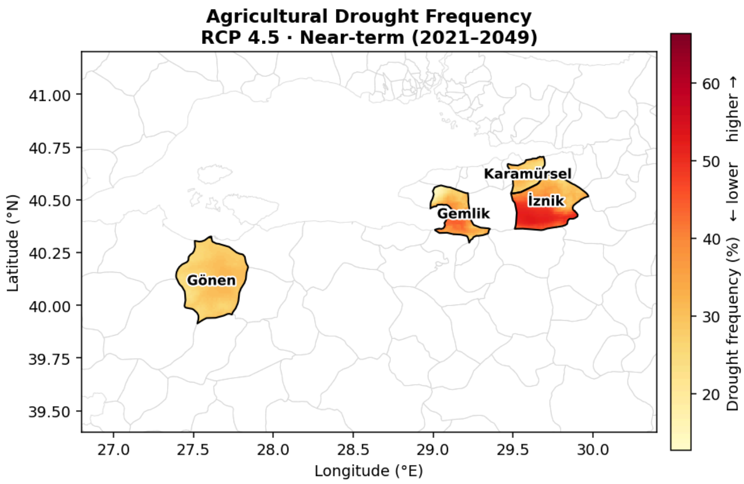

Figure 2-19: Agricultural drought frequency (%), ~1 km — RCP 4.5, near-term (2021–2049).

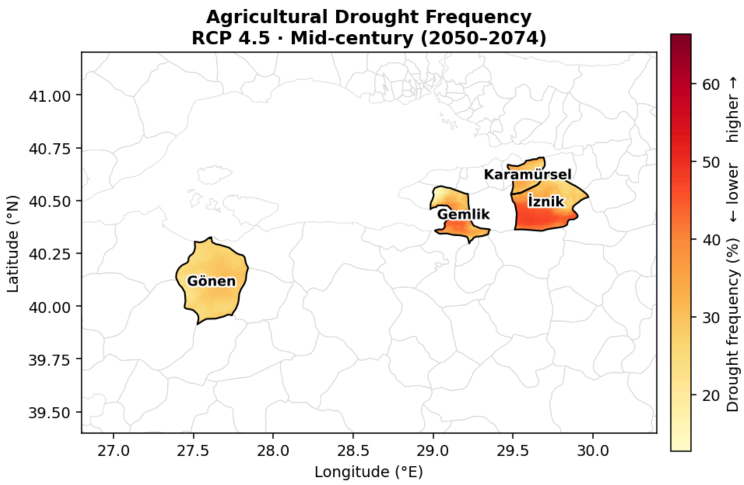

Figure 2-20: Agricultural drought frequency (%), ~1 km — RCP 4.5, mid-century (2050–2074).

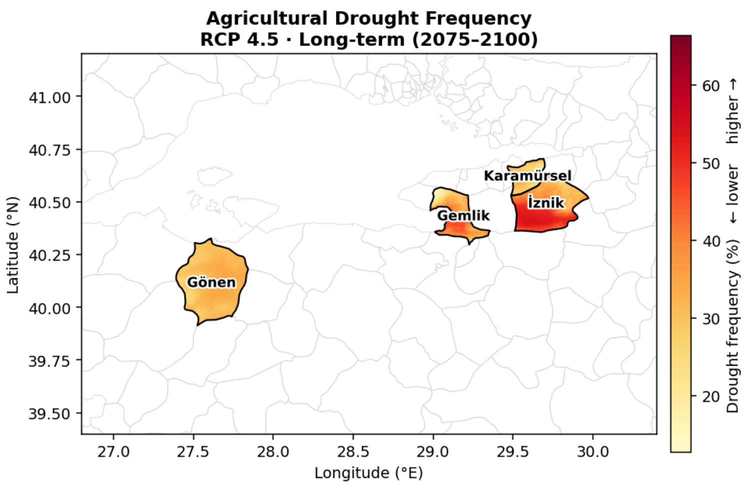

Figure 2-21: Agricultural drought frequency (%), ~1 km — RCP 4.5, long-term (2075–2100).

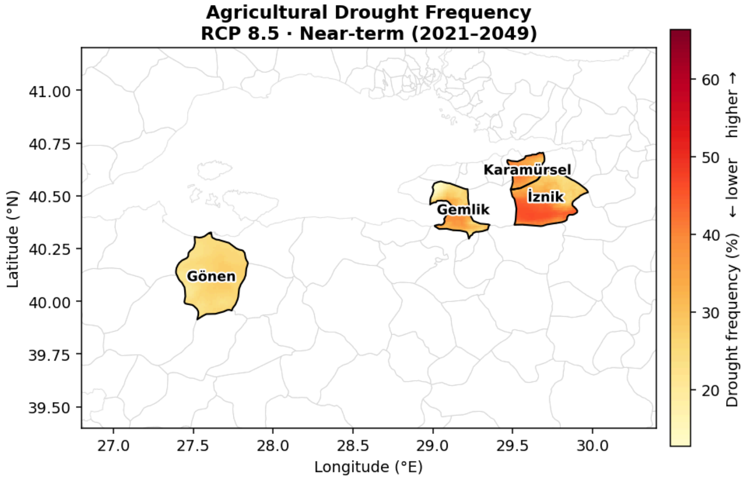

Figure 2-22: Agricultural drought frequency (%), ~1 km — RCP 8.5, near-term (2021–2049).

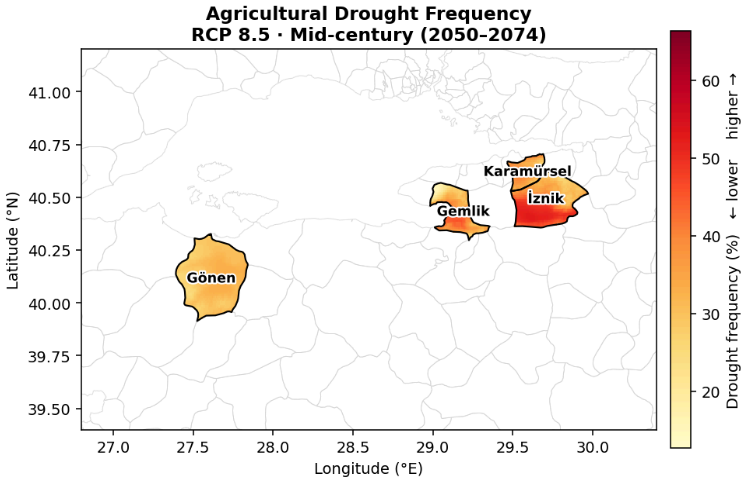

Figure 2-23: Agricultural drought frequency (%), ~1 km — RCP 8.5, mid-century (2050–2074).

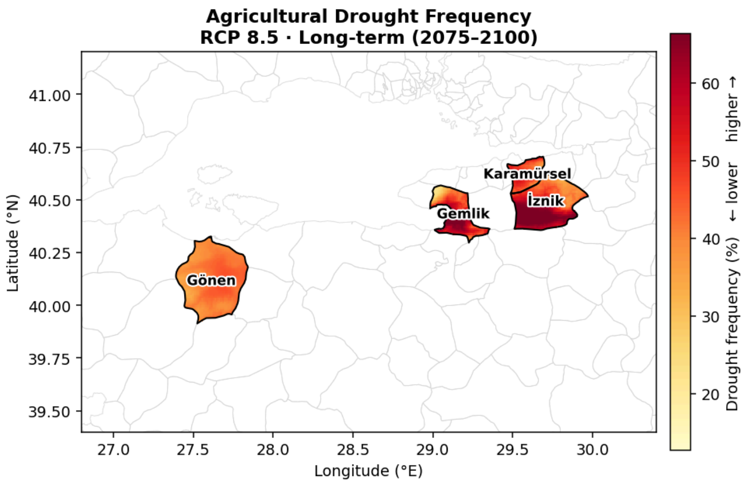

Figure 2-24: Agricultural drought frequency (%), ~1 km — RCP 8.5, long-term (2075–2100).

Across both metrics, İznik emerges as the most exposed borough, combining the deepest growing-season deficit (−703 mm historically, deepening to −874 mm under RCP 8.5 long-term) with the highest drought frequency (17% rising to 54%). Gönen carries the second-largest deficit (−695 to −839 mm), consistent with its irrigation-dependent rice economy, while its frequency increase is more moderate (18% to 41%) — indicating that in Gönen the dominant signal is the depth rather than the frequency of deficit. Gemlik, despite the smallest absolute deficit, shows the steepest relative rise in drought frequency (18% to 51% under RCP 8.5 long-term), confirming that its comparatively favourable annual water balance masks a pronounced intensification of growing-season drought episodes. Hazard increases consistently from RCP 4.5 to RCP 8.5 and from the near- to the long-term horizon across all four boroughs. The 1 km texture additionally reveals coherent intra-borough gradients — notably the wetter northern uplands of İznik and Karamürsel toward the Samanlı range versus their drier southern lowlands.

The complete set of fourteen layers is provided as georeferenced GeoTIFF rasters (EPSG:4326), together with the borough boundary file, in the supporting documentation, enabling direct reuse in GIS environments.

Summary of hazard findings by borough

Gönen. The clearest and most extensively documented hazard. Nineteen SPI-12 drought episodes over 1968–2025, with 38% of months in 2020–2025 classified as drought. The current episode (November 2024–present) has reached SPI-12 = −3.09 — the lowest in the 58-year record. Gönen Çayı also has the highest historical Exposure Index (0.894) in the Marmara DMP analysis.

İznik ★. The highest drought frequency of the four boroughs at 19.2% (ERA5-filled), consistent with below-average mean annual precipitation (~490 mm). ERA5 gap-filling reveals two major episodes previously invisible in the discontinuous MGM record: April 1985–January 1987 (21 months) and July 1993–October 1994 (15 months). The Marmara DMP projects a near-term vulnerability escalation from Low to High (2021–2049), driven by precipitation decline and the long investment cycles of perennial crops (olives, cherries) that cannot be rapidly adjusted.

Gemlik ★. ERA5 gap-filling reveals three previously invisible episodes in the 1992–2005 gap period: October 1993–October 1994 (12 months, peak = −1.66), February 2007–November 2008 (10 months, peak = −2.14), and the current 2025 episode (12 months, peak = −2.70). Total drought frequency rises to 14.8% on the filled series. Partial exposure to the Körfez WEI trajectory compounds the meteorological hazard with structural demand-side pressure on water availability.

Karamürsel ★★. The two-stage gap-filling (ERA5 + neighbour regression) now yields a 1983–2025 continuous series, revealing drought frequency of 15.2% and identifying the 2008 and 2014–2015 episodes previously invisible in the discontinuous MGM record. The main episode is revised to 38 months (1984–1987, peak = −3.09). Gap-filled values for Karamürsel carry reduced reliability (layered regression) and should be interpreted with appropriate caution. The structural WEI exposure — the most acute in the Marmara Basin — positions this borough as the most at-risk from long-term water scarcity, independent of meteorological drought trends.

2.3.1.2 Risk Assessment

The hazard assessment established that, under both emissions scenarios, drought frequency rises and the growing-season water balance deteriorates across all four boroughs, driven principally by increasing evaporative demand. This section translates that hazard into agricultural risk: the additional irrigation water it requires, the crop yield and revenue placed at risk where that water cannot be supplied, and the resulting socio-economic exposure. Consistent with the scenario framework (§2.2.3), all results are reported for RCP 4.5 and RCP 8.5 across three horizons — near-term (2021–2049), mid-century (2050–2074), and long-term (2075–2100).

Exposure: agricultural land cover and crop distribution

Risk materialises only where the hazard coincides with exposed assets. For agricultural drought the exposed asset is cultivated land, and its spatial extent and crop composition determine where a deteriorating water balance is translated into economic loss. The exposure layer is derived from the CORINE Land Cover 2018 inventory (Copernicus Land Monitoring Service) at 100 m resolution, clipped to each borough. CORINE resolves land use into standardised classes rather than individual crop species; for the present assessment the relevant distinction is between the agricultural classes — non-irrigated arable land, permanently irrigated land, rice fields, olive groves, fruit trees, vineyards, and complex or mixed cultivation — and the surrounding forest, shrub, urban and water classes. Figures 2-25 to 2-28 map this land cover for each borough.

Two of the region's signature crops are resolved explicitly by CORINE: rice (class 213) in Gönen and olive groves (class 223) in Gemlik and İznik. Other locally important crops — maize, watermelon, tomato, cherry, peach, fig and walnut — fall within the broader arable and mixed-cultivation classes and cannot be separated spatially by land cover alone. The crop-level risk analysis in the sections that follow therefore does not rely on CORINE to distinguish these crops; it applies the locally-calibrated crop coefficients developed in Phase 1 to each borough's crop set, using the land cover here to locate agricultural land. The exposure maps thus establish where farming occurs and which crop types dominate the landscape, framing the crop-specific risk quantified subsequently.

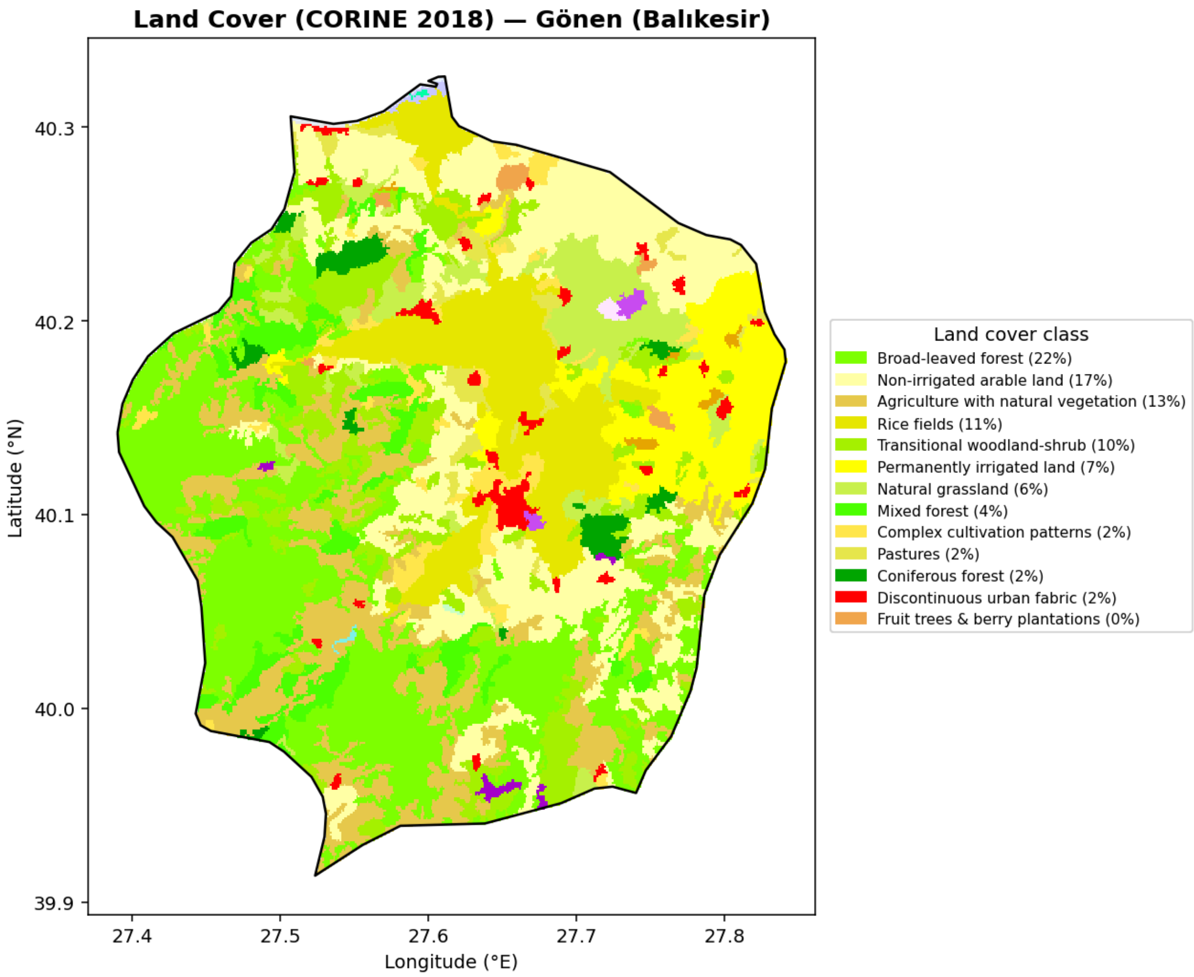

Figure 2-25: Agricultural land cover (CORINE 2018), Gönen (Balıkesir). Rice fields (11%) and non-irrigated arable land (17%) dominate the cultivated plain, with rice concentrated on the eastern lowlands. Percentages are shares of borough area.

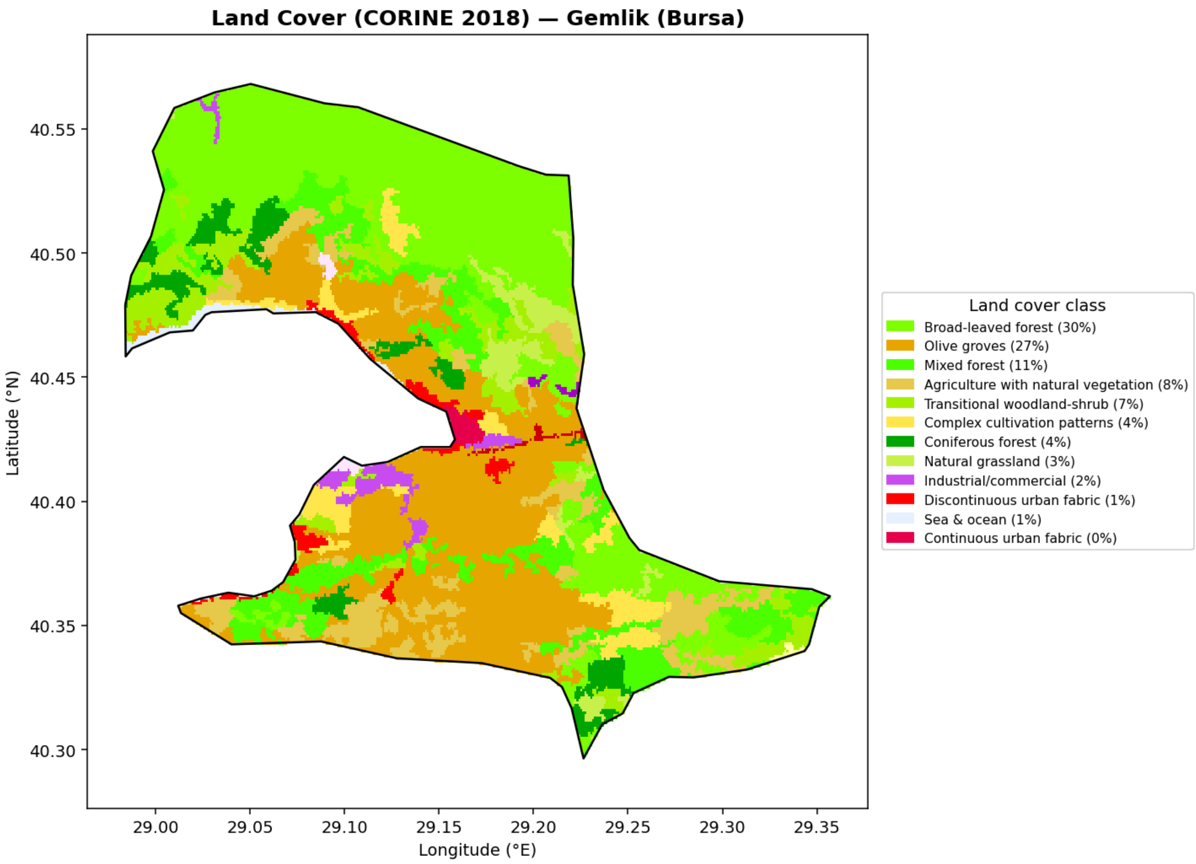

Figure 2-26: Agricultural land cover (CORINE 2018), Gemlik (Bursa). Olive groves (27%) form the principal agricultural cover, occupying the slopes that wrap around the Gulf of Gemlik. Percentages are shares of borough area.

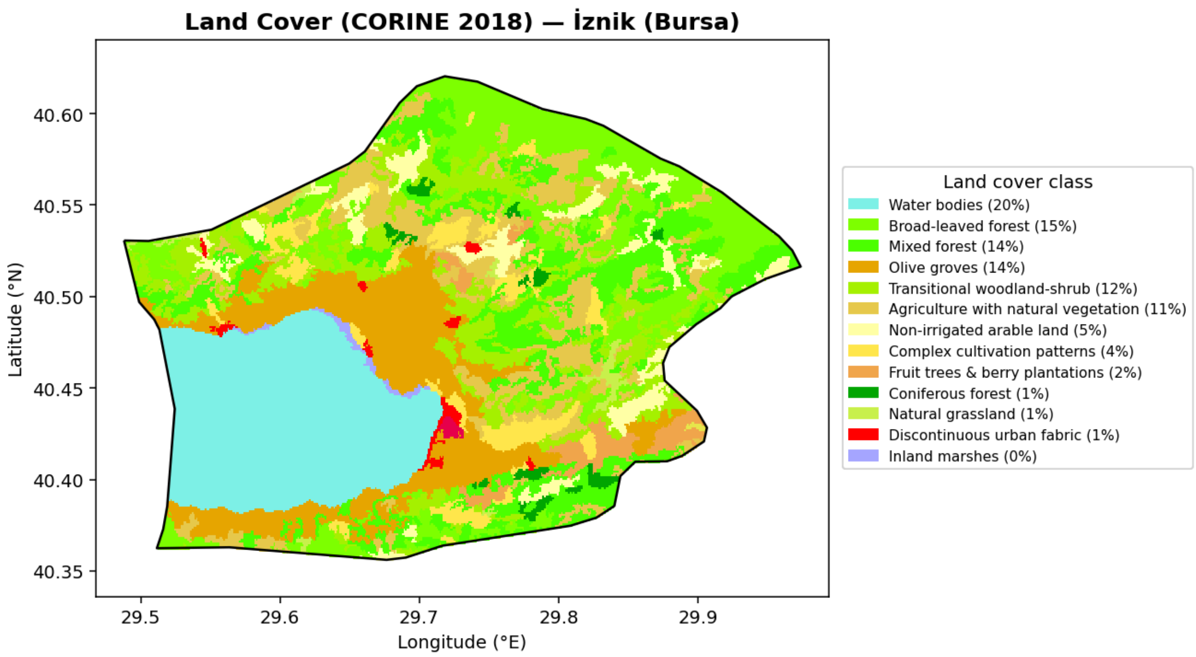

Figure 2-27: Agricultural land cover (CORINE 2018), İznik (Bursa). Lake İznik (20% water) is fringed by an olive-grove belt (14%) set within forest and mixed cultivation. Percentages are shares of borough area.

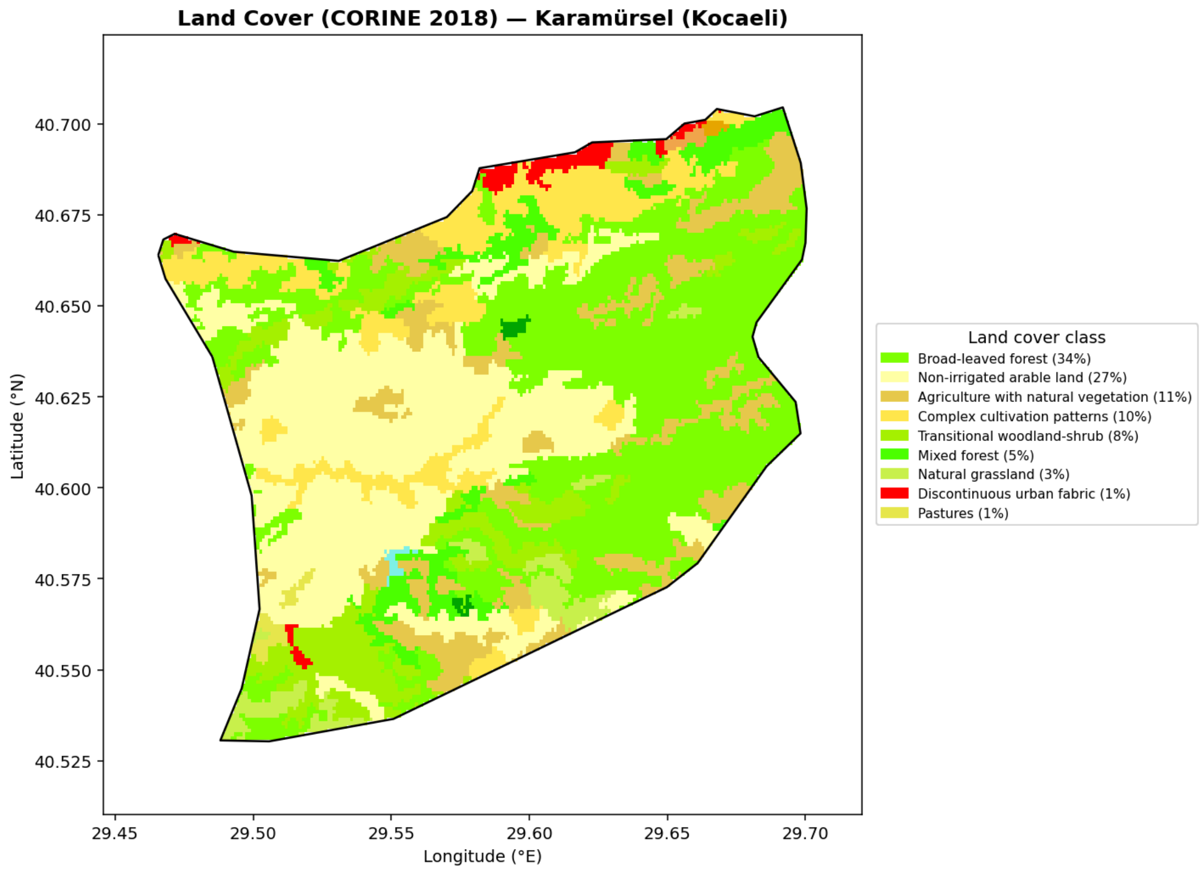

Figure 2-28: Agricultural land cover (CORINE 2018), Karamürsel (Kocaeli). Non-irrigated arable land (27%) is the dominant agricultural class, interleaved with broad-leaved forest. Percentages are shares of borough area.

The four boroughs present distinct exposure profiles. Gönen carries the largest cultivated footprint — more than half its area is agricultural — anchored by the irrigation-dependent rice plain in the east and extensive rainfed arable land, making it acutely exposed to growing-season water deficit. Gemlik's agriculture is dominated by perennial olive groves on the slopes around the gulf; this exposure is structurally different, since orchards cannot be replanted seasonally and drought stress therefore accumulates across successive years. İznik combines a substantial water body — Lake İznik, itself sensitive to the deteriorating water balance — with a lakeside olive belt and mixed cultivation. Karamürsel is dominated by rainfed arable land interleaved with forest. These contrasts — annual rice and arable in Gönen, perennial orchards in Gemlik and İznik, rainfed arable in Karamürsel — explain why a single hazard signal produces a different economic risk in each borough, and they motivate the crop-specific risk quantification that follows.

The four land-cover layers are provided as georeferenced GeoTIFF rasters (EPSG:4326, with an embedded CORINE colour table) together with the borough boundary file in the supporting documentation.

Vulnerability: agricultural sector susceptibility

Vulnerability is the third determinant of risk: for a given hazard and exposure, it captures how susceptible the agricultural system is to drought, combining its sensitivity — the structural dependence on water — with its adaptive capacity, the socio-economic and infrastructural means to cope. Rather than constructing an independent index, this assessment adopts the sectoral vulnerability rating of the Marmara Basin Drought Management Plan (2023), the most authoritative basin-scale source for the region. The DMP evaluates the agricultural sector's drought vulnerability at sub-basin level on a four-point scale (1 Low to 4 Very High), integrating indicators such as crop water dependency, the adequacy of irrigation infrastructure, inter-sectoral water competition, and the socio-economic profile of the rural population. Each borough is assigned the rating of its sub-basin — Gönen to the Gönen Stream sub-basin, İznik to the Lake İznik sub-basin, and Gemlik and Karamürsel to the Gulf (Körfez) sub-basin. Figure 2-29 maps the current rating.

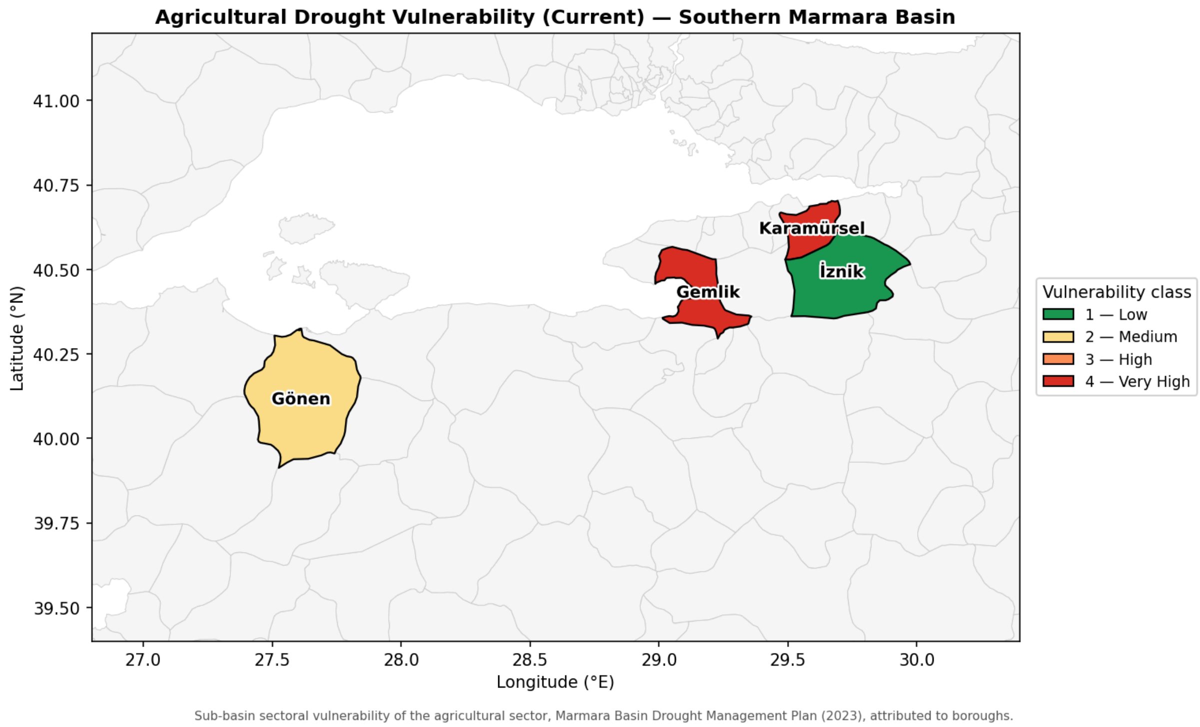

Figure 2-29: Agricultural drought vulnerability (current), Southern Marmara Basin. Each borough is shaded by the sub-basin sectoral vulnerability rating of the Marmara DMP (2023), from 1 (Low) to 4 (Very High).

The vulnerability pattern is, strikingly, the inverse of the hazard pattern. İznik — which carries the most severe hazard, with the deepest growing-season deficit and the highest drought frequency — currently records the lowest vulnerability (Low), indicating an agricultural sector structurally better able to absorb water stress. Conversely, Gemlik and Karamürsel, in the Gulf sub-basin, are rated Very High despite a comparatively milder hazard: their susceptibility is driven not by the climate signal but by acute inter-sectoral water competition, as agriculture around the industrialised Gulf of İzmit competes with dense urban and industrial demand. Gönen occupies an intermediate position (Medium), consistent with a large but relatively self-contained irrigated rice-and-arable economy. This divergence between where drought is most severe and where the sector is most vulnerable is precisely why risk cannot be inferred from hazard alone, and it motivates the integrated risk synthesis that follows, which combines the hazard, the exposed agricultural land, and this vulnerability layer.

Three caveats attach to this layer. First, the DMP reports vulnerability at sub-basin rather than borough resolution, so each borough inherits its sub-basin rating and finer socio-economic differentiation between boroughs within the same sub-basin is not resolved. Second, Gemlik lies near the boundary of the Gulf and Lake İznik sub-basins and is attributed here to the Gulf sub-basin, consistent with the Phase 1 assignment; were it attributed to the Lake İznik sub-basin its current rating would fall to Low. Third, the DMP provides a single vulnerability projection without an emissions-scenario split, so — unlike the hazard and risk layers — the vulnerability layer is not differentiated by RCP scenario; the current rating is used here as a static snapshot.

The vulnerability layer is provided as a vector dataset (GeoJSON, EPSG:4326, carrying the rating as an attribute) in the supporting documentation.

Method: from water deficit to economic risk

The risk is quantified through a water-balance chain rather than by applying the climatic deficit directly to yields. For each crop, growing-season water demand is computed as $ET_C = K_C \times ET_0$ over the crop's phenological calendar, using the region-specific crop coefficients (K_C) and yield-response factors (K_Y) developed for each borough in Phase 1 (Deliverable 1 regional crop tables). Effective rainfall is estimated by the USDA-SCS method, and the net irrigation requirement is the demand not met by rainfall. Because the projected rise in ET_0 increases ET_C while precipitation changes little, the irrigation requirement grows; the increase relative to the observed baseline is the climate-driven additional irrigation demand. Yield loss is then estimated only for the portion of that additional demand that cannot be met under constrained water availability, via the FAO-33 relation (relative yield loss = K_Y × relative evapotranspiration deficit) — consistent with the scenario assumption (§2.2.3) that irrigation infrastructure remains at current coverage absent active intervention. District-level production and producer-price data from TÜİK convert yield loss into revenue at risk. The figures reported are upper bounds, corresponding to the case in which none of the additional demand is met; realised impact is bounded below by zero where irrigation keeps pace with demand.

Additional irrigation demand

The deepening water deficit translates into a substantial increase in irrigation water demand (Table 2-9). Aggregated across the four boroughs, the additional requirement grows from roughly 10–13 million $m^3\ yr^{-1}$ in the near term to about 17 million $m^3\ yr^{-1}$ under RCP 4.5 and 34 million $m^3\ yr^{-1}$ under RCP 8.5 by the long term. Gönen and İznik account for the largest volumes — reflecting their extensive irrigated rice, maize, and tomato areas — and Karamürsel the smallest. Critically, this additional demand materialises precisely as regional water availability tightens (the WEI projections above) and against substantial projected population growth in the Körfez sub-basin (§2.2.3), sharpening competition between agricultural, municipal, and industrial users.

Table 2-9: Additional Annual Irrigation Demand by Borough (million $m^3\ yr^{-1}$, relative to observed baseline).

Borough	4.5 Near	4.5 Mid	4.5 Long	8.5 Near	8.5 Mid	8.5 Long
Gönen	3.9	2.9	5.8	2.7	3.4	14.1
Gemlik	3.4	3.3	3.5	1.9	1.9	7.6
İznik	5.7	6.1	7.6	5.0	5.9	11.0
Karamürsel	0.2	0.6	0.3	0.6	0.6	1.4
Total	**13.3**	**13.0**	**17.2**	**10.2**	**11.7**	**34.0**

Note: Values are the increase in net irrigation requirement above the 1965–2025 baseline, summed over the nine analysed crops. Near = 2021–2049, Mid = 2050–2074, Long = 2075–2100.

Yield and revenue at risk

Where the additional irrigation demand cannot be met, crop yields decline and farm revenue is lost (Table 2-10). The four-borough agricultural economy analysed here is worth approximately 12.5 billion TL annually (2025 producer prices). Under RCP 4.5 the share of this revenue placed at risk remains modest — around 7% even by the long term — but under RCP 8.5 it rises in the long term to about 13% — some 1,565 million TL (≈1.57 billion) — as an upper bound under the no-additional-irrigation assumption. The risk is therefore concentrated in the second half of the century and under the high-emissions pathway; near- and mid-term exposure stays below 9% under both scenarios.

The most instructive result is at the crop level. Olive carries the largest single share of revenue at risk (351 million TL under RCP 8.5, long term) despite being the least climate-sensitive crop in the set (K_Y = 0.60) — because of its very high value and volume in Gemlik and İznik. Paddy rice in Gönen (345 million TL) and tomato (334 million TL basin-wide, 257 million TL of it in İznik) follow closely, combining high water-sensitivity with large production. Economic risk is thus not a simple function of climate sensitivity: a drought-tolerant but high-value perennial can carry more revenue exposure than a sensitive but lower-value annual. At the borough level, İznik has by far the largest absolute exposure, reflecting its large, high-value horticulture, while Gönen carries the highest relative exposure among the annual-crop economies through its rice monoculture.

Table 2-10: Agricultural Revenue at Risk by Borough (upper bound; 2025 producer prices).

Borough	Ag. revenue (M TL)	RCP 4.5 Long (% at risk)	RCP 8.5 Long (% at risk)	RCP 8.5 Long (M TL)
Gönen	**2.818**	**8%**	**15%**	**427**
— Paddy rice				345
— Tomato				36
— Peach				13
— Cherry				10
— Walnut				7
— Watermelon				6
— Olive				6
— Maize				3
— Other crops				1
Gemlik	**2.433**	**5%**	**9%**	**210**
— Olive				176
— Walnut				15
— Cherry				9
— Fig				5
— Peach				3
— Other crops				2
İznik	**6.293**	**8%**	**13%**	**792**
— Tomato				257
— Peach				185
— Olive				168
— Cherry				111
— Walnut				50
— Fig				21
Karamürsel	**942**	**8%**	**15%**	**137**
— Cherry				55
— Tomato				39

Borough	Ag. revenue (M TL)	RCP 4.5 Long (% at risk)	RCP 8.5 Long (% at risk)	RCP 8.5 Long (M TL)
— Peach				20
— Walnut				11
— Watermelon				9
— Other crops				3
Total	**12.486**	**7%**	**13%**	**1.565**

Note: Revenue at risk = upper-bound yield loss (FAO-33, K_Y) × production × producer price, summed over crops, under the assumption that none of the additional irrigation demand is met. Realised loss is bounded below by zero where irrigation is maintained. Long = 2075–2100; M TL = million Turkish lira (2025 prices). Indented crop rows give each crop's RCP 8.5 long-term contribution and sum to the borough total (minor crops grouped as "Other crops").

Spatial yield-loss mapping by crop

The borough-level revenue-at-risk in Table 2-10 aggregates across crops, yet the underlying yield loss is crop-specific and spatially uneven. To resolve it, the FAO-33 yield-loss function — relative loss = $K_Y \times (1 - ET_a/ET_C)$, evaluated over each crop's phenological calendar with the Phase 1 regional K_C and K_Y coefficients — was applied on the 1 km grid for every scenario and period. Each crop's loss is anchored to its borough-level value, distributed by the growing-season water-deficit texture, and masked to agricultural land: rice to the CORINE rice class (213) and olive to the olive-grove class (223), with the remaining crops shown on each borough's general agricultural land, since CORINE does not resolve them as distinct cover types. Figures 2-30 to 2-34 present a representative selection at the most severe combination (RCP 8.5, long-term); the complete set of 54 layers (nine crops × six scenario–period combinations) is provided in the supporting documentation. A common 0–15% colour scale is used throughout, so losses are directly comparable across crops.

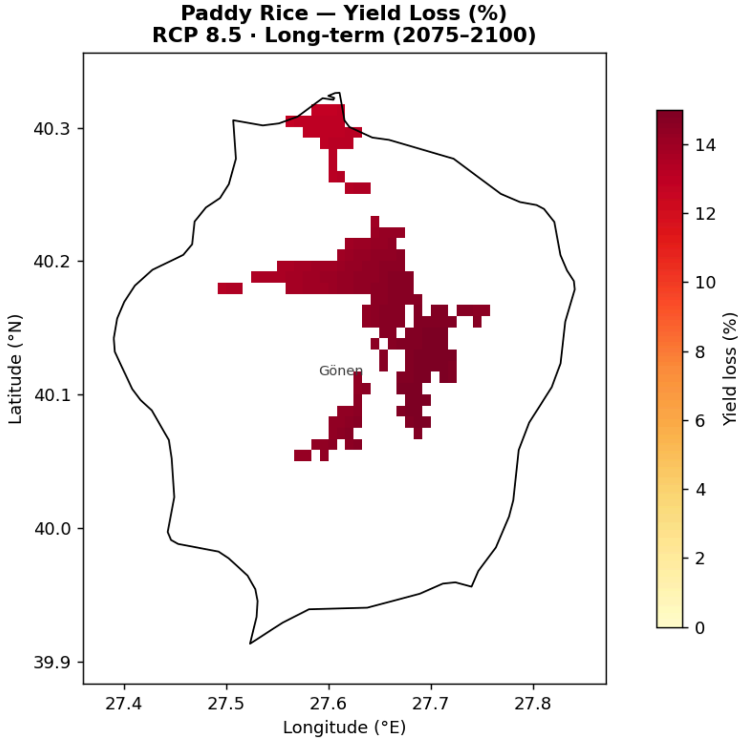

Figure 2-30: Paddy rice yield loss (%), Gönen, RCP 8.5 long-term (2075–2100); shown on CORINE rice fields.

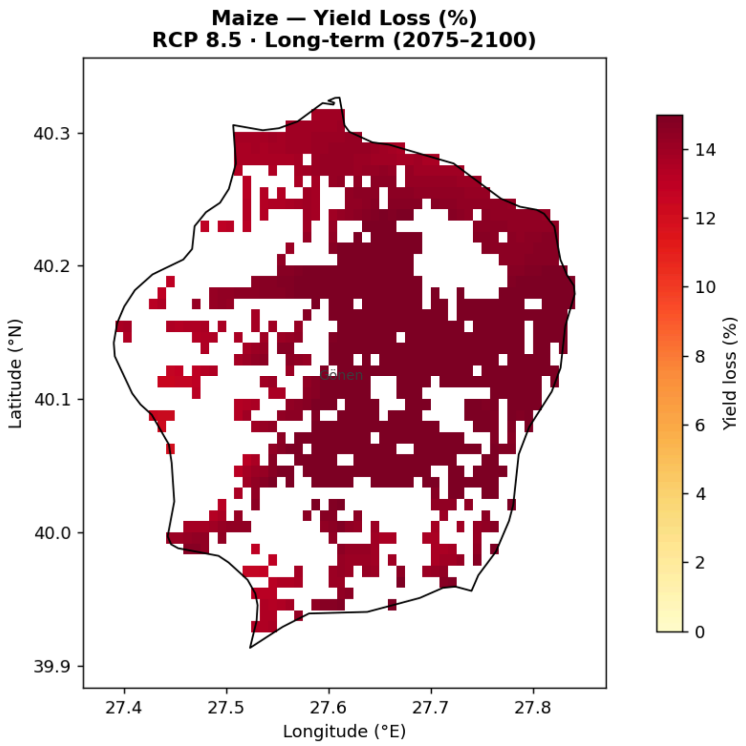

Figure 2-31: Maize yield loss (%), Gönen, RCP 8.5 long-term (2075–2100); shown on general agricultural land.

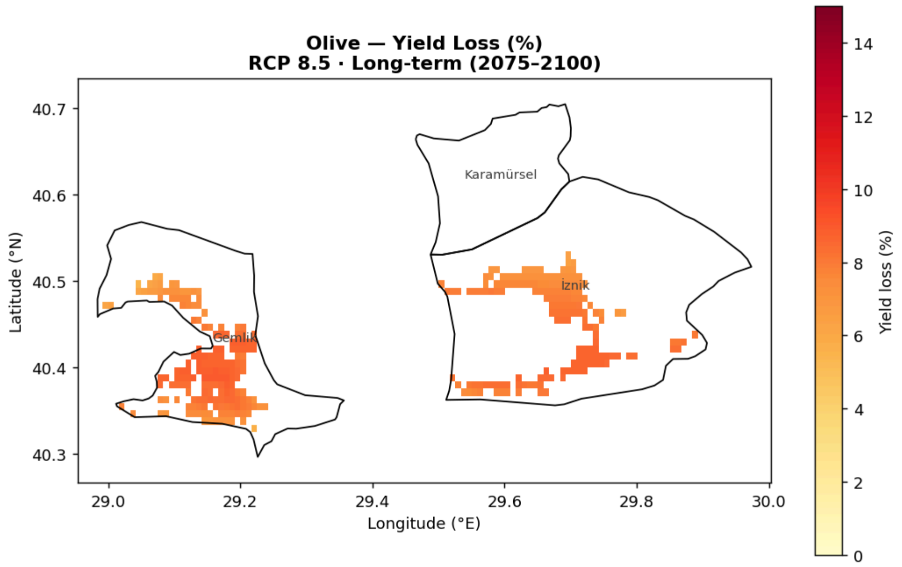

Figure 2-32: Olive yield loss (%), Gemlik and İznik, RCP 8.5 long-term (2075–2100); shown on CORINE olive groves.

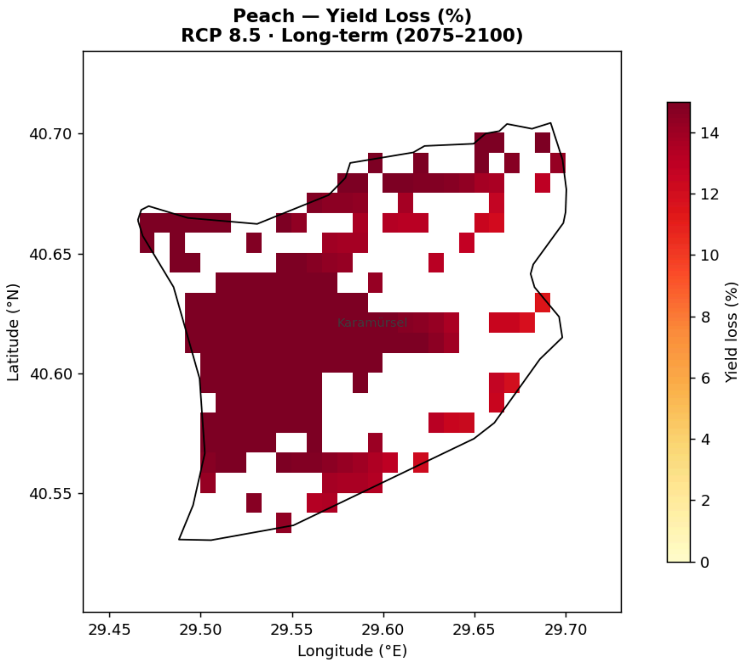

Figure 2-33: Peach yield loss (%), Karamürsel, RCP 8.5 long-term (2075–2100); shown on general agricultural land.

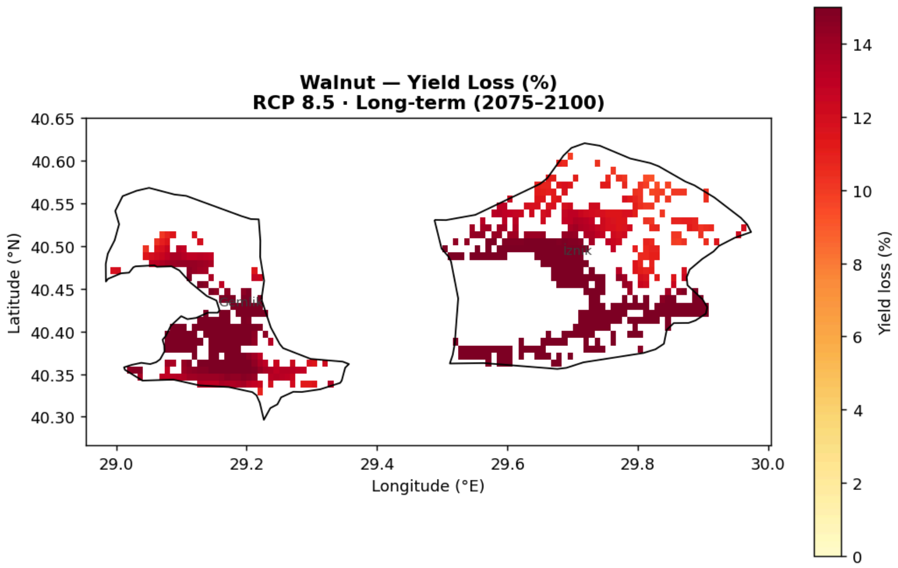

Figure 2-34: Walnut yield loss (%), İznik and Gemlik, RCP 8.5 long-term (2075–2100); shown on general agricultural land.

The crop maps make the role of the yield-response factor (KY) explicit. The water-intensive annuals and stone fruit — maize (KY 1.25), paddy rice (KY 1.20) and peach (KY 1.15) — sustain the largest relative losses (≈15–17% under RCP 8.5 long-term), followed by walnut and tomato; olive (KY 0.60) is the most resilient (≈8%). This is why, although olive carries the largest absolute revenue at risk, its per-hectare yield loss is comparatively modest. Within each borough the loss intensifies on the cells with the deepest growing-season deficit, so the maps locate where, not only how much. Because losses are defined relative to the present-day baseline, the historical case is zero by construction and the maps exist for the six future combinations only.

Integrated agricultural drought risk

The final step of the CRA framework combines the three determinants into a single agricultural drought risk. For each scenario and period the gridded hazard (drought frequency) is multiplied by the borough vulnerability rating (normalised to 0–1) on agricultural land only, giving a risk score that is comparable across all six combinations (Figures 2-35 to 2-40). Exposure enters as the agricultural mask, hazard as the spatially-resolved drought signal, and vulnerability as the DMP sub-basin rating. Because the vulnerability layer is a single current snapshot, the scenario and temporal evolution of the composite derives from the hazard component, with the vulnerability weighting held constant.

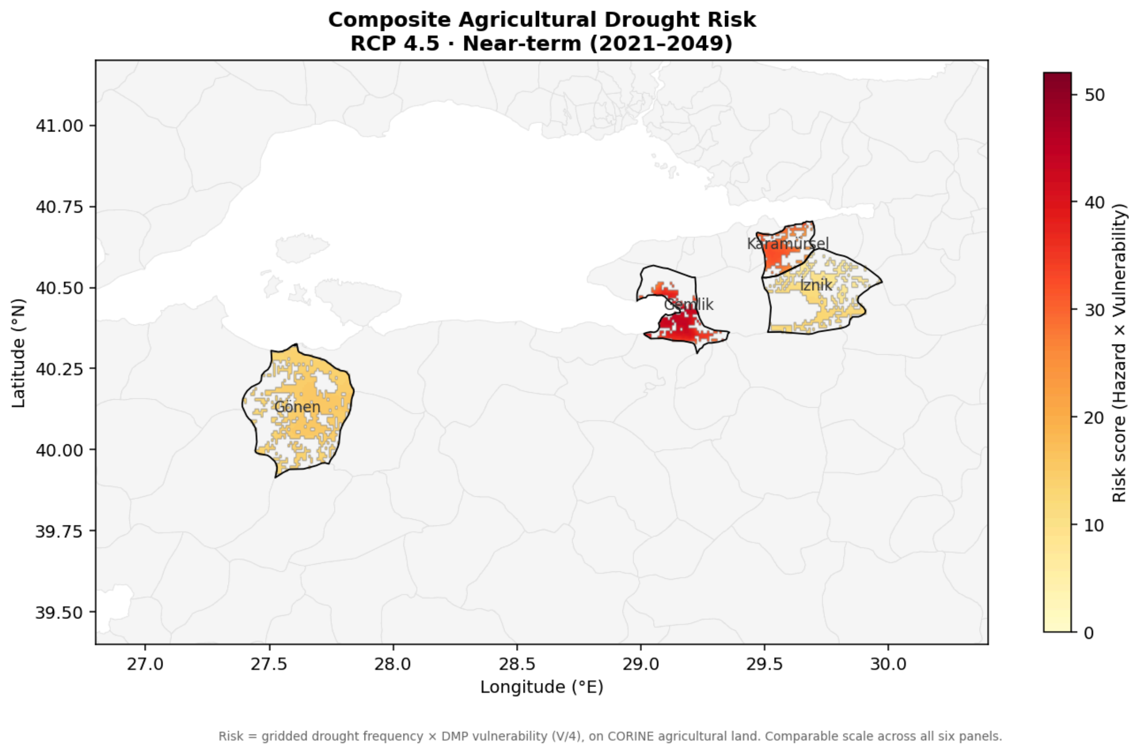

Figure 2-35: Composite agricultural drought risk, RCP 4.5 near-term (2021–2049). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

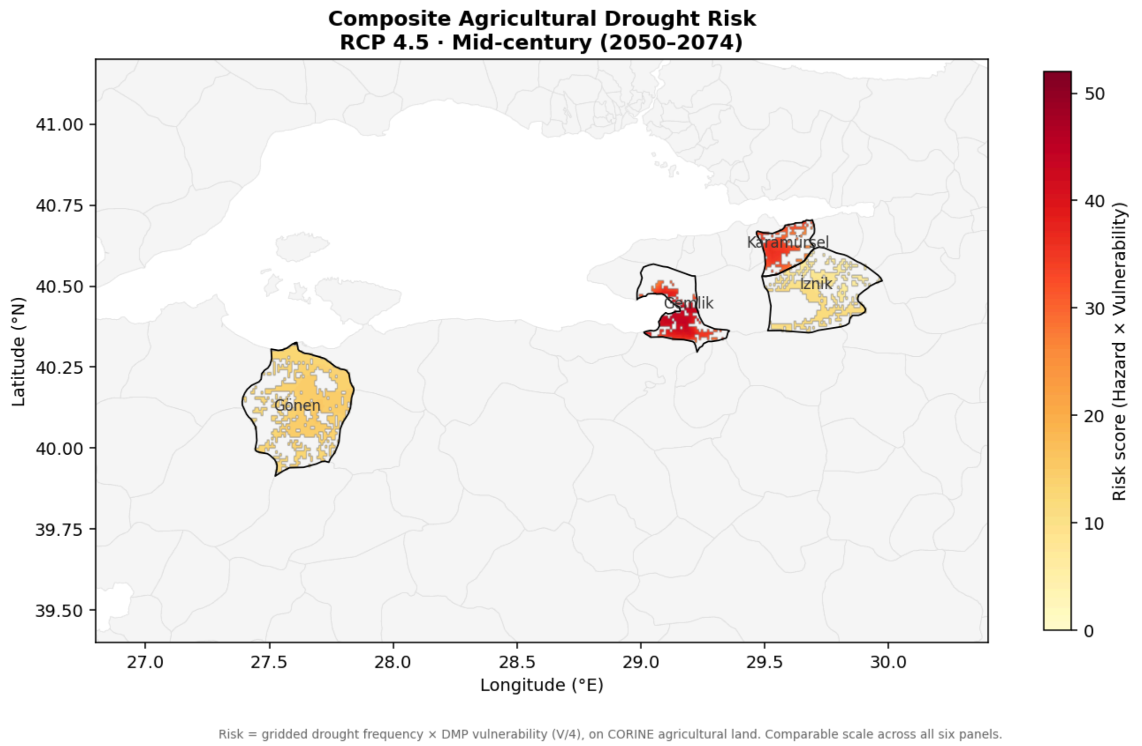

Figure 2-36: Composite agricultural drought risk, RCP 4.5 mid-century (2050–2074). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

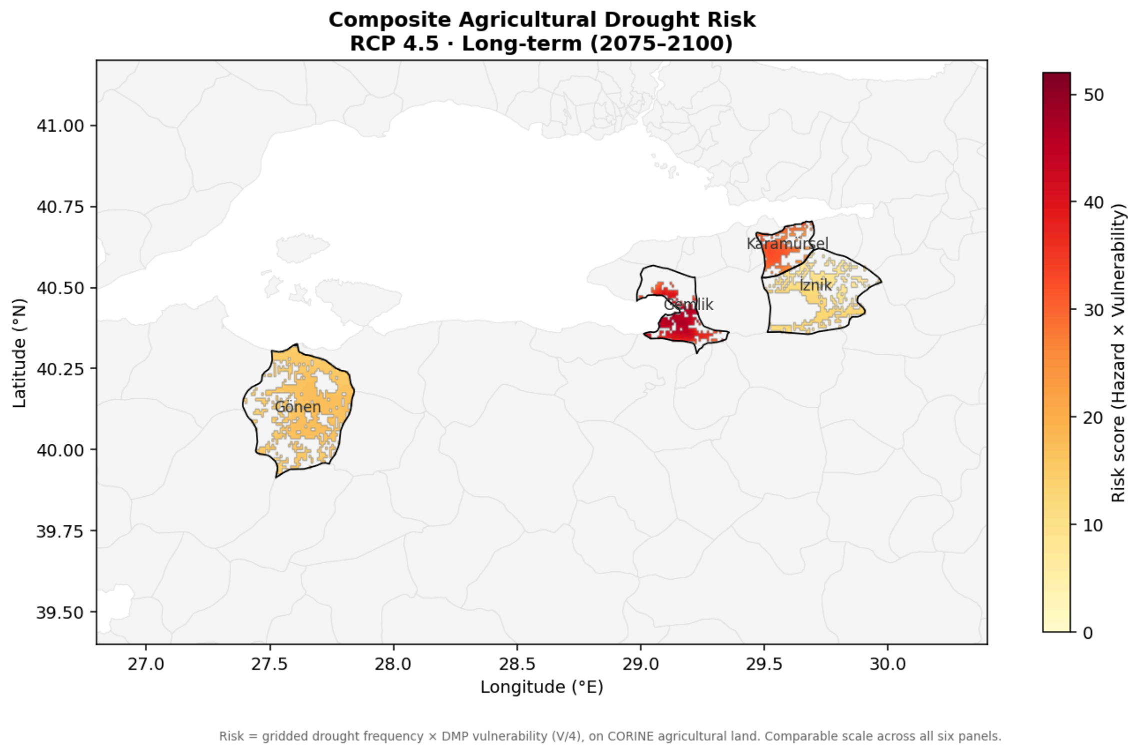

Figure 2-37: Composite agricultural drought risk, RCP 4.5 long-term (2075–2100). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

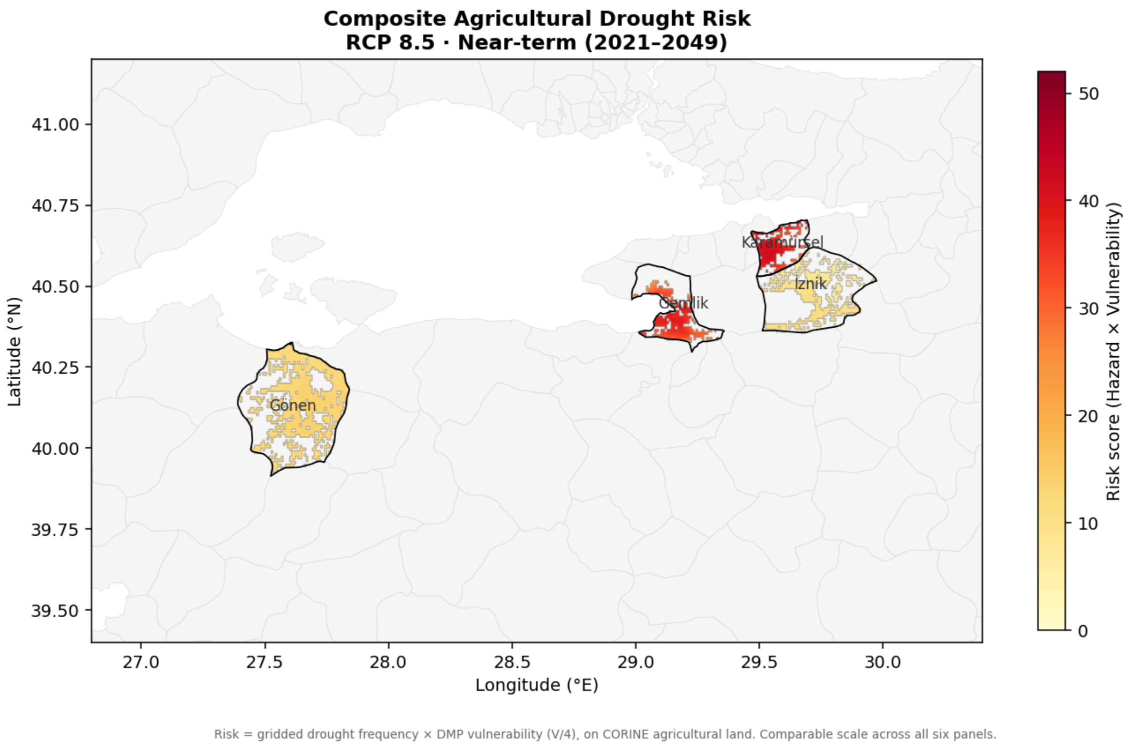

Figure 2-38: Composite agricultural drought risk, RCP 8.5 near-term (2021–2049). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

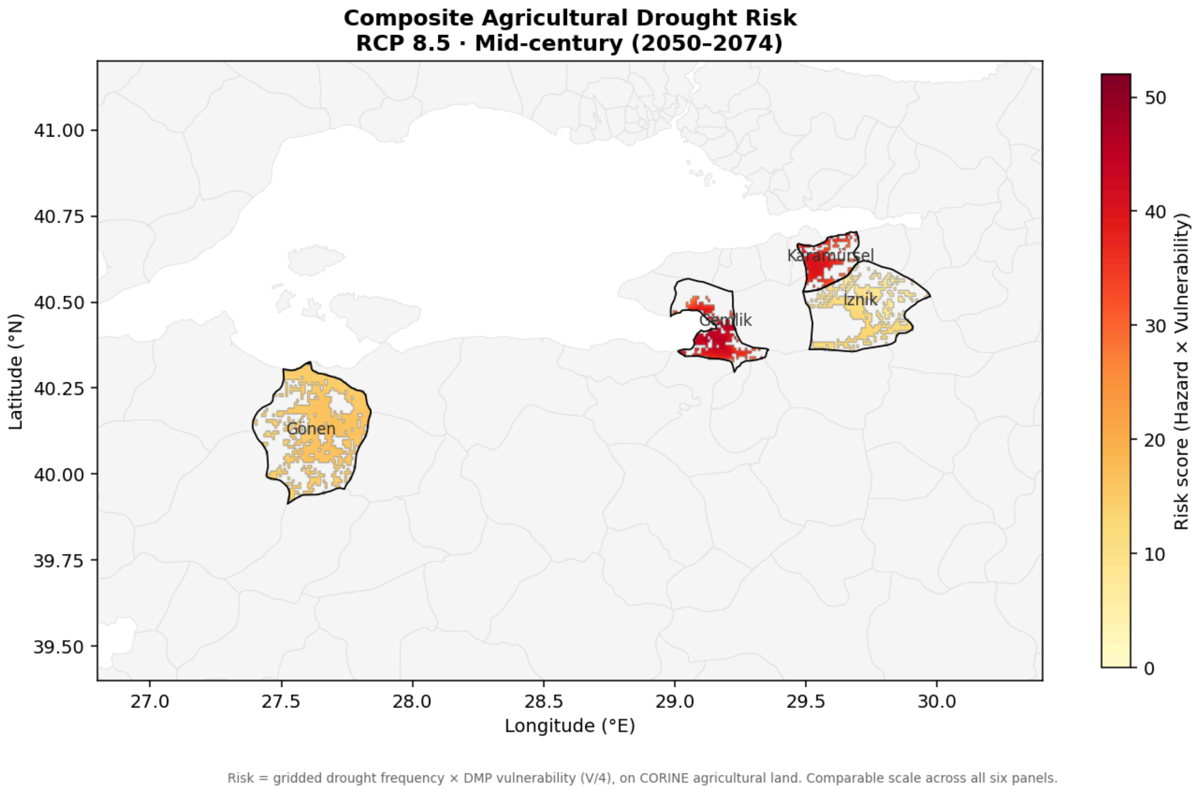

Figure 2-39: Composite agricultural drought risk, RCP 8.5 mid-century (2050–2074). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

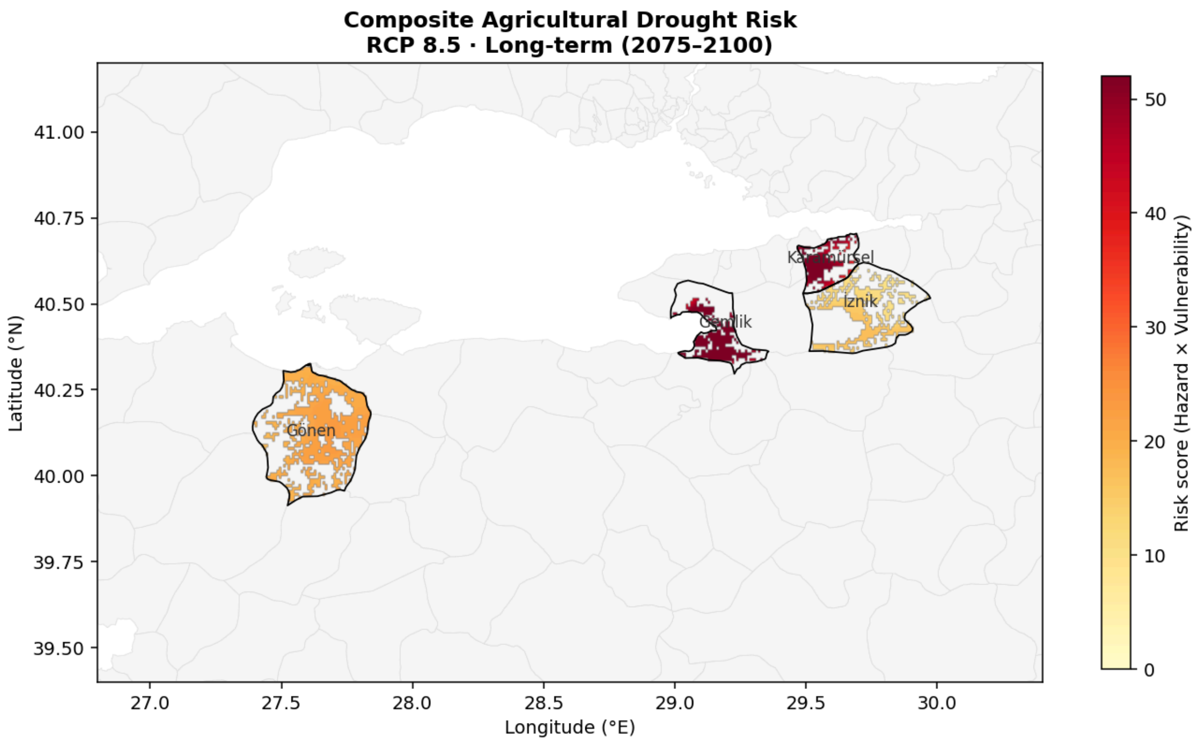

Figure 2-40: Composite agricultural drought risk, RCP 8.5 long-term (2075–2100). Risk = gridded drought frequency × vulnerability, on agricultural land; common scale across all six panels.

The composite resolves the tension between hazard and vulnerability identified earlier. İznik, despite carrying the most severe hazard, records the lowest integrated risk, because its agricultural sector is currently the least vulnerable. Conversely Gemlik and Karamürsel — in the Very-High-vulnerability Gulf sub-basin — emerge as the highest-risk boroughs even though their hazard is milder, as acute inter-sectoral water competition amplifies a moderate climate signal into a severe agricultural risk. Gönen occupies an intermediate position. Risk rises consistently from RCP 4.5 to RCP 8.5 and from the near term to the long term across all four boroughs, with the Gulf boroughs reaching the top of the scale by the late century under RCP 8.5. The pattern underscores the central message of the assessment: agricultural drought risk in Southern Marmara is governed as much by where the sector is least able to cope as by where the climate hazard is most severe.

All sixty risk layers (fifty-four crop-specific yield-loss maps and six composite-risk maps) are provided both as images and as georeferenced GeoTIFF rasters (EPSG:4326) in the supporting documentation.

Socio-economic implications

Three features make this revenue exposure socially consequential. First, the boroughs are agriculturally specialised — Gönen in rice, Gemlik and İznik in olive and tree fruit, Karamürsel in horticulture — so climate risk concentrates rather than diversifies across each local economy; a poor water year strikes the dominant livelihood directly. Second, even where irrigation maintains yields, meeting the higher water demand raises pumping, energy, and water-acquisition costs, compressing farm margins; this cost burden falls hardest on smallholders with limited capital and adaptive capacity. Third, the most exposed crops — olive and tree fruit — are perennials on multi-decade investment cycles that cannot be rapidly switched or relocated, so adaptation is slow and sunk costs are high.

These pressures compound with the socio-economic trajectory assumed in the scenario framework (§2.2.3): growing food-price volatility — more pronounced under RCP 8.5 — amplifies income instability, while rising population in the Körfez sub-basin increases non-agricultural water demand, leaving agriculture as the residual claimant on a tightening resource. Adaptive options exist — conversion to pressurised and deficit-irrigation systems, deficit-tolerant varieties and rootstocks, and agronomic water-conservation practices — but their uptake is constrained by infrastructure coverage, capital access, and the physical limits of water availability documented above. A fuller treatment of agricultural insurance penetration (TARSİM) and of the irrigation-cost and employment dimensions is identified as a priority for the key-risk and adaptation stages of the assessment.

Livelihoods and employment. Agriculture is not merely an economic sector in these boroughs but the basis of rural livelihoods, so the revenue at risk maps directly onto household income and employment. Where farming is the dominant source of rural income, a sustained 10–19% loss of agricultural revenue (Table 2-10) implies a comparable erosion of farm-household earnings and reduced demand for seasonal and permanent agricultural labour. Smallholders — with the least financial buffer and the weakest access to capital for irrigation upgrades — are the most exposed, so the adaptive capacity of the sector is unevenly distributed and the largest losses are likely to fall on those least able to absorb them. A full quantification of the farming population and agricultural workforce exposed would draw on TÜİK farmer-registry and employment statistics, recommended for the next phase.

Differential exposure across crop systems. The social consequences differ by crop system. In Gönen the rice and field-crop economy faces year-on-year yield variability that can be partly managed through annual planting decisions, but at the cost of income instability. In Gemlik and İznik the olive economy rests on perennial orchards representing decades of accumulated investment; drought stress there is cumulative and slow to reverse, so income loss is more persistent and recovery more costly. The concentration of olive value in these two boroughs — olive carries the single largest share of revenue at risk (351 million TL) — reflects a structurally specialised local economy with limited short-term substitutability.

Food security and adaptive capacity. Beyond local incomes, the four boroughs contribute to national food supply — Gönen is among Türkiye's principal rice-producing areas — so sustained drought-driven yield loss carries implications for regional food availability and price stability that extend past the boroughs themselves. The principal buffers against these outcomes — agricultural insurance (TARSİM), irrigation modernisation and water-allocation reform — exist but are unevenly taken up; gaps in drought coverage and in smallholder participation in insurance schemes represent a key adaptive-capacity deficit, and closing that gap is a natural focus for the resilience and adaptation planning addressed in Section 2.4.5.

Caveats

The risk figures should be read as a scenario-bounded upper envelope rather than a forecast. They assume no expansion of irrigation supply, stable crop composition and cultivated area, and constant 2025 relative prices, and they inherit the hazard-side caveats (single-model HadGEM2-ES projections and the Karamürsel grid offset). The FAO-33 Kʏ and crop-coefficient values are the borough-specific parameters established in Phase 1. Realised impacts will depend on the pace of irrigation modernisation, varietal adaptation, water-allocation policy, and price dynamics, all of which can move the outcome between the zero and upper-bound limits reported here.

2.3.2 Additional assessments based on local models and data

Hazard assessment

The hazard analysis was re-grounded in observed and national data. Station precipitation and temperature records from the Turkish State Meteorological Service (MGM) were combined with ERA5 reanalysis to gap-fill and back-extend the series, and cross-checked against the Copernicus European Drought Observatory Combined Drought Indicator. Standardised indices (SPI-3/6/12 and SPEI-3/9) were recomputed on these local series, and reference evapotranspiration was derived by the Hargreaves method. Future hazard was generated through a HadGEM2-ES delta-change procedure applied to a high-resolution CHELSA climatology, producing borough-level projections (Table 2-8) that were spatially downscaled to a ~1 km grid (Figures 2-11 to 2-24) — a resolution beyond that of the city-level EU toolbox. This local re-analysis exposed drought episodes not visible in the raw station record (notably via ERA5 gap-filling for Gemlik and Karamürsel) and identified İznik as the most hazard-exposed borough.

Risk assessment

The risk analysis was parameterised with local agronomic and statistical data. The regional crop tables of Deliverable 1 — supplying locally-calibrated crop coefficients (Kc) and yield-response factors (Ky) for the nine crops of the four boroughs, including crops absent from the standard toolbox (rice, watermelon, walnut, fig) — were applied within the FAO-33 yield-loss model on the 1 km grid. Exposure was resolved from CORINE 2018 land cover, vulnerability from the Marmara Basin Drought Management Plan (2023) sub-basin ratings, and revenue at risk from TÜİK production statistics and 2025 producer prices. The result is a locally-grounded risk product of 54 crop-specific yield-loss layers and 6 composite agricultural drought risk layers (Figures 2-30 to 2-40), with supporting GeoTIFF datasets — extending the preliminary, EU-data-based assessment of Deliverable 1 into the borough-resolved, locally-parameterised assessment required for Deliverable 2.

2.4 Key Risk Assessment Findings

2.4.1 Mode of engagement for participation

Stakeholder engagement specifically for risk evaluation has not yet taken place. By the design of the project the first two phases are analytical — Phase 1 produced the preliminary assessment and Phase 2 the regionalised CRA — and the structured participation of stakeholders, experts and priority groups begins in Phase 3. Phase 2 has, however, prepared for it by documenting the stakeholder map and risk-ownership structure (Section 2.1.5). The mode of engagement planned for evaluating these findings is a series of workshops with farmers, local producers, agricultural cooperatives and the government departments responsible for agriculture, in which the risk findings will be presented and ground-truthed and Community Adaptation Action Plans co-produced. Feedback gathered through that process will be reflected in subsequent revisions of the assessment.

2.4.2 Gather output from Risk Analysis step

Hazard. The historical record establishes a drying baseline — a 58-year minimum SPI-12 of −3.09 at Gönen (March 2025) and current agricultural drought frequencies of 16–18% across the four boroughs. Under the projections (HadGEM2-ES, delta-change), drought frequency rises to 41–54% and the growing-season water deficit deepens from −554…−703 mm to −703…−874 mm by the long term under RCP 8.5 (Table 2-8; Figures 2-9 to 2-24). İznik carries the most severe hazard signal.

Exposure. CORINE 2018 land cover (Figures 2-25 to 2-28) quantifies the agricultural assets exposed: rice (11%) and non-irrigated arable land in Gönen, olive groves dominating Gemlik (27%)

and fringing Lake İznik (14%), and rainfed arable land in Karamürsel (27%). The exposed crop set spans nine crops, ranging from highly water-sensitive annuals (maize, rice) to drought-resilient perennials (olive).

Vulnerability. The Marmara DMP sub-basin ratings (Figure 2-29) classify the agricultural sector's susceptibility as Very High in the Gulf sub-basin (Gemlik, Karamürsel), Medium in the Gönen Stream sub-basin, and Low in the Lake İznik sub-basin — a pattern driven by inter-sectoral water competition rather than by the climate signal itself.

Integrated risk. Two risk outputs are carried forward. First, crop-level yield loss (FAO-33; Figures 2-30 to 2-34): up to ≈15–17% for maize, rice and peach and ≈8% for olive under RCP 8.5 long-term, translating into a total agricultural revenue at risk of roughly 1.57 billion TL — about 13% of the four-borough agricultural economy — with olive carrying the largest single share (351 million TL) and İznik the largest absolute exposure (792 million TL) (Table 2-10). Second, the composite agricultural drought risk (Figures 2-35 to 2-40), integrating all three determinants, which identifies Gemlik and Karamürsel as the highest-risk boroughs and İznik — despite its severe hazard — as the lowest, owing to its low current vulnerability.

2.4.3 Assess Severity

Severity was assessed for both current and projected agricultural drought risk against the four-category scale of the CLIMAAX Key Risk Assessment Protocol — limited, moderate, substantial and critical — drawing on the consolidated outputs of Section 2.4.2. The judgement is differentiated by time horizon, scenario and, where the evidence supports it, by borough. In summary, the risk is assessed as moderate under current conditions and substantial by the late century under RCP 8.5, reaching the substantial–critical boundary in the Gulf sub-basin (Gemlik, Karamürsel).

Current conditions — moderate. Agricultural drought is already a recurrent feature of the region: current drought frequencies of 16–18% mean that roughly one growing season in five is drought-affected, and the historical record includes a 58-year minimum SPI-12 of −3.09 at Gönen (March 2025). Impacts to date are real but are largely absorbed by existing irrigation infrastructure, so financial damage remains intermittent rather than structural. The severity is therefore moderate — material impacts on a key economic sector, but not yet of a magnitude that threatens the viability of the agricultural economy.

Future risk — substantial under RCP 8.5. The projections mark a clear escalation. Drought frequency more than doubles, reaching 41–54%, and the growing-season water deficit deepens by up to roughly 170 mm, so water stress shifts from episodic to near-permanent. The associated agricultural revenue at risk — about 1.57 billion TL, some 13% of the four-borough agricultural economy — affects a region of national importance for food production, most notably Gönen as one of Türkiye's principal rice basins. Large agricultural areas are affected and the financial damage is significant and recurrent, placing the future risk in the substantial category. Under the more moderate RCP 4.5 pathway the revenue at risk is lower (around 7% basin-wide), keeping severity at the moderate–substantial range; the substantial rating is reached chiefly under RCP 8.5 and in the long term.

Spatial differentiation. Severity is not uniform. In the Gulf sub-basin (Gemlik, Karamürsel) a high hazard coincides with very high sectoral vulnerability, pushing severity to the substantial–critical boundary by the late century. İznik, despite the most severe hazard, registers a lower effective severity because of its low current vulnerability, while Gönen occupies an intermediate position in which the depth of the water deficit, rather than its frequency, is the dominant driver.

Irreversibility and cascading effects. Agricultural drought does not produce sudden catastrophic loss, but it carries two aggravating features. First, the region's perennial crops — olive, walnut, cherry and fig — cannot be replanted seasonally, so repeated drought years inflict cumulative, slow-to-reverse damage on orchards that may take several seasons to recover. Second, sustained yield and revenue loss cascades into rural livelihoods: erosion of farm incomes, pressure on agricultural employment and, at the extreme, land abandonment and rural out-migration, with knock-on effects for regional food supply. These pathways raise the effective severity of the future risk beyond what the direct yield figures alone convey.

This severity judgement is consistent with the prioritisation of agricultural drought as the principal climate risk for the Southern Marmara boroughs (Section 2.2.2), reflecting the region's economic dependence on agriculture and the limited substitutability of its most exposed crops.

2.4.4 Assess Urgency

Urgency was assessed against the four-category scale of the CLIMAAX Key Risk Assessment Protocol — no action needed, watching brief, more action needed, and urgent action needed. The agricultural drought risk is judged to require more action than is currently in place. A watching brief would understate a risk whose severity rises clearly over time and whose adaptation responses have long lead times; an 'urgent action' rating is reserved here for imminent, sudden-onset threats, which agricultural drought is not. The 'more action needed' rating reflects a risk that is not an immediate emergency but that demands proactive planning and investment beginning in the near term.

A risk that escalates over time. Severity changes markedly from current (moderate) to late-century (substantial; Section 2.4.3): drought frequency more than doubles, from 16–18% today to 41–54% under RCP 8.5, and the growing-season balance shifts from episodic deficit to structural deficit. A significant change of this kind, rather than a stable risk, is itself a primary signal of urgency.

Timing of impact versus timing of action. The most severe impacts are projected for the second half of the century, yet the near term (2021–2049) already shows elevated drought frequencies of roughly 28–41% in several boroughs and a measurably deepening deficit, so the trend is not a distant prospect but one already underway. Crucially, the responses that would reduce this risk — modernising irrigation networks, reforming inter-sectoral water allocation, shifting to drought-tolerant cultivars, and managing the transition of perennial orchards — all have lead times of years to decades. The window in which action remains effective is therefore the near term, well ahead of the period when impacts peak.

Slow onset rather than sudden shock. Agricultural drought is a slow-onset process, not a sudden event such as flooding. This carries two implications for urgency. It provides a window in which planned, incremental adaptation is feasible — an advantage that sudden hazards do not afford. But it also means impacts accumulate quietly and can be under-prioritised until entrenched, while the long lead times of water-management and perennial-crop responses leave little margin for delay. On balance, the slow-onset character argues for acting early rather than deferring.

Persistence. The projected deficit does not abate: by the late century the growing-season water balance is in near-permanent deficit across all four boroughs, so the risk has a high potential to persist rather than to resolve. A persistent, worsening risk reinforces the case for sustained rather than reactive action.

Urgency is highest in the Gulf sub-basin (Gemlik, Karamürsel), where substantial late-century severity combines with very high vulnerability and where competing urban and industrial water demand will only intensify; here the assessment edges toward urgent. Across the four boroughs, the overall judgement of 'more action needed' implies that adaptation planning should be initiated within the current programming period rather than deferred to later phases.

2.4.5 Understand Resilience Capacity

Resilience capacity was assessed against the four-category scale of the CLIMAAX Key Risk Assessment Protocol — low, medium, substantial and high — considering the financial, social, human, physical and natural means available to the boroughs to manage agricultural drought. Resilience is, in effect, the obverse of the vulnerability layer (Section 2.3.1): where sectoral vulnerability is high, coping capacity is correspondingly low. Overall the region's resilience capacity is assessed as medium, but it is strongly differentiated by borough — substantial in İznik, medium in Gönen, and low in the Gulf boroughs (Gemlik, Karamürsel).

Measures already in place. Several instruments contribute to current coping capacity. Financially, the national agricultural insurance scheme (TARSİM) provides a mechanism for compensating drought losses, although — as noted in Section 2.3.1 — its drought coverage and smallholder uptake remain partial. Physically, the irrigation networks operated by the State Hydraulic Works (DSİ) underpin the baseline water supply on which the region's annual and perennial crops depend, most notably the Gönen rice plain. Institutionally and in human-capacity terms, the Marmara Basin Drought Management Plan (2023) provides a governance framework with sub-basin action plans, and the present assessment — with Deliverable 1 — adds a borough-resolved evidence base to support local decision-making. Natural buffers, chiefly surface water (Lake İznik, the Gönen Çayı) and groundwater, remain available but are themselves under growing stress from the deepening water deficit.

Sufficiency of capacity. These measures are necessary but not yet sufficient to neutralise the projected risk. The baseline irrigation that absorbs current drought impacts is already operating close to the limit of available water in several boroughs, so it offers diminishing headroom against the deepening deficit; financial protection through insurance is incomplete; and the principal natural buffers are declining rather than expanding. The capacity that exists is therefore broadly adequate for the current, moderate level of risk, but is unlikely — without enhancement — to be adequate for the substantial late-century risk under RCP 8.5.

Spatial differentiation. The Gulf sub-basin (Gemlik, Karamürsel) has the lowest resilience: agriculture there competes for water with dense urban and industrial demand, so the very resource needed to cope with drought is contested and the option of expanding irrigation is constrained. İznik retains comparatively substantial capacity, reflecting its lower sectoral vulnerability and less acute water competition, while Gönen occupies an intermediate position in which a large irrigated economy provides real but water-limited buffering. This gradient mirrors, in reverse, the composite risk pattern: resilience is weakest precisely where risk is highest.

Implemented and planned interventions. The interventions most relevant to reducing the risk — modernising and pressurising irrigation networks to raise water-use efficiency, reforming inter-sectoral water allocation in the Gulf sub-basin, broadening drought-resilient cultivars and rootstocks, and extending insurance coverage to smallholders — are identified in the Drought Management Plan and in the present assessment, but are for the most part not yet implemented. Their development is the natural subject of the adaptation planning and stakeholder engagement scheduled for Phase 3. On balance, the medium rating reflects a region with a meaningful institutional and infrastructural base but a coping capacity that is unevenly distributed and not yet scaled to the projected risk.

2.4.6 Decide on Risk Priority

Risk priority integrates the three preceding judgements — severity (Section 2.4.3), urgency (Section 2.4.4) and resilience capacity (Section 2.4.5) — together with the absolute economic stakes, and assigns a priority to each borough. Because the assessment addresses a single hazard, prioritisation operates spatially, across the four boroughs and their sub-basins, rather than between competing hazards. The synthesis is summarised in the evaluation dashboard below and is consistent with the composite risk maps (Figures 2-35 to 2-40), which already integrate hazard, exposure and vulnerability.

Table 2-12: Risk evaluation dashboard — agricultural drought priority by borough.

Borough (sub-basin)	Severity	Urgency	Resilience	Risk priority
Gemlik (Gulf / Körfez)	Substantial–critical	More action needed	Low	High (1)
Karamürsel (Gulf / Körfez)	Substantial–critical	More action needed	Low	High (1)
Gönen (Gönen Çayı)	Substantial	More action needed	Medium	High (2)
İznik (Lake İznik)	Substantial hazard; lower integrated risk	More action needed	Substantial	Moderate (3) — preventive

Highest priority — the Gulf boroughs. Gemlik and Karamürsel carry the highest priority. They combine a substantial-to-critical late-century severity with the lowest resilience capacity, because agriculture competes for a contested water resource with urban and industrial demand. This is the configuration the composite risk maps identify as most severe, and it is where adaptation action is at once most needed and most constrained.

High priority — Gönen. Gönen ranks next. Its severity is substantial and its resilience only medium, but the decisive factor is the scale and strategic role of its agricultural economy: as one of Türkiye's principal rice basins it carries both a large absolute revenue at risk and a food-security significance extending beyond the borough. The risk here is driven by the depth of the water deficit on an irrigation-dependent crop system.

Moderate, preventive priority — İznik. İznik presents a more nuanced case: it carries the most severe underlying hazard yet the lowest integrated risk, because its agricultural sector is currently the least vulnerable and the most resilient. Its priority is therefore moderate but preventive — precisely because a severe hazard is currently held in check by strong coping capacity, the objective is to preserve that capacity, since any erosion of resilience would convert İznik's high hazard directly into high risk. Its large absolute revenue exposure, the highest of the four boroughs, reinforces the case for safeguarding rather than neglecting it.

Overall, agricultural drought is confirmed as the priority climate risk for the Southern Marmara boroughs, with action most urgent in the Gulf sub-basin, strategically important in Gönen, and preventive in İznik. This spatial prioritisation provides the basis for the monitoring and evaluation framework (Section 2.5) and for the adaptation planning and stakeholder engagement scheduled for Phase 3.

2.5 Monitoring and Evaluation

Monitoring and evaluation in the CLIMAAX framework is iterative: each phase is reviewed so that lessons, data needs and stakeholder input feed the next. This section reflects on the second phase — the regionalised Climate Risk Assessment — identifies what was learned and where difficulties arose, sets out the role of stakeholders, and describes the monitoring and communication arrangements that carry the work into Phase 3.

What was learned, and what worked well. The assessment confirmed a clear, policy-relevant message: agricultural drought risk in the four boroughs is governed as much by the agricultural sector's capacity to cope as by the severity of the climate hazard. The most hazard-exposed borough (İznik) is not the highest-risk one, while the Gulf boroughs (Gemlik, Karamürsel) emerge as the priority for action because high vulnerability compounds a moderate hazard. Methodologically, two choices proved especially valuable: building directly on the Deliverable 1 evidence base rather than re-deriving it, and grounding the analysis in local and national datasets (MGM, ERA5, CORINE, the Marmara DMP, TÜİK) parameterised for the boroughs. Re-grounding the hazard in observed records and downscaling it to a ~1 km grid gave a spatial resolution and local credibility that the city-level toolbox alone could not provide.

Difficulties encountered. The principal difficulties were data-related. Temperature records from MGM were not available on the original timetable, so reference evapotranspiration and the SPEI were derived from a high-resolution CHELSA climatology and ERA5 reanalysis rather than from station temperature; atmospheric-pressure and precipitation-record gaps required gap-filling and proxy stations; and the Marmara DMP reports vulnerability at sub-basin rather than borough resolution, requiring an explicit attribution step. Reliance on a single climate model (HadGEM2-ES) and on CORINE for crop exposure — which resolves only rice and olive as distinct classes — are recognised constraints documented in the limitations table (Table 2-11). None prevented a complete assessment, but each is a candidate for refinement.

Stakeholders and the role of Phase 3. By the design of the project the first two phases were analytical: Phase 1 established the preliminary assessment and Phase 2 produced the regionalised CRA. Structured stakeholder engagement has therefore not yet taken place, and no formal stakeholder feedback on the CRA has yet been gathered — Phase 2 documents the stakeholder map and risk-ownership structure in preparation for it. The substantive engagement begins in Phase 3, when the findings of this assessment will be taken to farmers, local producers, agricultural cooperatives and the government departments responsible for agriculture through a series of workshops. These workshops serve two purposes: communicating and ground-truthing the CRA findings with those who experience the risk directly, and co-producing Community Adaptation Action Plans (CAAPs). In monitoring-and-evaluation terms, this is the point at which the assessment is validated and refined against local knowledge and its findings are translated into agreed action.

Ensuring learning, data needs and ongoing monitoring. Learning is ensured by the iterative structure itself: the borough-resolved evidence base produced here is the explicit input to the Phase 3 co-production, and the workshops are designed to feed local knowledge back into the assessment. Several data improvements would strengthen future iterations — the outstanding MGM temperature series (for a fully station-based SPEI), TÜİK farmer-registry and agricultural-employment statistics and TARSİM insurance-coverage data (to make the socio-economic analysis quantitative), and periodic updates to land cover and to the Drought Management Plan. For ongoing monitoring, the indicators developed here — standardised drought indices (SPI/SPEI), the growing-season water deficit, drought frequency, irrigation demand, yield loss and revenue at risk — provide a ready monitoring set, and the Copernicus European Drought Observatory offers a near-real-time complement for tracking conditions between assessment cycles.

Communicating outcomes, resource use and value. The outcomes are communicated in three forms: this Deliverable 2 report for the funder and partners; the full set of georeferenced map layers (GeoTIFF and GeoJSON) for technical and GIS users; and, in Phase 3, accessible workshop materials for farmers, cooperatives and local authorities. The assessment used resources efficiently by reusing the Deliverable 1 parameters and open national and European datasets and by automating the mapping and document workflow, which allowed a large output — sixty risk layers and a borough-resolved report — to be produced without proportionate cost; the main inefficiency was time lost to the data-availability delays noted above. The principal value of the CRA lies in converting a recognised but diffuse concern into a spatially explicit, borough-prioritised evidence base that sharpens institutional understanding of where drought risk is concentrated and provides the targeting needed to direct adaptation planning and investment in the next phase.

2.6 Work plan Phase 3

Phase 3 constitutes the participatory and applied phase of the AGROSHIELD project. Its central purpose is to translate the analytical findings of Phase 2 into policy-relevant, co-produced Community Adaptation Action Plans (CAAPs) at the borough level — a task that requires structured engagement with the stakeholders who are most directly affected by agricultural drought and most responsible for responding to it.

The main activity of Phase 3 is a series of stakeholder workshops, one per target borough, organised in coordination with and hosted by the four borough municipalities: Gönen (Balıkesir), Gemlik (Bursa), İznik (Bursa), and Karamürsel (Kocaeli). Each workshop will bring together both public-sector and private-sector participants. Public stakeholders will include representatives of the relevant District Directorate of Agriculture, the borough municipality, and — where feasible — the Provincial Directorate of Agriculture. Private stakeholders will include local farmers, particularly small-scale producers who bear the highest drought exposure, and agricultural cooperatives, which serve as the organised voice of the farming communities.

The workshops will serve three interconnected functions. First, awareness-raising: the Phase 2 risk findings — borough-level drought hazard characterisations, crop-specific yield loss projections, socio-economic impact estimates, and the risk priority ranking — will be presented to participants in accessible, locally meaningful terms. This is the first time borough-resolution evidence on agricultural drought risk will be placed directly before the communities it concerns. Second, ground-truthing: participants will be invited to validate the findings against local knowledge and provide qualitative context on the lived experience of recent drought events, current adaptive practices, and real-world constraints that shape farmers' ability to respond. Third, co-production: drawing on the presented evidence and the feedback gathered through roundtable discussion with key stakeholders and experts, the workshops will provide the foundation for drafting the CAAPs. The CAAPs will identify priority adaptation measures for each borough, matched to its specific risk profile and institutional context, and will outline the roles of the relevant actors in their implementation.

Those aspects of agricultural drought risk that fall outside the scope of Phase 3 include further quantitative modelling or additional data collection; these analytical tasks were completed in Phase 2. Phase 3 will also not extend the assessment to additional boroughs or hazards beyond the four-borough, single-hazard scope established in Phase 1. The focus is exclusively on translating and applying the existing evidence base.

3 Conclusions — Phase 2 Climate Risk Assessment

This second-phase deliverable has produced a regionalised Climate Risk Assessment of agricultural drought for the four Southern Marmara boroughs of Gönen, Gemlik, İznik and Karamürsel. Building on the preliminary assessment of Deliverable 1, it deepened every layer of the CLIMAAX risk framework — hazard, exposure, vulnerability and risk — by replacing EU-level, city-scale inputs with local and national data (MGM, ERA5, CORINE, the Marmara Basin Drought Management Plan and TÜİK) and by resolving the analysis to a ~1 km grid. The result is a borough-level, spatially explicit and locally parameterised evidence base, accompanied by sixty georeferenced risk layers.

The hazard analysis confirmed a drying trajectory. Against a historical baseline that already includes severe episodes — a 58-year minimum SPI-12 of −3.09 at Gönen — agricultural drought frequency is projected to rise from 16–18% today to 41–54% by the late century under RCP 8.5, and the growing-season water deficit deepens from episodic to near-permanent, driven principally by rising evaporative demand rather than by declining rainfall. İznik carries the most severe hazard. The exposure layer mapped the assets at stake: an irrigation-dependent rice and arable economy in Gönen, perennial olive groves dominating Gemlik and fringing Lake İznik, and rainfed arable land in Karamürsel.

The decisive contribution of the assessment is the integration of vulnerability. Drawing on the Drought Management Plan, the analysis showed that the sector's susceptibility is highest in the Gulf sub-basin (Gemlik, Karamürsel) and lowest in İznik — a pattern set by inter-sectoral water competition rather than by the climate signal. Combined into a composite risk, this yields the central finding of the report: agricultural drought risk in Southern Marmara is governed as much by where the sector is least able to cope as by where the hazard is most severe. İznik, despite the most severe hazard, carries the lowest integrated risk, while the Gulf boroughs, with a milder hazard but very high vulnerability, carry the highest. In economic terms the upper-bound revenue at risk approaches 1.57 billion TL — some 13% of the four-borough agricultural economy — by the late century under RCP 8.5, with olive the single largest exposure.

On this basis the risk was judged moderate today and substantial by the late century, reaching the substantial–critical boundary in the Gulf; its urgency was assessed as requiring more action than is currently in place, given a slow-onset hazard whose adaptation responses have long lead times; and resilience capacity was found to be medium overall but lowest in the Gulf. The resulting risk priority is clear: action is most urgent in Gemlik and Karamürsel, strategically important in Gönen as a nationally significant rice basin, and preventive in İznik, where strong coping capacity currently holds a severe hazard in check and must be preserved.

Several challenges were addressed in the course of the work. Gaps in the meteorological record were filled through ERA5 reanalysis and a high-resolution climatology, allowing reference evapotranspiration and the SPEI to be derived despite the unavailability of station temperature; the mismatch between sub-basin vulnerability data and borough units was handled by explicit attribution; and crops absent from the standard toolbox were incorporated through the regional crop tables. Other limitations remain open: the projections rest on a single climate model, CORINE resolves only rice and olive as distinct crop classes, and a fully quantitative socio-economic analysis awaits farmer-registry, employment and insurance data. These are documented transparently and form the agenda for refinement in subsequent work.

The assessment is analytical by design, and its findings now pass to Phase 3, in which they will be taken to farmers, local producers, cooperatives and the responsible government departments through workshops that will both validate the results against local experience and co-produce Community Adaptation Action Plans. In converting a recognised but diffuse concern into a spatially explicit, borough-prioritised evidence base, this deliverable provides the targeting that the next phase of adaptation planning and investment requires.

4 Progress Evaluation

This deliverable is the second phase of the AGROSHIELD Climate Risk Assessment. It advances directly from Phase 1 by replacing the EU-level, city-scale CLIMAAX toolbox outputs with a locally grounded, borough-resolution assessment built on MGM station data, ERA5 reanalysis, CORINE land cover, the Marmara Basin Drought Management Plan, and TÜİK production statistics. The sixty georeferenced risk layers and the structured socio-economic impact analysis produced in Phase 2 are the direct inputs to the Phase 3 participatory process.

The key performance indicators and milestones achieved in Phase 2 are summarised in the tables below.

Table 4-1 Overview key performance indicators

Key performance indicators	*Progress*
CLIMAAX Agricultural Drought Workflow Implemented	Agricultural Drought Workflow implemented successfully
Regional High Resolution Risk Assessment Conducted	Regional High Resolution Risk Assessment implemented successfully under Phase 2
Organization of Community Workshops for Adaptation Planning	Workshops will be organized under Phase 3
Community Adaptation Action Plans Developed	CAAPs will be developed under Phase 3
Stakeholders Actively Engaged	Data-collection engagement with MGM, RTMAF-GDWM, and District Directorates of Agriculture completed; broader stakeholder groups to be engaged in Phase 3

Table 4-2 Overview milestones

Milestones	*Progress*
M1: CLIMAAX Agricultural Drought Workflow Implemented	Completed
M2: CLIMAAX Workshop in Barcelona Attended	Completed
M3: High Resolution Climate Risk Assessments Implemented	Completed
M4: Community Adaptation Action Plans Drafted	To be completed under Phase 3
M5: CLIMAAX Workshop in Brussels Attended	To be completed under Phase 2
M6: Final Consultations and Policy Recommendations and Finalization of CAAPs	To be completed under Phase 3

5. Supporting Documentation

The outputs produced during this phase are listed below, grouped by type. The complete set of spatial layers and datasets is to be deposited in the project's Zenodo repository, arranged in the same order.

Main Report.

- Deliverable 2 report (PDF), incorporating the full Climate Risk Assessment with forty embedded figures and the supporting tables.

Datasets.

- marmara_agri_droughts_hazard_cdi.xlsx
- marmara_agri_droughts_exposure_crop_coefficients.xlsx
- marmara_agri_droughts_hazard_spei.xlsx
- marmara_agri_droughts_hazard_temperature_et0.xlsx
- marmara_agri_droughts_vulnerability_producer_prices_tuik.xlsx
- marmara_agri_droughts_vulnerability_production_statistics_tuik.xlsx
- marmara_agri_droughts_hazard_precipitation_spi.xlsx

Spatial Data Layers (Images and Georeferenced Rasters).

A. **Exposure**

- gonen_agri_droughts_exposure_landcover_clc2018_raster.tif
- gonen_agri_droughts_exposure_landcover_clc2018_raster.png
- gemlik_agri_droughts_exposure_landcover_clc2018_raster.tif
- gemlik_agri_droughts_exposure_landcover_clc2018_raster.png
- iznik_agri_droughts_exposure_landcover_clc2018_raster.tif
- iznik_agri_droughts_exposure_landcover_clc2018_raster.png
- karamursel_agri_droughts_exposure_landcover_clc2018_raster.tif
- karamursel_agri_droughts_exposure_landcover_clc2018_raster.png

B. **Hazard**

- marmara_agri_droughts_hazard_water_deficit_historical_raster.tif
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C. Risk

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D. Vulnerability

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