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Multi-dimensional Assessment of the Water-Food Nexus in a Semi-Arid Watershed

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Abstract
The availability of water is crucial for ensuring global food security, particularly in regions most affected by climate change. Understanding the trade-offs and synergies between the availability of water and the food sector is crucial for ensuring water and food security. This study employs a holistic approach to aid decision-makers in the water and food sectors for developing sustainable strategies in Upper Sakarya Watershed located in a semi-arid region dominated by agricultural activities. Several agricultural water management scenarios are assessed based on various criteria: *i)* water budget at the basin scale, *ii)* economic feasibility, and *iii)* stakeholder opinions. The WEAP model was used to evaluate the hydrological analysis of management scenarios. In addition, socioeconomic analyses and stakeholder perspectives on the management scenarios are incorporated into the integrated investigation of the water-food nexus. The most effective scenario in terms of water consumption relative to the baseline scenario can result in a reduction of 60 million m^3 of irrigation water per year. According to the economic analysis, significant contributions to the farmer's income by €5.4–13.5 per m^3 of water use compared to reference scenarios can be achieved by the most feasible scenarios. The most effective scenarios show parallel trends between water conservation and positive economic contribution. Moreover, stakeholders anticipated that the implementation and sustainability of the most effective scenarios can be vulnerable to technical, practical, and political constraints. This holistic approach demonstrated the need for a multi-dimensional assessment of the water-food nexus that incorporates the perspective of stakeholders.

Keywords Water-Food Nexus · WEAP · Socio-economic analyses · Sustainable agriculture · Stakeholder perspective · Irrigation water use

1 Introduction

Agriculture, the most water-intensive economic sector, necessitates accelerated efforts to achieve Sustainable Development Goals related to water scarcity (UN-Water 2021a), as irrigation already uses 72 percent of all freshwater withdrawals (FAO 2021). Wealth and popu-

Extended author information available on the last page of the article lation growth will not ease the pressure on water withdrawals; instead, they will increase water consumption as agricultural production increases (UN-Water 2021b). In 2023, 28.9% of the global population (2.33 billion people) experienced moderate or severe food insecurity, including over 864 million facing severe food insecurity, reflecting the persistent impact of the COVID-19 pandemic and the lack of considerable progress since the sharp rise observed between 2019 and 2020 (FAO, et al. 2024). In addition, climate change models predict a 1–180 million increase in the number of people at risk of hunger compared to a world without climate change (IPCC 2019). Water is inextricably linked to many other goals, including SDG 2, Zero Hunger, so effectively managing limited water resources will be critical to fully achieving the SDGs (FAO 2020). This necessitates the implementation of an approach such as Water-Food Nexus that facilitates the understanding of the interdependence between the water and food sectors and provides potential solutions to minimize the trade-offs between them.

The nexus approach systematically analyses the interaction between the environment and human activities and leads to integrated natural resources management across various sectors and scales (FAO 2014). Multidirectional and complex interactions exist between the water-food nexus components. Water is used in the production, processing, preparation, and transportation of food; however, agriculture, aquaculture, and other food systems may have detrimental effects on the quality and quantity of water. Each of these bilateral relationships is impacted by climate change, economic and population growth, regulations/governance, and technological advancement.

Over the last decade, WEF Nexus has emerged as an integrated approach to address issues that threaten water, energy, and food security. Although similar holistic approaches such as integrated resource management have a long history, WEF nexus framing, which concerns resource-related problems in water, energy and food systems, accelerated in the late 2000 s (Leck et al. 2015). Due to various global crises regarding food security that emerged in 2008, the interlinkages between the WEF nexus were brought into focus (Aboelnga et al. 2018).

The nexus of water and food often focuses on the efficient use of water required to produce food; in other terms investigates pathways to increase the product yield while reducing the water used. Food systems may potentially have negative impacts on the quality and quantity of water. The research on the water-food nexus focuses primarily on enhancing the positive impact on the environment or ecology (Campana et al. 2022; Yao et al. 2021; Lee et al. 2020; McNally et al. 2019; Xu et al. 2019). Many recent studies examine the nexus from both environmental and economic perspectives (Zhang et al. 2023; Song et al. 2022; Guo et al. 2022; Shen et al. 2022; Yue and Guo 2021; Chen et al. 2020), but few studies integrate socio-economic or political/regulatory/governance dimensions (Francisco et al. 2023; Karamian et al. 2023; Correa-Cano et al. 2022; Cui et al. 2022; Caputo et al. 2021; Zeng et al. 2019). Several studies in the literature on the Nexus emphasize the importance of integrating these dimensions to achieve sustainable development goals (Hamidov and Helming 2020; Gevelt 2020; Simpson and Jewitt 2019). Moreover, in the recent literature, there are various studies that covered Water-Food interactions through WEF Nexus approach. Asadabadi et al. (2025) optimized the primary crops through the WEF nexus using pressure-state-response approach, Dias et al. (2025) used WEAP model to simulate two Brazilian watersheds for the 2020 to 2050 period and developed sustainability index in which total production of foods (kg) for reference crops, water consumptions and energy indicators used, and Khosravi et al. (2024) developed a model to achieve sustainable agriculture based on WEF Nexus.

Although the water-food (and broader WEF/FEW) nexus is widely used to frame agricultural sustainability, existing nexus evaluations in water-stressed and developing regions often do not represent the coupled interactions among environmental impacts, socioeconomic outcomes, and governance structures in a single, empirically grounded assessment. Multiple syntheses converge on three recurring weaknesses.

First, nexus assessments remain methodologically and disciplinarily fragmented. Albrecht et al. (2018), reviewing 245 nexus studies, report that methods frequently fall short of capturing the linkages they conceptually purport to address; only about one-quarter of studies use social-science methods and only about one-quarter combine methods from diverse disciplines. Hamidov and Helming (2020), in a review of 194 irrigated-agriculture studies, similarly conclude that most work approaches the nexus from a single foregrounded category (socioeconomic, technological, or environmental) rather than integrating them. In practice, this fragmentation encourages evaluations where biophysical performance (e.g., irrigation efficiency, yields, water withdrawals) is optimized while distributional impacts, behavioural constraints, and institutional feasibility are treated as assumptions rather than modelled drivers.

Second, the socioeconomic dimension is often underspecified at the scales where water–food trade-offs are experienced. Household- and community-level studies still tend to overemphasize models and quantitative process representation while paying limited attention to social factors (Itayi et al. 2021). Region-specific reviews also note limited emphasis on socioeconomic perspectives and underrepresentation of social inclusion in developing-region nexus work (Cho et al. 2023). These omissions matter because they can conceal who benefits from water-saving interventions, who bears transition costs, and how incentives shape adoption issues that determine whether technically promising measures translate into improved water and food security.

Third, governance is repeatedly identified as the missing integrative mechanism, despite its demonstrated influence on outcomes under scarcity. Al-Saidi and Elagib (2017) characterize nexus governance as a *missing link* and policy-focused studies show that non-consideration of interdependencies and divergence of policy goals can be a major cause of unsustainable resource governance (Vogeler et al. 2019). Empirical evidence from water-stressed contexts further indicates that limited governance and socioeconomic capacity can be more decisive for access to FEW services and associated outcomes than the availability of primary resources (Ding et al. 2019). Methodological critiques reinforce that many tools still do not explicitly consider biophysical and socioeconomic aspects simultaneously (Correa-Cano et al. 2022) and that interconnections are not systematically integrated into project design at local levels in developing countries (Terrapon-Pfaff et al. 2018). Taken together, the literature indicates a persistent gap: evaluations rarely explain how environmental pressures, farm-level decisions, and institutional arrangements jointly shape water-food security pathways in specific basins.

This study addresses the above gaps by implementing an integrated, basin-scale water–food nexus evaluation for the semi-arid Upper Sakarya watershed (drainage area approximately 21,000 km^2; agricultural lands about 70% of the basin), where farming is the dominant economic activity (DSİ 2017). The context is strongly water-constrained (mean annual precipitation approximately 390 mm) and exposed to climate-change risk, with projections indicating basin flows may decrease by up to 77% by 2070 (Ministry of Forestry and Water Affairs, 2016). Against this background, the novelty is not only evaluating technical water-saving measures but linking them to producer economics and governance-relevant stakeholder priorities in a single decision-oriented framework.

Concretely, the study combines: *i*) hydrologic and allocation modelling using WEAP to quantify the water-resource consequences of demand-oriented management scenarios; *ii)* scenario design spanning improvements in irrigation technology, shifts in crop patterns, and water-saving irrigation strategies; *iii*) explicit incorporation of stakeholder perspectives from water and agriculture sectors in scenario development and evaluation; and *iv*) socioeconomic (producer-finance) assessment of each technically evaluated alternative to illuminate adoption feasibility and distributional implications. By integrating technical performance, economic outcomes, and stakeholder-informed governance considerations within one basin case, the study responds directly to calls for mixed-method and transdisciplinary nexus evaluations (Albrecht et al. 2018) and helps operationalize nexus analysis as a tool for sustainable water governance in semi-arid agricultural systems.

2 Material and Methods

This study employs a holistic approach to aid decision-makers in the water and food sectors in the development of sustainable strategies at a basin scale. The WEAP model was used to evaluate the hydrological analysis of management scenarios in addition to economic analyses. Furthermore, stakeholder's perspectives are incorporated into evaluations as a part of multi-dimensional decision-making strategies. There are 4 steps of the study as follows: *i)* Characterization of the Basin & Identification of Issues, *ii)* Hydrological Model Setup *iii)* Development of the Scenarios and *iv)* Evaluation of Effectiveness of Scenarios. The study outline is depicted under a few methodological steps as shown in Fig. 1.

Characterization of the Basin & Identification of Issues In the first step, information gathered from field studies, surveys, stakeholder interviews, official technical reports, and published sources was used to characterize the basin and identify agricultural and water management issues. Meetings and field visits were made to stakeholders including the Turkish State Hydraulic Works (DSI), the Eskişehir Directorate of Provincial Agriculture and Forestry (DoPAF), the Tepebaşı District Directorate of Agriculture and Forestry, the Seyitgazi Municipality, Ministry of Agriculture and Forestry General Directorate of Agricultural Research and Policies (TAGEM) and irrigation unions. Following the collection of basin-specific information and data, the pressures on water resources by all sectors, such as withdrawals, discharges, and hydro-morphological alterations, are identified, and water management issues in the watershed are determined. In Sect. 2.3, the data used to setup the model is described in detail.

Stakeholders listed in Table 1 were selected based on their formal governance responsibilities, operational roles in water and agricultural management, and direct relevance to irrigation planning and policy implementation within the study area.

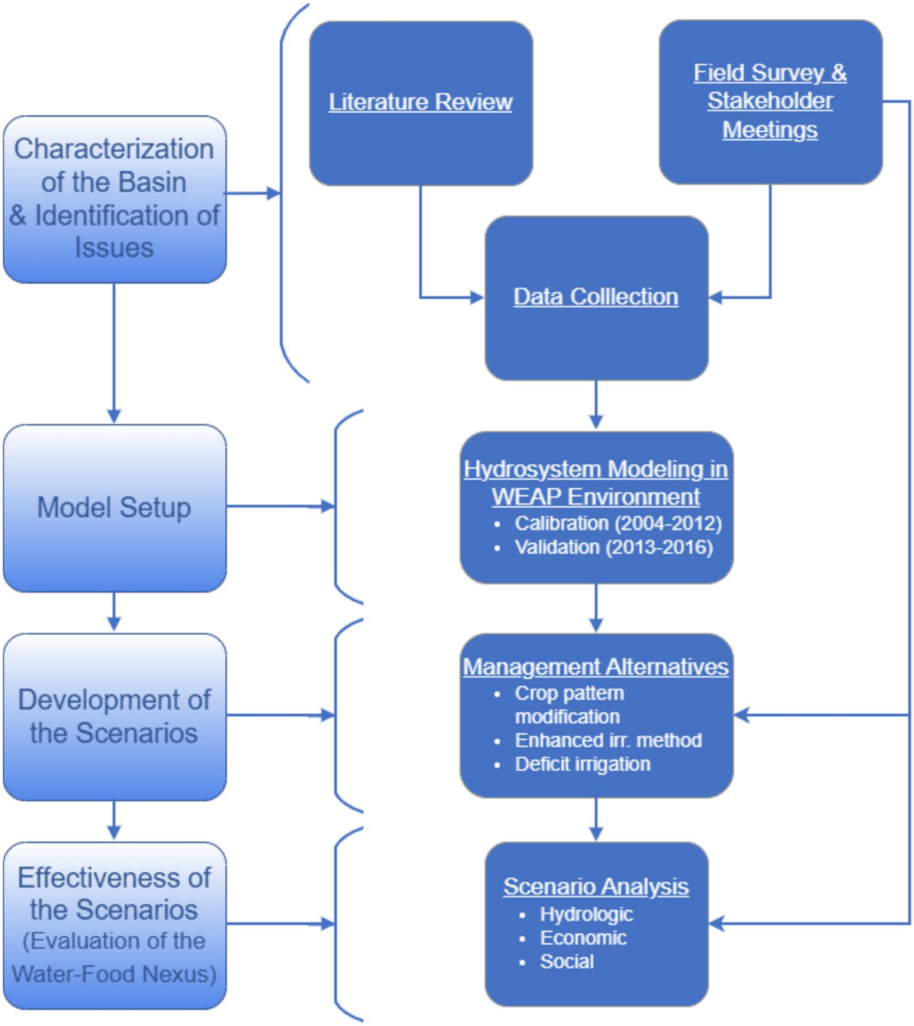

Fig. 1 The framework for the multi-dimensional assessment of Water-Food Nexus

Hydrological Model Setup As a nexus evaluation tool, the Water Evaluation and Planning System (WEAP) model was used (please see Sect. 2.2). The calibration and verification procedures are explained in Sect. 2.4.

Development of the Scenarios Based on the information gathered in the first step of the study, alternatives to existing agricultural water management practices, such as technological advancements in irrigation, shifts in cropping patterns, and water-saving irrigation strategies, were developed following the model setup. Section 2.5 describes the detailed methodology for configuring scenarios in the WEAP model.

Table 1 Stakeholders participated in the co-development of the research

Stakeholder Name	Description	Experts/Expertise
Turkish State Hydraulic Works (DSİ)	The 3rd and 5th Regional Directorates of DSİ are responsible for planning, management, development, and operation of water resources located in Eskişehir and Ankara provinces, which intersect the study area	Public officials, civil engineers
Eskişehir Provincial Directorate of Agriculture and Forestry	Provincial directorate under the Ministry of Agriculture and Forestry. Responsible for preparing and implementing strategic and action plans aligned with the Ministry's medium- and long-term policies and the agricultural infrastructure of Eskişehir province, in coordination with relevant implementation units	Public officials, agriculture, and forestry experts
Tepebaşı District Directorate of Agriculture and Forestry	District-level directorate under the Ministry of Agriculture and Forestry. Operates in coordination with the Provincial Directorate to plan, implement, guide, coordinate, and supervise agricultural activities aimed at improving the district's agricultural potential and production, within the relevant legal framework	Public officials, agriculture, and forestry experts
General Directorate of Agricultural Research and Policies (TAGEM)	Soil, Fertilizer and Water Resources Central Research Institute operating under TAGEM and the Ministry of Agriculture and Forestry. Conducts research related to soil, fertilizer, and water resources	Agricultural economics experts
Seyitgazi Municipality	The district municipality of Eskişehir is responsible for regulating the Seyitgazi irrigation area, which is one of the most critical irrigation zones supplied by Çatören and Kunduzlar dams and groundwater resources within the study area	Municipal officials, farmers
Sakaryabaşı Irrigation Association	Implements irrigation activities within its service area, operating under the coordination of the relevant Regional Directorate of Turkish State Hydraulic Works, in accordance with national irrigation legislation	Head of Irrigation Association, agricultural experts, engineers
Yukarı Sakarya Irrigation Association	Responsible for implementing irrigation activities under the coordination of the Regional Directorate of Turkish State Hydraulic Works, in line with the national legal framework governing irrigation associations	Head of Irrigation Association, agricultural experts
Eskişehir Irrigation Association	Implements irrigation operations coordinated by the Regional Directorate of Turkish State Hydraulic Works, following the national legislation applicable to irrigation associations	Head of Irrigation Association, agricultural experts

Evaluation of the Effectiveness of the Scenarios To aid decision-makers in the water and agriculture sectors, the effectiveness of agricultural water management scenarios was evaluated based on *i)* hydrological impacts, *ii)* economic criteria, and *iii)* stakeholder perspectives. The hydrological analysis was carried out using the WEAP hydrologic model, with a focus on water efficiency in agricultural water demand and use. Following that, a socioeconomic evaluation was carried out based on the unit prices of water used for agricultural services and harvested crops. In Sect. 2.6, the socioeconomic evaluation methodology is detailed. Furthermore, the perspectives of stakeholders as indicated in Table 1 were obtained via a semi-structured questionnaire and incorporated into the integrated evaluation of the scenarios. (Sect. 3.4).

2.1 Study Area

Sakarya Watershed, with a drainage area of 63,300 km^2 is Türkiye's third-largest river basin. Sakarya Watershed has six sub-basins: Upper Sakarya, Porsuk, Middle Sakarya, Ankara, Göksu, and Lower Sakarya (Fig. 2) and the population density is 119 per capita/km^2 (DSİ

Fig. 2 Location of The Upper Sakarya River Basin

2017). The Upper Sakarya basin, which is one of the sub-basins of the Sakarya Watershed and the study area, has a drainage area of approximately 21,000 km^2. The average yearly natural streamflow is 31 m^3/s, and the average yearly precipitation is 390 mm (DSİ 2017). In the study area, the agricultural lands account for nearly 70% of the total drainage area (5% of the agricultural area is permanently irrigated land primarily occupied by grain, sugar beet, and sunflower; 43% of the agricultural area is non-irrigated arable land primarily occupied by wheat, barley, and fallow; and 21% of the agricultural area is pastures). Agriculture is the most significant economic activity compared to livestock, industry, and mining. More than a million animals were raised in 2012 (DSİ 2017), and sugar mills and meat processing plants are the primary food production industries. Since the study area is in a semi-arid region, assessing the water-food nexus is crucial to find a balance between water and food security for sustainable economy and ecosystem integrity.

2.2 Water Resources Evaluation and Planning (WEAP) Model

In this study, the Water Resources Evaluation and Planning (WEAP) model was used to evaluate the hydrological analysis of the management scenarios, focusing on the dynamics between the irrigation demand and water supply through water budget. The WEAP system developed by Stockholm Environmental Institute (SEI), has been widely used as the decision support tool due to its accessibility, data adaptability, ease of use, the ability of scenario analysis, and capability in terms of representing effects of demand management on water systems. WEAP combines water supply and demands and addresses the system's problems on the supply side's demand side and dynamics to simulate water system operations. Water demand estimates are derived from the model's water usage profile, equipment efficiencies, water re-use strategies, costs, and water allocation schemes. Water supply is estimated by reproducing managed supply components (stream regulations, groundwater withdrawal, reservoirs, and water transfers) and natural supply components (evapotranspiration demand, surface flow, environmental flow). The main principle of the WEAP model is based on water balance accounting (World Bank 2017). Hydro system components within the WEAP model, such as rivers, reservoirs, hydropower plants, canals, are simulated according to user-defined management rules for many purposes. The model's hydrologic simulation includes evapotranspiration, snowmelt, snow accumulation, streamflow formation, soil moisture dynamics, and groundwater recharge. Several concepts incorporated within the WEAP structure to simulate hydrologic processes carried out in the catchment are available for user practice. In this study, Rainfall-Runoff Method (Soil Moisture Method) is applied to conceptualize a two-bucket scheme where empirical functions are embedded to simulate the hydrologic cycle in the catchment level using soil and climatic data.

The WEAP model has been used as a decision support tool in several studies examining the water-food nexus. In the literature, various agricultural water management strategies were evaluated with WEAP such as alterations in water allocation strategies and irrigation water management, capacity building of resources, dams, and canal management (Salomón-Sirolesi and Farinós-Dasí, 2019); practices such as treated wastewater use for irrigated agriculture (Alfarra et al. 2012); policies in the marketing of agricultural products (Darani et al. 2017) or management alternatives under drought impacts (Dehghanipour et al. 2019) for agricultural sustainability. Furthermore, the WEAP model is used to investigate the water–food (agriculture) nexus concerning climate change adaptation strategies in several studies (Golfam et al. 2019; Sridharan et al. 2019; Ahmadaali et al. 2018; Skoulikaris et al. 2017; Santikayasa 2016; Amisigo et al. 2015; Esteve et al. 2015; Yates et al. 2015; Jackson et al. 2012).

2.3 WEAP Model Development and Data Requirement

Table 2 provides an overview of the data descriptions and sources for the catchment, demand sites, supply and resources, and wastewater discharges that were used to develop the WEAP Model for the study area. The study area is divided into several sub-catchments, and data were introduced to distinguish the spatial characteristics for each catchment including a variety of land use/cover classes: artificial, agricultural, forest and semi-natural, wetlands, and water bodies (Copernicus 2018). Areal information for the irrigated and non-irrigated agricultural lands, including the crop pattern, was acquired from State Hydraulic Works and

Table 2 Data used in the WEAP model

	Data	Description	Source
Catchments	Digital Elevation Model (DEM)	Used to determine drainage area and river network	SRTM 1 Arc-Second Global (U.S. Geological Survey 2000)
	Land Use	Required to define the classes including agricultural, pasture, forest, wetland, residential area	CORINE 2018 LULC, DSİ Agricultural Economy and Public Irrigation Final Reports, TurkStat
	Climate	Meteorology data including precipitation, temperature, humidity and wind speed, latitude are required to run the model	Turkish State Meteorological Service (MGM) data
	Agriculture	Crop pattern and crop coefficient (Kc) are required to calculate the agricultural water demand in the basin	Crop pattern from DSİ and TurkStat; crop coefficient from the report "Türkiye'de Sulanan Bitkilerin Bitki Su Tüketimleri" (TAGEM and DSİ (2017)
Demand Sites	Industrial & Urban & Livestock	The amount of water supply for industrial, urban, and livestock demand and leakage or evaporative losses of the water supply network is required	SYGM "Sakarya Havza Koruma Eylem Planı", DSİ "Nüfus Projeksiyonu ve Su İhtiyaçları Raporu", DSİ "Hidrojeoloji Raporu", Annual Reports of Water and Sewerage Administrations, TurkStat Municipality Water and Wastewater Statistics, and literature
	Energy	Data regarding hydropower and thermal power plants are required to determine water consumed due to cooling water withdrawal and evaporation loss from reservoir surface	EPİAŞ, power plant visits, and literature
Supply and Resources	River	Required for characterization of the river by defining head flows and flow dynamics	DSİ; Streamflow Gauges data
	Reservoir	Observed volume, inflows and outflows, water uses of dams are required for characterization of the reservoirs	DSİ; Operation and Maintenance data
	Groundwater	Storage capacity, available storage, maximum withdrawal, and natural recharge are required for the simulation of groundwater	DSİ "Hidrojeoloji Raporu"
	Transmission Links	The amount of water drawn from the system at specific points along the water transmission links and the amount of water lost (e.g., evaporation, underground leakage) are required	World Bank (2016) report entitled "Türkiye Cumhuriyeti: Sürdürülebilir Kentsel Su Temini ve Sanitasyonu Raporu"
Discharges	Wastewater	Daily capacity of urban wastewater treatment plants	"Sakarya Havzası Master Plan Nihai Raporu" (DSİ 2017)

Table 3 Calibration parameters used in the WEAP model for Upper Sakarya Basin

Parameter	Default	Unit
Runoff Resistance Factor	2.00	-
Preferred Flow Direction	0.15	-
Soil Water Capacity	1000	mm
Deep Water Capacity	1000	mm
Root Zone Conductivity	20	mm/month
Deep Conductivity	20	mm/month
Initial Z2	30	%
Lower Threshold	35	%
Upper Threshold	65	%
Freezing Point	−5	ºC
Melting Point	5	ºC

Table 4 Model performance criteria and suitability ranges

Criteria	Range	Suitability (Flow)	Suitability (General)	Reference
R^2	$0 < R^2 < 1$	>0,70	>0,50	Moriasi et al. (2015)
NSE	$-\infty < NSE < 1$	>0,55	>0,50	Moriasi et al. (2015)
PBIAS	$-\infty < PBIAS < +\infty$	$\leq \pm 15$	$\leq \pm 25$	Moriasi et al. (2015)

TurkStat. Digital elevation data (SRTM 1 Arc-Second Global) was used to delineate the drainage area and the river network (U.S. Geological Survey 2000). Climate data required to run the model consist of precipitation, temperature, wind, humidity, and latitude were obtained from the Turkish State Meteorological Service. Information regarding water resources, including streamflow, discharges reservoir characteristics (surface and groundwater), and the water uses by sectors (domestic and industrial), are received from State Hydraulic Works and other official reports as summarized in Table 2.

2.4 Calibration and Verification of the WEAP Model

The model was calibrated and validated manually for the 2004–2012 and 2013–2016 time periods, respectively. The model performance is assessed using five gauging stations located at the outlets of two dams (Çatören and Kunduzlar), and three sub-basins (Aktaş, Ayvalı, and Aydnlı) Fig. 2. The list of calibration parameters used for the catchment simulation through the Soil Moisture method is given in Table 3. Calibration parameters are modified spatially for each catchment component.

The calibration and verification results of the WEAP model are evaluated based on multiple performance criteria such as R^2, Nash Sutcliffe Efficiency (NSE) Coefficient, PBIAS, and RMSE. The summary table of model performance criteria corresponding to a suitability range is provided in Table 4.

2.5 Scenario Development

The opinions of the stakeholders from the water and food sector were considered in developing agricultural management scenarios that promote effective water use and higher economic benefits. These scenario categories are described in the following paragraphs. An overview of the demand-management scenarios is given in Table 5 and explained in the following paragraphs.

Baseline Scenario (S0) The baseline scenario represents the business-as-usual agricultural management activities during calibration/verification period starting in 2004. In this scenario, water-intensive crops (e.g., alfalfa, forage maize, sunflower) are grown using low-efficiency irrigation methods (e.g., surface irrigation) without the implementation of water-saving practices such as deficit irrigation programs.

Crop Patterns Changes Scenarios (S1) This scenario promotes alternatives for water-efficient crops. Over the course of crop pattern change scenarios, the baseline crops (e.g., alfalfa, forage maize, sunflower) were gradually replaced by the target crop(s) (e.g., vicia, trefoil, safflower). The scenario group that applies crop pattern change is classified as S1 with further subdivisions for specificity; scenarios focused on forage crops (e.g., alfalfa, forage maize, vicia, trefoil) are categorized as S11, while those concerning oilseed crops (e.g., sunflower, safflower) are classified as S12.

Improved Irrigation Scenarios (S2) The effectiveness of various irrigation techniques has been covered in many studies in the literature such as Mehta et al. (2013), Joyce et al. (2011), and Purkey et al. (2008). In this study, improved irrigation scenarios were created by modifying the irrigation trigger mechanism to increase the efficiency of field applications. Scenarios applied for improved irrigation methods are grouped under the following three categories: Surface to Sprinkler (S21), Surface to Drop (S22), and Sprinkler to Drop (S23).

Table 5 Categorisation of management scenarios

Scenario	Description
S0	Business as usual
S11	Crop pattern changes for forage crops
alfalfa to vicia and trefoil	Three sub-categories are applied under this group based on modified crop percentage
forage maize to vicia	Three sub-categories are applied under this group based on modified crop percentage
alfalfa to forage maize	Three sub-categories are applied under this group based on modified crop percentage
S12	Crop pattern changes for oilseeds (i.e., sunflower to safflower). Three sub-categories are applied under this group based on modified crop percentage
S2	Field application efficiency raised for enhanced irrigation technique (i.e., sprinkler or drip). Three sub-categories are applied under this group based on irrigation technique alteration
S3	Deficit irrigation is applied to different crops. Three sub-categories are applied under this group based on crops of interest (i.e., grain, sugar beet, and maize)
C1 and C2	Selective combinations of the scenarios

In each scenario, threshold parameters (i.e., soil moisture lower and upper bounds at which irrigation starts and stops) are modified for the relevant crops to increase efficiency.

Deficit Irrigation Scenarios (S3) Through the practice of deficit irrigation, which exposes the plant to a certain level of water stress, it is possible to achieve irrigation water efficiency without experiencing significant yield reductions. In this scenario, deficit irrigation is practiced at stages when water stress has a less impact on crop yield. To increase water efficiency without diminishing crop yield, full irrigation is practiced during sensitive periods. Deficit irrigation, on the other hand, was used when the crops were more tolerant. The deficit irrigation program was applied for wheat, maize (including forage maize), and sugar beet in the scenarios S31, S32, and S33, respectively.

In scenario S31, summer wheat is fully irrigated in April and May, at the beginning of the heading and milk stage, and 50 percent less water is given in the later growth stages, based on the wheat growth stages deemed necessary to apply irrigation (Ünlü et al. 2008). According to Süheri et al. (2007), the most efficient use of water in terms of root and sugar yield occurs when full irrigation is applied during the vegetative growth and ripening stages, and 50 percent deficit irrigation is applied during the root swelling stage. Hence, in scenario S32, 50 percent less water was applied during the root swelling period of sugar beets, and full irrigation was applied during the other growth stages. Given that the tasseling stage of maize is said to be extremely sensitive to water stress (Ünlü et al. 2008), in scenario S33, full irrigation was applied during and before the tasseling stage, and 50 percent deficit irrigation was applied in other stages.

Combination scenarios (C1 & C2) Two selective combinations of the scenarios have been formed aiming at the highest impact on irrigation water use. C1 is composed of scenarios S113, S123, S23, and S31, whereas C2 comprises scenarios S119, S123, S23, and S31.

To implement irrigational water management scenarios, operational parameters that exclusively control the irrigated area and irrigation triggering mechanism in the WEAP model are modified as depicted in Table 6.

2.6 Socioeconomic Evaluation

A socioeconomic evaluation was conducted to provide insight into how the producer's finances would be affected by the implementation of the scenarios. Crop pattern change (S1) and deficit irrigation practices (S3) are two scenarios being evaluated economically. For an economic analysis of any agricultural product, it is necessary to know the production costs, yield, and sales price for the entire process, from planting the seed to selling the crop. In the scope of this study, the District Agriculture and Forestry Directorates of the Ministry of Agriculture and Forestry provided the cost and yield information for the products in each scenario in the Upper Sakarya Basin. Total production data in the region were obtained from Turkish Statistical Institute (TurkStat 2019).

The gross value of production (GVP) of crop production per unit area was determined by multiplying the selling prices of the produced goods by their yields per unit area. The GVP refers to the financial worth of plant and animal products produced in agribusiness, as

Table 6 Specifications regarding crop, parameter, and the corresponding change in the scenario application

Scenario	Description	Crop(s) of interest	Parameter(s)	Applied change(s)
S111	pattern change-forage crops	Alfalfa, vicia	Acreage (ha)	alfalfa: −0.4*alfalfa vicia: + 0.4*alfalfa
S112	pattern change-forage crops	Alfalfa, vicia, trefoil	Acreage (ha)	alfalfa: −0.66*alfalfa vicia: + 0.33*alfalfa trefoil: + 0.33*alfalfa
S113	pattern change-forage crops	Alfalfa, vicia, trefoil	Acreage (ha)	alfalfa: −1.0*alfalfa vicia: + 0.5*alfalfa trefoil: + 0.5*alfalfa
S114	pattern change-forage crops	Forage maize, vicia	Acreage (ha)	forage maize: −0.4*forage maize vicia: + 0.4*forage maize
S115	pattern change-forage crops	Forage maize, vicia	Acreage (ha)	forage maize: −0.7*forage maize vicia: + 0.7*forage maize
S116	pattern change-forage crops	Forage maize, vicia	Acreage (ha)	forage maize: −1.0 *forage maize vicia: + 1.0*forage maize
S117	pattern change-forage crops	Alfalfa, forage maize	Acreage (ha)	alfalfa: −0.4*alfalfa forage maize: + 0.4*alfalfa
S118	pattern change-forage crops	Alfalfa, forage maize	Acreage (ha)	alfalfa: −0.7*alfalfa forage maize: + 0.7*alfalfa
S119	pattern change-forage crops	Alfalfa, forage maize	Acreage (ha)	alfalfa: −1.0*alfalfa forage maize: + 1.0*alfalfa
S121	pattern change-oilseeds	Sunflower, safflower	Acreage (ha)	sunflower: −0.4*sunflower safflower: + 0.4* sunflower
S122	pattern change-oilseeds	Sunflower, safflower	Acreage (ha)	sunflower: −0.7*sunflower safflower: + 0.7*sunflower
S123	pattern change-oilseeds	Sunflower, safflower	Acreage (ha)	sunflower: −1.0*sunflower safflower: + 1.0 sunflower
S21	Improved irrigation-surface to sprinkler		Upper & lower thresholds	min, max (0.55, 0.95)*lower threshold min, max (0.80, 0.95)*upper threshold
S22	Improved irrigation-surface to drop		Upper & lower thresholds	min, max (0.55, 0.95)*lower threshold 1*upper threshold (i.e., no change)
S23	Improved irrigation-sprinkler to drop		Upper & lower thresholds	min, max (0.65, 0.93)*lower threshold 1*upper threshold (i.e., no change)
S31	Deficit irrigation-grain	Grain	Upper & lower thresholds	
S32	Deficit irrigation-sugar beet	Sugar beet	Upper & lower thresholds	
S33	Deficit irrigation-maize	Maize	Upper & lower thresholds	
C1	Combined setup 1	See scenarios: S113, S123, S23, S31	Acreage (ha), upper & lower thresholds	Applied changes for the scenarios S113, S123, S23, S31
C2	Combined setup 2	See scenarios: S119, S123, S23, S31	Acreage (ha), upper & lower thresholds	Applied changes for the scenarios S119, S123, S23, S31

well as the value increases in these production activities throughout the year. The variable costs were calculated by multiplying the unit prices of inputs such as seeds, pesticides, and fertilizers associated with each product on a per unit area basis. Furthermore, fixed costs are calculated by including other costs such as machinery and labour. Consequently, total production costs, which include all expenses incurred for a product, are determined by adding variable and fixed costs. Gross profit was calculated for each product by deducting variable costs from the GVP, and net income was calculated by deducting fixed costs from the gross profit figures. All associated products with each scenario undergo these computations.

The production quantity was calculated based on the recommended product pattern for each scenario, while the total GVP and net income were calculated based on €/km^2. This value is then divided by the amount of irrigation water calculated by the model, yielding an estimate of the net income to be obtained per cubic meter of irrigation water used. The objective of this calculation is to evaluate the contribution of respective measures to the country's income in proportion to each cubic meter of irrigation water used, based on the scenarios proposed within the scope of the study. Data used in socio-economical evaluations can be provided upon request.

2.7 Classifying Dry and Normal Years

The impacts of seasonal flow variation on outputs are reflected by evaluating scenarios under varying hydrologic conditions. To characterize the hydrological drought, the Streamflow Drought Index (SDI) is computed using observed streamflow data from the gauging station Ayvalı (E12A052) from 1989 to 2016. This study classified drought states described by Nalbantis and Tsakiris (2009) based on the SDI into two groups: normal and dry. Extreme, severe, or moderate drought states were categorized as dry years (2008, 2010, 2012, 2013, 2014, 2016), while non-drought or mild drought states were categorized as normal years (2005, 2006, 2007, 2009, 2011, 2015).

3 Results and Discussion

3.1 The Model Calibration and Validation

The model has been manually calibrated for 2004–2012 and validated in the period 2013–2016. For the model performance evaluation, five gauging stations located at the outlets of three sub-basins (Aktaş, Ayvalı, and Aydınlı) and the outlets of two dams (Çatören and Kunduzlar) are selected. The model performance has been evaluated for Nash Sutcliffe Efficiency (NSE) coefficient, PBIAS, R^2, and RMSE. The model evaluation statistics have been calculated for the calibration and validation periods based on the observed and modelled streamflow and the results are provided in Table 7. A general agreement regarding trends modelled and observed streamflow follows a similar pattern Fig. 3. Except for the gauges at dam outlets (D12A192 and D12A184), calibration results are proved better than the validation results. The plot Fig. 3 results indicate that baseflows are replicated throughout the calibration period yet are slightly overestimated in the validation period. On the other hand, flood peak estimates perform better regarding timing than magnitude. Within the scope of this study, model performance is more critical during low flows because demand-man-

Table 7 Calibration and validation results

Gauge	Calibration Results	Validation Results
D12A192 (Çatören dam outlet)	NSE = 0.44 PBIAS = −26.94 R^2 = 0.80 RMSE = 0.64	NSE = 0.70 PBIAS = −5.05 R^2 = 0.84 RMSE = 0.71
D12A184 (Kunduzlar dam outlet)	NSE = 0.47 PBIAS = 19.83 R^2 = 0.74 RMSE = 0.84	NSE = 0.75 PBIAS = 16.67 R^2 = 0.87 RMSE = 0.45
E12A024 (Aktaş sub-basin outlet)	NSE = 0.60 PBIAS = −0.71 R^2 = 0.79 RMSE = 1.19	NSE = 0.45 PBIAS = −24.68 R^2 = 0.84 RMSE = 1.79
E12A052 (Ayvalı sub-basin outlet)	NSE = 0.73 PBIAS = 2.40 R^2 = 0.86 RMSE = 3.40	NSE = 0.31 PBIAS = −18.39 R^2 = 0.76 RMSE = 5.39

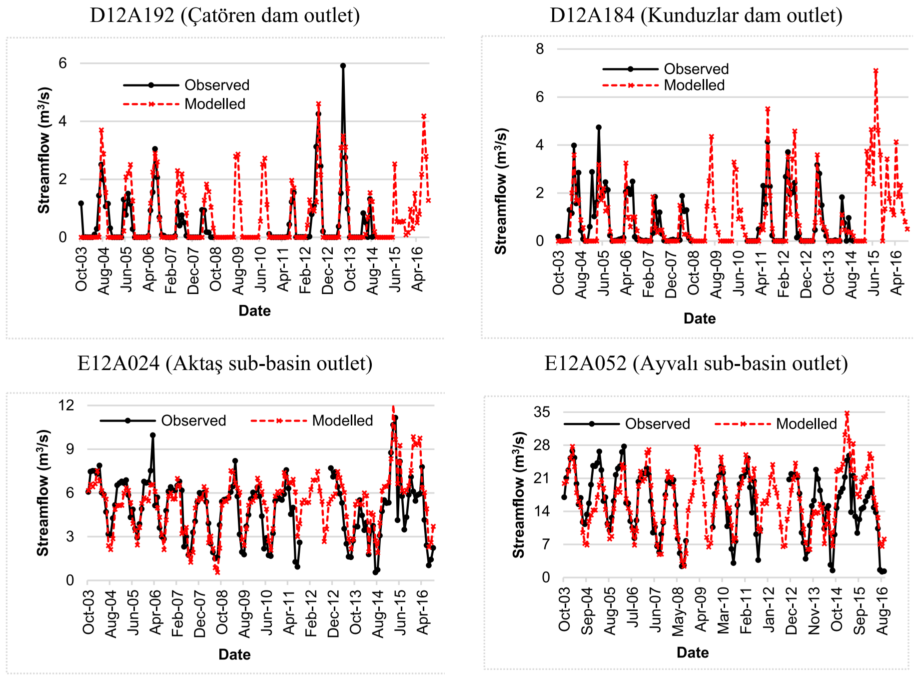

Fig. 3 Modelled and observed streamflow in monthly time series

agement scenarios will have the most impact in dry periods when the irrigation that crops need is not available. In periods when flow peaks, the impact of the scenarios will not be as effective compared to dry periods since most of the irrigation water needs will be met even under normal conditions.

Using the performance criteria in Table 4 the gauge-specific calibration/validation statistics in Table 7 indicate overall good agreement in correlation across all gauges. Overall, R^2 values are consistently high across gauges (0.74–0.86 in calibration and 0.76–0.87 in validation), indicating that the model captures the observed temporal dynamics and co-variability in streamflow. In contrast, NSE and PBIAS show more spatially variable skill, suggesting that reproducing flow magnitudes and event-scale variability remains challenging at some locations (e.g., lower NSE during calibration at the dam-outlet gauges and reduced validation efficiency at some sub-basin outlets). Negative PBIAS at selected gauges also points to a tendency toward underestimation in validation, which may reflect unmodeled or uncertain influences such as reservoir operations, abstractions/return flows, and spatial heterogeneity in rainfall-runoff response. Despite these limitations, the results are considered satisfactory for basin-scale interpretation because the key performance indicators meet (or approach) commonly used suitability thresholds at critical locations; notably, the Ayvalı sub-basin gauge (E12A052), representing the watershed outlet, exhibits promising skill and supports an overall satisfactory assessment of model performance for the watershed-scale analysis.

3.2 The Effectiveness of the Agricultural Water Demand Scenarios

The comparison of the results for demand, supply, deficit, and reliability in terms of % change is listed in Table 8 and Fig. 4. Scenarios that resulted in the highest net impact on irrigation water supply over their groups are S113, S123, S23, S31 and C1. In terms of supply required, irrigation supply, and shortfall parameters, C1 has the highest impact since it is the combination scenario that implements all other scenarios on the figure simultaneously. On the other hand, particular S-group scenarios are close in a narrow band regarding the net effect in output parameters. However, scenario outputs have demonstrated minor variations considering the hydrologic conditions.

In the WEAP model, the Demand Site Reliability in terms of surface water is computed as the percent of the timesteps in which a water demand is fully satisfied for a demand site (Sieber and Purkey 2015). In this case, reliability for demand sites that rely on groundwater is 100% (i.e., groundwater supply requirement was fulfilled at all months in simulation period). However, surface water reliability varies between 51–99% depending on the relevant scenario and corresponding demand site. Sub-basins located in upstream locations (i.e., 72–92% for Aktas, 91–99% for Aydınlı) result in higher reliability than downstream loca-

Table 8 Comparison of the results for demand, supply, deficit, and reliability in terms of % change*

Scenario	Supply Required	Irrigated	Shortfall	Reliability
	Median [min, max]			
S111-S119	−40.1 [−100.0, −7.1]	−39.9 [−100.0, −8.5]	−41.0 [−100.0, −5.4]	0.0 [0.0, 3.2]
S121-S123	−70.5 [−100.0, −40.6]	−69.6 [−100.0, −39.4]	−74.8 [−100.0, −46.0]	3.2 [0.0, 5.8]
S21-S23	−9.3 [−11.8, −8.7]	−15.1 [−15.9, −11.3]	−14.6 [−15.1, −10.2]	1.3 [0.6, 4.5]
S31-S33	−29.2 [−33.7, −27.6]	−28.7 [−29.4, −25.6]	−32.3 [−40.9, −30.2]	0.6 [−0.6, 7.7]
C1-C2	−39.0 [−43.2, −34.7]	−35.5 [−39.2, −31.8]	−51.7 [−59.1, −44.3]	8.7 [3.8, 19.9]

*Net change in irrigation water supply need, actual supply, and shortfall relative to the reference scenario

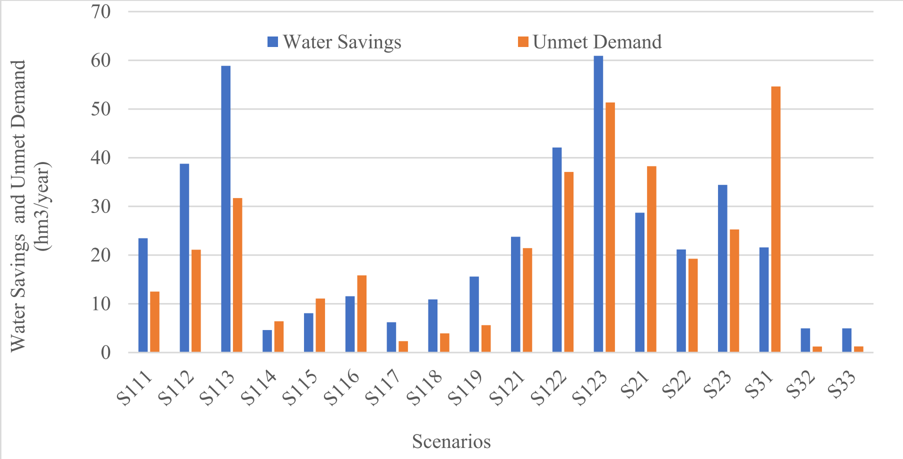

Fig. 4 Water savings and unmet demands (hm^3/year)

tions. (i.e., Ayvalı 51–60%). That can be relevant considering the impact of upstream uses on the available resources downstream. While considering the net change in reliability, C1 and C2 significantly impact the surface water reliability for all demand sites. Also, scenarios S31, S123, S21, and S23 are promising. Esteve et al. 2015 further suggested that adapting crop pattern optimization might have a positive contribution to the demand for reliability under climate change conditions. Furthermore, the results show that effective agricultural practices can increase water savings up to 60 hm^3/year (Scenario 123).

To determine the hydrological effects of the previously described scenarios, the model outputs were analysed under dry and normal conditions. Figure 5 depicts box and whisker plots for the most effective scenarios in terms of water savings. In general, S113 and S123 have a greater impact during drought years compared to normal years. In addition, under severe drought conditions in 2007 and 2008, Fig. 5 reveals few outliers for the parameters of supply demand change and irrigation deficit. In this instance, it is evident that crop pattern change is most effective during dry periods. This may occur because less precipitation is received during dry periods, necessitating increased irrigation to compensate for evapotranspiration loss. In the current dry state, irrigation has been observed to be greater than normal, while inflow has been observed to be lower. Since surface water and groundwater irrigation supplies are significantly higher during dry periods, switching to non-irrigated crops S113 (vicia and trefoil) and S123 (safflower) is more effective in terms of irrigation water efficiency. Similarly, in the S31 scenario, the net change in the supply need and irrigation shortfall parameters is higher in dry years than in normal years. However, the net change in the irrigation amount parameter is calculated to be close to each other in dry and normal periods. In addition, the S31 scenario shows the net change in the amount irrigated in 2014, which is the least dry.

The S23 is the scenario with the least net change compared to the reference when evaluated among the other most effective alternatives. At the same time, when this scenario is evaluated under hydrological drought conditions, it is seen that it causes different effects in different parameters. These effects might be related to the variety of products to which the scenario is practiced and the competition between the products that the scenario is not

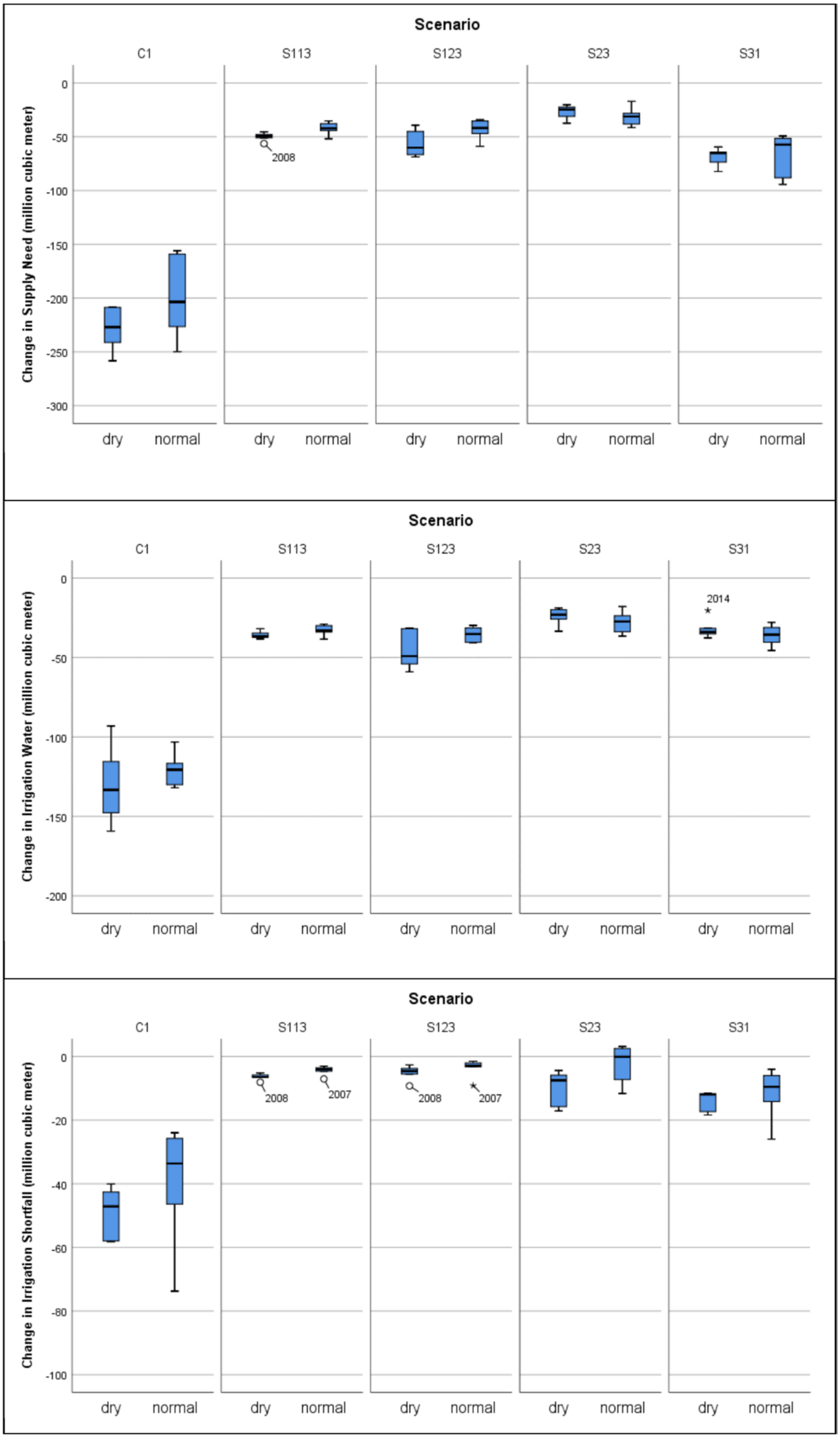

Fig. 5 Box and whisker plots for the most effective scenarios

applied to. It is observed that the net change in irrigation demand and supply parameters in normal years is more than in dry years. In the irrigation shortfall output, it is determined that there is more water deficit in the normal period compared to the reference. Especially in the normal years 2009, 2011, the 2015 sugar beet has more water deficit than the reference. The reason for this situation has been investigated with detailed analysis. In a further study, it is noticed that during the dry periods of 2008, 2010, and 2014, there is more irrigation requirement for grain than normal years within the scope of the study area. However, this product is not included in the S23 scenario as the transition to drip irrigation is not applicable in the grain. Therefore, while this high irrigation requirement is met for grain during dry periods, the irrigation deficit of sugar beet in normal years following the dry years could not be compensated. Competing water demand is available, especially in 2011, since the irrigation needs of both crops are the same. However, in scenario S23, the irrigation demand of this product is met as the irrigation efficiency of the grain is not reduced. At the same time, the water deficit of sugar beet increased due to the competing water use between those crops.

3.3 Socioeconomic Analysis

As a part of the integrated assessment of the agricultural scenarios, socioeconomical evaluations are conducted as explained in Sect. 2.6. GVP and net income results obtained for the S11, S12, and S3 scenarios are given in Table 9. The economic evaluation of S2 scenarios remains infeasible due to data uncertainty and the variability of inputs and outputs across regions, crops, and producers. The values obtained as a result of the cost profit analysis for the products related to the scenarios are shown in proportion to the area covered and the irrigation water used.

Considering the shifting pattern scenarios for forage crops (S11), the biggest reason for the net income difference between alfalfa and other forage crops is that alfalfa is a perennial plant and can be harvested 5–6 times a year on average. For this reason, when the farmer's income is considered, the high yield of the alfalfa plant is an important reason for preference. However, when growing alfalfa, it requires very intensive irrigation. GVP obtained for 1 cubic meter of irrigation water occurs highest for S113 scenario and is €32.3. Considering the production costs, the net income for 1 cubic meter of irrigation water in the same scenario is €14.7. On the other hand, the S119 scenario, which is the scenario where the forage maize replaces the entire alfalfa area, is the scenario where the GVP and net income obtained for 1 cubic meter of irrigation water are the lowest.

When the profits to be obtained from forage crops per unit of acreage are compared, there is a significant difference in terms of the farmer's net income based on forage selection. However, considering the value of water as input and production value as output, when the difference between economic gains is examined, it can be said that these changes can

Table 9 GVP and Net income results obtained for the scenarios in S11, S12 and S3 groups

Scenario Group	S11				S12		S3		
Crop	alfalfa	vicia	trefoil	forage maize	sunflower	safflower	Wheat	maize	sugar beet
GVP (€/da)	422.2	89.7	157.8	224.3	138.4	65.7	54.3	353.2	163.5
Net Income (€/da)	300.5	22.2	90.3	48.6	30.3	29.2	13.7	130.2	40.5
GVP (€/m^3)	min, max (0.6, 2.6)				min, max (1.0, 19.1)		4.9	0.7	2.7
Net Income (€/m^3)	min, max (0.3, 14.7)				min, max (0.3, 8.5)		1.2	0.2	1.0

be supported economically as well as providing the protection of natural resources. In cases where farmers are encouraged shifting to less water-intensive forage crops, financing the governmental subsidies by considering the income to be obtained based on irrigation water can be effective in accelerating the acceptance of the pattern change by reducing the adaptation period of the farmers.

Regarding the shifting pattern scenarios for oilseeds (S12), the production value per unit area of the safflower is at the same level as the sunflower. The highest GVP obtained for 1 cubic meter of irrigation water occurs in the S123 scenario and is €19.1. Subtracting the production costs, the net income for 1 cubic meter of irrigation water in the same scenario is €8.5. There is no significant difference between the net income provided to the farmers, but there are significant differences in terms of production values and income per unit of irrigation water used.

Safflower is an oilseed that has become widespread especially in recent years due to studies showing its positive effects on health and increasing cultivation areas. The ability to grow in dry conditions makes it a particularly suitable alternative in conditions where sunflowers cannot be grown dry. Moreover, the fact that the net incomes provided by these two crops to the farmers are remarkably close to each other may facilitate the adaptation of the farmer regarding the recommended pattern changes. Considering the decrease in irrigation as well, replacing irrigated sunflower fields with the safflower is therefore considered highly feasible.

In terms of deficit irrigation scenarios (S3), a decrease in yield is not expected due to the application of full irrigation during periods that are promoted for healthy growth and preventing plant loss. Therefore, the production costs decreased due to the reduction in irrigation water while the yield remained constant. In this case, both the net income per area increased and the GVP and net income per 1 cubic meter of irrigation water increased for each scenario. Net income per 1 cubic meter of irrigation water increased from €0.5 to €1.2 for wheat, from €0.4 to €1 for sugar beet, from €0.05 to €0.2 for maize. The implementation of S3 scenarios is easily applicable as it increases the net income for the farmer. Thus, in addition to preserving natural resources, the value of agricultural production will increase.

The data presented in Table 9 clearly demonstrates the divergence between land-based net income and water-based productivity. Given the constraints on water resources, decoupling agricultural growth from water consumption is not merely a technical preference but a national imperative. When water is regarded not simply as an agricultural input but as a form of national capital that must be safeguarded in the context of climate change, the results of this study become particularly instructive.

The findings indicate that increasing net income per unit of water is linked to Türkiye's agricultural gross domestic product objectives. In particular, the transition to safflower under the S123 scenario simultaneously enhances water-use efficiency and offers significant potential to reduce external dependence on vegetable oils. By lowering the opportunity cost of water, this shift enables limited resources to be reallocated toward higher value-added agricultural activities.

While the model updates support levels according to production costs, it also envisages a framework that promotes the economic sustainability of producers who adopt limited irrigation practices and achieve water-use efficiency, as emphasized in the S3 scenario. Nevertheless, given the prevailing dominance of alfalfa cultivation, driven by its high yields and frequent harvest cycles, there remains a clear need to revise the support coefficients within the current model to effectively address this imbalance.

3.4 Integrated Evaluation of the Scenarios

In this section, most feasible agricultural scenarios (S113, S123, S31, and S23) listed in the previous sections are assessed in an integrated manner using economical (the increase in GVP or net income), technical criteria (the decrease in irrigation water) and stakeholder perspectives. As seen in Fig. 6 (*left*), the results obtained from the economic analysis of the scenarios are evaluated in terms of farmers' net income per 1m^3 of irrigation water used. Significant contributions to the farmer's income by €5.4–13.5 per m^3 of water use compared to reference scenario can be achieved by scenarios S113 (shifting forage crop pattern from alfalfa to vicia and trefoil), S123 (shifting oilseeds pattern from sunflower to safflower) and S116 (shifting forage crop pattern from maize to vicia). Deficit irrigation practices have a €0.8 per m^3 contribution at most in scenarios S31-S33. In contrast, a negative impact on the net income is observed for shifting the forage crop pattern from alfalfa to maize in scenarios S117-S119. While considering the decrease in irrigation water use provided in Fig. 6 (*right*), options that have considerable support to the economic gain besides serving to protect water resources are S113 and S123.

The Planned Production Support scheme, which forms the basis of Türkiye's latest support model for the 2025–2027 period, provides additional coefficient-based payments to farmers who prioritize designated crops within planned production systems in 52 basins identified as water-constrained. This development demonstrates that the scenarios proposed in this study represent not only a technical solution but also a current policy priority.

An examination of Türkiye's agricultural policy history reveals that safflower deficiency payment supports introduced in 2006 and the Basin-Based Support Model implemented in 2017 constitute important precedents for encouraging crop pattern transformation. However, as evidenced by the results of this study, product-based support alone is insufficient. To incentivize farmers to move away from high-income yet water-intensive crops such as alfalfa, a more dynamic incentive structure grounded in economic water productivity is required.

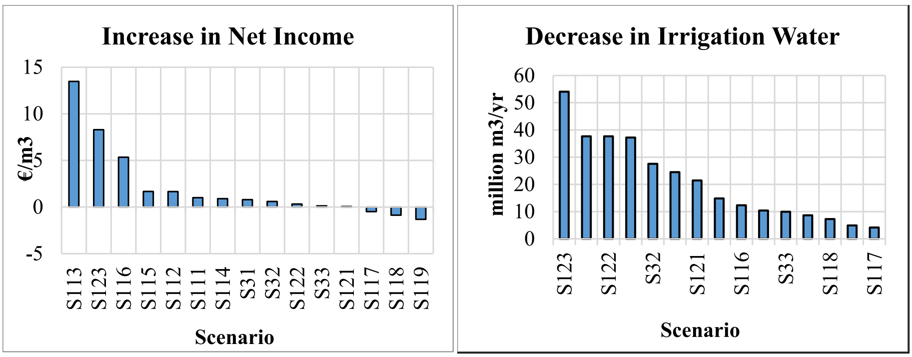

Fig. 6 Increase in the net income value relative to the reference scenario (*left*) and Decrease in the irrigation water supply relative to the reference scenario (*right*)

Furthermore, stakeholders were consulted to obtain feedback about the scenarios evaluated in this study. Representatives from several stakeholders, including Third Regional Directorate of State Hydraulic Works in Eskişehir, Eskişehir Directorate of Provincial Agriculture and Forestry, Tepebaşı District Directorate of Agriculture and Forestry, Seyitgazi Municipality, and irrigation associations (Sakaryabaşı and Eskişehir). The evaluation results emphasize that irrigation systems with open canal structures face significant inefficiencies, with up to 40% of water allocated for irrigation lost through soil infiltration. Efforts to replace these systems with closed canal structures have been hindered by financial constraints, highlighting the urgent need for cost-effective solutions. Given the complex interplay of factors such as crop water needs, climate conditions, soil structure, water transmission methods, and field application efficiency, optimizing irrigation water distribution through remote sensing technology emerges as a promising state-of-the-art approach. This method ensures precise water delivery, reducing wastage, and improving crop productivity. Additionally, transitioning to efficient irrigation techniques such as drip systems can further enhance water use efficiency despite their high installation and maintenance costs. Integrating these advancements with targeted crop management strategies offers a practical pathway to mitigate resource losses and improve agricultural sustainability.

Table 10 provides a comparative summary of the advantages and limitations of various best management alternatives to support decision-making by authorities. The most favourable scenario, S31 (deficit irrigation for grain), is widely practiced and well-suited for dry periods, but while it has an average environmental impact in terms of irrigation water use, it is less economically effective due to yield reduction risks and crop losses. In contrast, S123 (crop pattern change from sunflower to safflower) and S113 (crop pattern change from alfalfa to vicia and trefoil) are considered the most environmentally and economically effective scenarios. These scenarios achieve significant water savings and improve net income, but they rank second in favourability among stakeholders due to challenges such as lower yields, limited subsidies, and market constraints. This highlights the trade-offs inherent in each option, underscoring the need for careful prioritization of criteria (i.e., environmental, economic, and stakeholder preferences) when selecting the most suitable management practices.

To support decision making, the outputs were integrated based on three evaluation criteria: environmental, economic, and social Fig. 7. In addition, a rating from 1 (least preferred) to 3 (the most preferred) was applied to given scenarios, considering advantages and limitations stated by stakeholders and incorporated into the evaluation as a third criterion. The most favourable scenario by stakeholders (S31), has an average environmental impact in terms of irrigation of water use, yet is less economically effective. On the other hand, the most environmentally and economically effective scenarios (S123 and S113) come second in favourability among stakeholders, yet have an average impact based on the third criterion. Moreover, as the decrease in irrigation water use increases, the economic benefit also increases, which aligns with stakeholders' perspectives. The integrated evaluation reveals a strong correlation between environmental effectiveness, economic benefit, and social acceptability, demonstrating that scenarios performing well environmentally also tend to achieve both economic and social objectives, providing a balanced and reliable basis for decision-making.

These findings can be directly operationalized within Türkiye's water and agricultural policy agenda for climate resilience and sustainable agriculture. From a *water-governance*

Table 10 An overview incorporating advantages and limitations of best management alternatives

Scenario	Advantages	Limitations
S113 (crop pattern change: from alfalfa to vicia & trefoil)	The highest contribution to the net income Significant decrease in irrigation water use Trefoil grows on arid, weak, and gravelly soils that are not suitable for alfalfa cultivation Trefoil is funded equally to alfalfa under forage crop production support R&D to compensate financial losses of farmers Trefoil is a perennial such as alfalfa	Alfalfa has a higher yield than vicia or trefoil Vicia has less fund than alfalfa
S123 (crop pattern change: from sunflower to safflower)	A significant contribution to the net income The highest decrease in irrigation water use Safflower has a wide range of uses, rich in content and high quality Safflower is drought and cold resistant, suitable for arid land	Low yield Sales problems due to lack of industry No available government subsidies Downside of decreasing the soil moisture and nutrition level
S23 (improved irrigation: from sprinkler to drip)	The government loan is available for drip irrigation as well as sprinkler Product yield increases proportionally to irrigation efficiency The drip irrigation is more favourable after the sprouting The suitable method to apply water with fertilizer	Not practicable to install cultivated lands due to higher effort & cost compared to sprinkler
S31 (deficit irrigation: grain)	Already practiced widely by farmers Alternative wheat type is suitable for dry periods	Risk of yield decreases & crop loss Restrictions on the export & import of wheat Negative impacts of climate change on grain yield
S32 (deficit irrigation: sugar beet)	To grow economically valuable product even in the drought season	Has a quota defined Risk of yield decreases & crop loss
S33 (deficit irrigation: maize)	Has no quota defined Government subsidy for maize production is available	Risk of yield decreases & crop loss

perspective, the observed reliability gradient motivates making downstream reliability an explicit basin-management objective, supported by allocation rules that transparently account for upstream–downstream trade-offs and by monitoring systems that track compliance and effectiveness. In practice, this means that irrigation-development approvals and

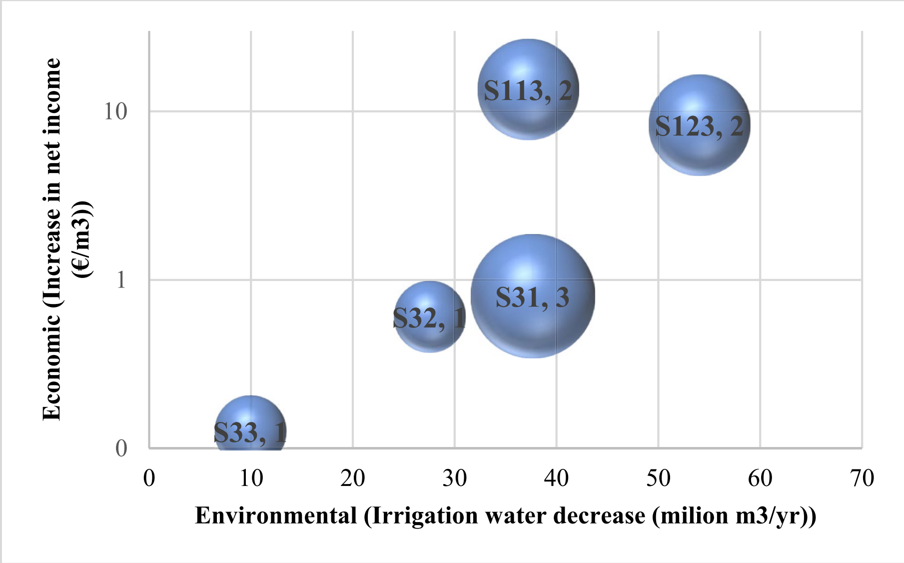

Fig. 7 Integrated evaluation based on environmental, economic, and social criteria (y axes is in logarithmic scale)

seasonal operating decisions can be evaluated against reliability targets for downstream demand sites (e.g., Ayvalı), rather than only against annual basin totals.

From an *agricultural support* perspective, the socioeconomic results show that maximizing income per hectare can conflict with minimizing water use; therefore, support schemes are more likely to accelerate adoption if they reward *economic water productivity* (e.g., net income per m^3) and share transition risks for farmers moving away from water-intensive crops. A practical policy instrument is to couple planned-production and basin-based supports with *i)* time-bound *transition* payments for crop switching (e.g., toward safflower and less water-intensive forages), *ii)* performance-based incentives linked to verified reductions in irrigation withdrawals or improved application efficiency, and *iii)* extension and demonstration programs that reduce uncertainty about yields and management.

Finally, the stakeholder feedback on conveyance losses and the high cost of modernization underscores a *public-investment* priority: pairing farm-level measures with targeted investments in delivery efficiency (e.g., canal rehabilitation/closure where feasible) and operational tools (remote-sensing-informed scheduling and advisory services) so that modelled water savings translate into real water available for drought buffering, ecosystem protection, and downstream users. Taken together, the results support a policy pathway in which drought-year planning, incentive design, and infrastructure investments are coordinated around measurable outcomes such as reliability, shortfall reduction, and water-based economic productivity.

4 Conclusions

This study developed and applied an integrated decision framework for agricultural water management in the Upper Sakarya basin, combining WEAP-based scenario analysis (demand, supply, shortfall, and reliability) with a producer-oriented economic assessment and a stakeholder-informed feasibility review. The scenario results indicate that substantial demand reduction is achievable through a portfolio of measures: crop-pattern shifts and improved management practices can reduce irrigation supply requirements and shortfalls, and the largest benefits occur in dry years-a critical finding for planning under increasing drought risk. Crop-pattern change scenarios (S113 and S123) and selected deficit-irrigation strategies (S31 group) stand out as high-potential options, while combined measures (C-group) demonstrate that integrating interventions can yield the strongest overall system response. The analysis further shows that effective agricultural practices can deliver water savings of up to about 60 hm^3/year (S123), while socioeconomic results highlight an important policy message: land-based profitability and water-based productivity can diverge, so incentives should reward income per unit water rather than only output per hectare.

A second key finding is the spatial distribution of service: groundwater-based demand sites achieve full reliability in the simulations, whereas surface-water reliability remains heterogeneous (51–99% across scenarios and sites), with upstream locations more reliable than downstream locations (e.g., Ayvalı). This upstream–downstream gradient implies that basin-wide *water saving* does not automatically translate into improved downstream water security unless allocations, operating rules, and monitoring are aligned with equity and reliability objectives.

Decision-makers can use these findings to improve agricultural water management through the following targeted actions:

Adpot a Portfolio Implementation Pathway: prioritize S113 and S123 as drought-resilient demand-reduction measures, and pair them with deficit-irrigation programs (S31 group) where agronomically suitable to reduce risk and broaden applicability across crops and sub-basins.

Make Reliability an Explicit Planning Target: set minimum surface-water reliability objectives for downstream demand sites (e.g., Ayvalı) and evaluate any planned upstream expansion against these thresholds to manage upstream–downstream trade-offs.

Reform Support Schemes Toward Water Productivity: calibrate planned-production and basin-based supports so that payments reflect economic water productivity (e.g., net income per m^3) and compensate farmers for switching away from water-intensive crops (notably alfalfa) during the adaptation period.

Remove Adoption Barriers for High-performing Options: complement crop-pattern recommendations with market and value-chain measures such as contract farming, offtake guarantees, processing capacity for safflower and alternative forages, and expand extension services to reduce perceived yield and market risks.

Target Loss Hotspots in the Delivery System: prioritize investments that reduce conveyance losses (transition from open to closed canals where feasible) and deploy remote-sensing-supported irrigation scheduling and monitoring to ensure that modelled savings materialize in practice.

The effectiveness of individual scenarios depends on hydrologic variability, local crop suitability, and economic/market conditions; consequently, the highest-ranked technical options may not be adopted at scale without coordinated incentives and implementation support. The heterogeneous reliability outcomes also indicate that additional operational analysis (e.g., reservoir operation rules, abstraction/return-flow representation, and compliance monitoring) is needed to ensure that water savings translate into downstream service improvements.

Overall, the integrated evaluation demonstrates that jointly considering environmental performance (water savings and reliability), economic outcomes (profitability and water productivity), and stakeholder feasibility yields a practical basis for drought-aware, equity-sensitive policy design. Finally, improvements observed at the Ayvalı sub-basin outlet (E12A052), representing the watershed outlet, provide a promising basin-scale signal: strengthening outlet performance is likely to reflect and reinforce improved system-wide functioning, supporting the overall conclusion that the proposed demand-side strategies can contribute meaningfully to sustainable agricultural water governance in the Upper Sakarya basin.

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Authors Contributions All authors contributed to the study of conception and design. Beyza Özel: Conceptualization, Methodology, Formal analysis, Visualization, Writing the original draft and editing; Yasemir Demir: Conceptualization, Methodology, Supervision, Writing the original draft; Emre Alp: Methodology, Visualization, Supervision, Editing, Project Administration, Funding acquisition. All authors read and approved the final manuscript.

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Data Availability The data are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

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