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A Coupled Hydrological–Multi-Criteria Framework for Irrigation Water Allocation in Regulated Canal–Aquifer Systems: Design and Demonstration on TIKEVIR (Hungary)

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Abstract

The Hajdúhát loess plateau in eastern Hungary has no perennial watercourse and overlies a drought-sensitive shallow aquifer, so irrigation supply security and allocation both constrain production. We coupled a dry-2018/wet-2020 MIKE Hydro River model of the East Main Canal (EMC) with a seventeen-year (2009–2025) MIKE SHE groundwater model, and a decision-support layer that couples conveyed-water allocation across sectors with a ranking of management responses. Calibration attains Moriasi Very Good bias-and-balance skill (mean |PBIAS| 1.59%/0.86%), with a head MAE of 1.431 m over 132 wells, and continuous validation reproduces measured discharge to within −7.7% bias over 2022–2025. Growing-season evapotranspiration (448 mm) exceeds precipitation (309 mm), leaving a 314 mm unsaturated-zone deficit; the dry-year canal terminus shows 34 of 92 no-flow days and a sustainability index of 0.09, against 0.34 when wet. A reconciled reach × sector balance and an isolating hydraulic test show the deficit is an allocation problem, not a conveyance limit. A Leopold/analytic-hierarchy-process ranking favors priority-ordered allocation over new capacity, and, in a two-objective time–quantity allocation, re-timing 8.57×10^6 m³ of fish-pond filling into winter would remove the spring deficit without new infrastructure. Dry-year supply is thus a problem of allocation and timing as much as of capacity.

Keywords: irrigation water allocation; conjunctive use; multi-criteria decision analysis; transferable decision-support framework; sustainability index; MIKE SHE; MIKE Hydro River; unsaturated-zone deficit; regulated canal; Hajdúhát; TIKEVIR



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1. Introduction

Across the Pannonian Basin, croplands occupy roughly 71% of the land surface and are predominantly rain-fed, so rising temperatures and reference evapotranspiration progressively expose them to agricultural drought [1]. In the Carpathian region, the warming is strongest in summer, lowland spring and autumn precipitation has fallen by more than 20%, and evaporative demand is rising [2]; standardized-precipitation analyses link these trends directly to maize and wheat yield losses [3]. Hungary depends on transboundary inflow for most of its water, and its evaporative demand already rivals annual precipitation, with evapotranspiration returning close to 90% of the water balance [4,5]; the recurrent drought is now tracked continent-wide and reported through European information systems [6,7]. The eastern Hungarian plains (Tiszántúl) are the country's most drought-prone

region, where a west-to-east precipitation gradient and a persistently negative summer climatic water balance make water availability the binding constraint on production. Where that balance turns negative, supplemental (blue-water) irrigation becomes structurally necessary [8], and field-scale work confirms that matching supplemental water to the soil-moisture deficit through precision irrigation raises crop water productivity [9,10]. The modeling problem is therefore a service question: how much supplemental water can be delivered in dry growing-season weeks, from which source, and at what groundwater cost?

Within the Tiszántúl, the Hajdúhát is a loess-mantled plateau ridge around Debrecen (Hungary's second-largest city, about 103–145 m a.s.l., 550–600 mm mean annual precipitation, sandy loess over Quaternary sands; [11,12]). Two features make its supply precarious. It carries no perennial natural watercourse, so agricultural water must come from groundwater or imported canal water; and its shallow aquifer is itself drought-sensitive—across 216 wells of the north-eastern plain, droughts produced significant water-table declines averaging about 0.5 m in 89% of wells, with loss of the normal annual periodicity [13,14]. A multi-decadal decline of regional groundwater storage is well documented [15–17], and end-of-century drought hazard is projected to rise most for the Great Hungarian Plain [18], so groundwater cannot be assumed to be a limitless stand-alone supply [19,20].

The imported alternative is the East Main Canal (EMC; Keleti-főcsatorna, abbreviated KFCS in Hungarian sources), the backbone of the Tisza–Körös Valley Cooperating Water Management System (TIKEVIR), which conveys Tisza water southwards from the Tiszalök barrage to the eastern plains [21,22]. It has distributed irrigation water for more than half a century [23] but is an operator-regulated watercourse whose regime is strongly tested under extremes, when irrigation, navigation and fishpond withdrawals compete for a limited conveyed volume [24]. Regional strategies already flag the growing mismatch between conveyed supply and demand [25,26] and identify the Hajdúhát loess plateau as a priority area of uncertain supply security [27,28]. The canal's reliability is bounded by the Tisza source, which periodically enters hydrological drought [29]: over 2011–2020 mean annual inflow to the Tisza catchment fell 10–40% below its 1981–2010 average outside flood years, steepest in the late-summer low-flow that coincides with peak irrigation [30,31]. The Hajdúhát loess plateau thus sits between two stressed supplies, which makes its problem a practical allocation problem—canal water, storage and groundwater compared in below-threshold days, serviceable area, storage duration, groundwater cap and seasonal recovery.

Disentangling these supplies calls for a physically based, distributed model coupling surface-water conveyance with the unsaturated and saturated subsurface. Coupled codes such as the MIKE Hydro River–MIKE SHE stack have a long record in lowland, human-influenced catchments [32–34]. Calibrating them on heavily regulated networks is intrinsically difficult: classical streamflow efficiency metrics were developed for natural rainfall-runoff transposability [35] and lose interpretability on operator-controlled reaches, where ignoring operational infrastructure lets models reach a deceptively good efficiency through parameter compensation [36] and multi-site, multi-variable calibration becomes necessary [37]; experience from data-scarce managed systems favors a multi-metric, internal-state-aware calibration over a single headline statistic [38–40]. A transparent, bias-and-balance-oriented calibration with explicit data-limitation disclosure is therefore a prerequisite for any defensible supply assessment here.

Translating a calibrated model into a decision-relevant assessment requires a quantitative reliability framework. The Hashimoto reliability, resilience and vulnerability measures [41] and the Loucks/Sandoval-Solis sustainability index [42,43] give a compact, comparable basis for judging whether a source can meet a demand, and recent semi-arid irrigation studies use exactly this family to rank supply- against demand-side options [44,45];

those applications, however, concern systems with explicit reservoir or transfer infrastructure rather than a loess plateau served by a single regulated canal and a thin aquifer.

Multi-criteria decision-making has become a standard instrument for evaluating and improving irrigation-district performance. Recent applications span the prioritization of technical irrigation projects by the analytic hierarchy process [46], the ranking of canal-operation alternatives by a hybrid AHP–entropy–WASPAS weighting [47], fuzzy multi-criteria strategy selection in large irrigation-and-drainage networks [48], entropy-TOPSIS benchmarking of district management modes and water-user associations [49,50], GIS-integrated AHP siting of irrigation systems in semi-arid conditions [51], and fuzzy risk-management frameworks for the conveyance and distribution network itself [52]. A parallel strand addresses infrastructure rather than operation: multi-dimensional resilience indices for irrigation-district assets [53], modernization-level scoring with obstacle-factor diagnosis [54], climate-resilience frameworks for collective canal systems [55], and fuzzy maintenance prioritization of irrigation channels [56], a response to the well-documented global fragility of ageing irrigation assets [57]. A third strand concerns allocation itself, where statutory or security-differentiated priority regimes have been tested against proportional sharing under drought [58,59], multi-criteria sorting has been used to assign priority classes in drought-affected regions [60], and MCDM has ranked climate-adaptation allocation options [61,62], alongside scenario assessments of alternative drought-adaptation water policies in Mediterranean basins [63], of practical allocation scenarios for future water security in drought-prone watersheds [64], and of persistent irrigation-driven scarcity in arid basins [65]. Finally, hybrid weighting–ranking architectures now dominate the field: impact-matrix scores feeding a separate MCDM ranking operator [66–68], subjective AHP weights combined with objective entropy weights [69], AHP–TOPSIS and fuzzy AHP–TOPSIS pairings applied to reservoir siting and reservoir-system operation [70,71], and best-worst-method or fuzzy-AHP alternatives to crisp AHP [72,73], within the broader use of MCDM as an integrated water-resources-management instrument [74] and with dedicated method-selection [75] and problem-structuring [76] guidance now available.

Despite this volume of work, the decision layer in the great majority of these studies is fed by elicited, aggregated or accounting-model data rather than by the output of a calibrated physical model: reviews of water-management multi-criteria analysis [77] and of multi-sectoral simulation–optimization approaches [78] confirm this asymmetry, and where a coupled hydrological model is used it typically terminates in hydrological diagnostics [79,80] rather than in a ranked management decision; the few exceptions [81–84] confirm the design is viable but remain confined to single-sector or single-process settings. A second, related gap is that statutory abstraction-priority orders are asserted as legal constraints but are seldom evaluated quantitatively against the physical supply they constrain: priority-rights regimes have been assessed economically [58,59] and preference-elicited sorting into priority classes has been proposed [60], but neither is closed against a hydraulically calibrated conveyance model. Third, asset resilience and delivered-supply reliability are measured by two largely unconnected literatures: the Hashimoto–Loucks–Sandoval-Solis reliability–resilience–vulnerability and sustainability-index family [41,43,85–87] measures outcome reliability, while indicator-based frameworks [53–55] measure asset and organizational resilience, and the two are not usually linked through a single calibrated model. The absence of a coupled assessment for the Hajdúhát loess plateau is therefore not merely a geographical gap: it is an instance of this broader methodological gap in how the decision-support literature scores and ranks irrigation-supply alternatives.

None of the framework’s individual components is new: coupled MIKE SHE/MIKE Hydro River modeling has an established record [32–34,79,80], the Hashimoto–Loucks–Sandoval-Solis reliability and sustainability-index family is well established [41–43], and

the Leopold impact matrix [88], the analytic hierarchy process [89] and even Leopold-matrix scores feeding a separate MCDM ranking operator [66,67,90] are all precedented, chiefly in water-reuse allocation rather than irrigation districts. The contribution claimed here is not the pairing of these methods but the closure of the loop between them: the impact scores that enter the Leopold matrix and the AHP hierarchy are derived from the calibrated model's reach-level deficits rather than estimated independently of it, and the resulting ranking is fed back as an allocation mask constrained by the statutory priority order and the hydraulic capacity envelope. The new scientific capability this creates is that a change in the physical system—a modified withdrawal rate, a re-timed abstraction, an added storage volume—propagates deterministically through the hydraulics, the reliability metrics, the impact scores and the final ranking, so the decision output is anchored to, and testable against, the calibrated model's reported reach-level outputs rather than resting only on expert consensus. Precedents exist for arguing the value of such a coupling in single-sector or urban settings [81,82], but, to our knowledge, not yet for a multi-sector, statutorily prioritized, groundwater-dependent regulated-canal district.

Building on this gap, the aim is to couple a calibrated MIKE Hydro River model of the EMC with a seventeen-year MIKE SHE model of the Hajdúság–Hortobágy catchment to characterize the per-zone water budget of the plateau, to map its spatially resolved supplemental-water indicator, to evaluate the reliability of the imported supply at the terminus, and to compare surface-water and hybrid scenarios while treating groundwater-only use qualitatively, reporting the calibration metrics together with the model's data-limited and structural caveats so the ranking rests on a defensible, reproducible basis.

This study therefore pursues six aims: (i) to calibrate a coupled, wet/dry operationally conditioned canal–aquifer model of this regulated lowland system and to report the full Moriasi metric suite rather than a single headline statistic; (ii) to derive a spatially explicit growing-season supplemental-water indicator directly from the modeled unsaturated-zone deficit; (iii) to extend the reliability–resilience–vulnerability and sustainability-index framework, previously applied to reservoir and inter-basin-transfer systems [44,45], to a canal-fed loess plateau with no perennial watercourse, screening surface-water and hybrid supply configurations against a study-defined wet-year reference while treating groundwater-only use qualitatively; (iv) to reconcile, with a calibrated companion canal water-distribution model, the reach-by-sector cubic-metre balance of the conveyed supply and to rank candidate management strategies by Leopold and analytic-hierarchy-process multi-criteria analysis; (v) to resolve the seasonal deficit in time as well as in space through a two-objective time–quantity allocation that asks not only how much water each sector receives but when; and (vi) to demonstrate how the framework translates these diagnostics into management-relevant terms—service reliability, storage sufficiency, capped-groundwater rules and priority-ordered, re-timed allocation—illustrated for TIKEVIR in a form interpretable by water authorities and agricultural users.

2. Materials and Methods

2.1. Study Area

The model domain is the Hajdúság–Hortobágy (HaHo) sub-catchment of the TIKEVIR system, approximately 4100 km² on the eastern Great Hungarian Plain (Figure 1). The catchment is divided into four hydrogeomorphic zones: A (Hortobágy alluvial lowland), B (Nyírség-margin plain), C (Hajdúhát, the loess plateau that is the focus of this study) and D (Sárrét marshland). The East Main Canal runs along the western edge of the plateau from the Tiszalök barrage to Bakonszeg, the canal's downstream terminus, a regulated reach of about 98 km divided into three impounded sections named for their downstream control structure: Reach I (Tiszalök to Balmazújváros), Reach II (Balmazújváros to Hajdúszoboszló),

and Reach III (Hajdúszoboszló to Bakonszeg), the terminal reach. Land cover (CORINE 2018) is dominated by non-irrigated arable land (78%), confirming an extensive rain-fed cropping system dependent on supplemental water in dry summers.

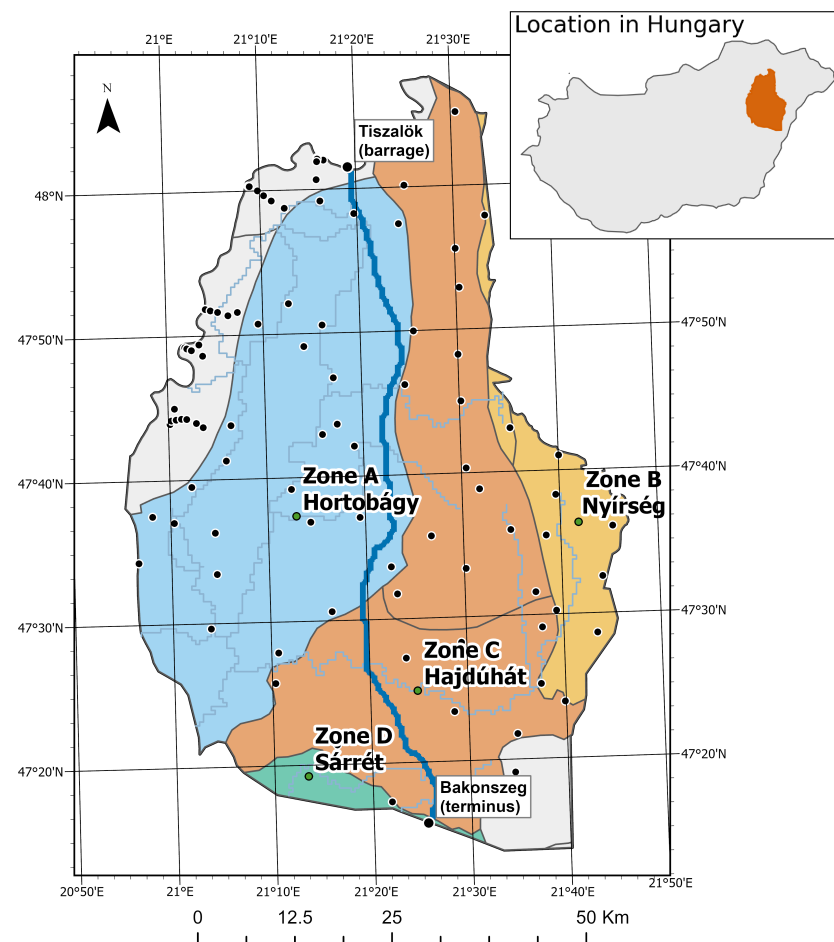


Figure 1. Study area: the Hajdúság–Hortobágy sub-catchment of the TIKEVIR system on the eastern Great Hungarian Plain, the EMC from Tiszalök to Bakonszeg (Keleti-főcsatorna in Hungarian), the four model zones (A–D), and the 132 groundwater monitoring wells. Zone C, the Hajdúhát loess plateau assessed in this study. Colour fills denote the four model zones: blue = Zone A (Hortobágy), yellow = Zone B (Nyírség margin), orange = Zone C (Hajdúhát) and green = Zone D (Sárrét); grey areas lie outside the modeled HaHo domain. The thick dark-blue line is the EMC from the Tiszalök barrage to the Bakonszeg terminus, thin blue lines are the secondary canal network and thin grey lines administrative boundaries. Black dots mark the 132 groundwater monitoring wells and the green-outlined circles the representative wells whose simulated and observed heads are reported in the Results; the inset shows the location of the catchment (orange) within Hungary.

Daily meteorological forcing, precipitation, temperature, and reference evapotranspiration computed by the Penman–Monteith method, are taken from HungaroMet gridded products (<https://odp.met.hu>, accessed 15 September 2025) [91,92]. The unsaturated-zone soil-hydraulic parameters follow the national HU-SoilHydroGrids van Genuchten retention parametrization for the loess cover [93]. Groundwater observations come from 132 monitoring wells (data from OVE, Hungary’s national water directorate; <https://www.vizugy.hu>, accessed 15 September 2025); the 1 January depth-to-water provides the year-specific initial state for the groundwater simulation.

2.2. Coupled Model and Calibration

The assessment uses a coupled MIKE Hydro River model (1-D channel hydraulics) and a MIKE SHE model (distributed groundwater, unsaturated zone and evapotranspiration) of the HaHo catchment (Figure 2). The SHE grid is 140×200 cells at 500 m resolution, with three saturated-zone layers and a full-Richards unsaturated zone model. The model inputs are the daily HungaroMet precipitation, temperature and Penman–Monteith reference evapotranspiration grids, the HU-SoilHydroGrids unsaturated-zone hydraulic parameters, the surveyed EMC cross-section geometry and documented control-structure operation, and the observed 1 January groundwater heads; the reported model outputs are the simulated saturated-zone heads, the unsaturated-zone deficit, actual evapotranspiration and the per-section canal discharge. Figure 2 sets out this architecture: the MIKE Hydro River canal model supplies the EMC boundary and the river–aquifer exchange, while the MIKE SHE model resolves the distributed saturated zone, the unsaturated zone and evapotranspiration, with the forcing data, boundary conditions, calibration targets and per-zone aggregation for the Hajdúhát loess plateau diagnostics shown as labeled inputs and outputs. The two components exchange water through river–aquifer leakage, so canal stage and groundwater head interact during the simulation; the irrigation-allocation analysis, however, is evaluated offline on the calibrated supply series rather than as a demand-constrained two-way coupling, a simplification revisited in the limitations.

The MIKE Hydro River component was calibrated for the EMC reach in the spirit of the differential split-sample philosophy [35], through a dry-year (2018) and a wet-year (2020) configuration sharing an identical cross-section topology from the surveyed geometry [23] and network structure. The two differ only in the year-specific operational parameters that reflect the documented, season-dependent canal management [24]: the Manning/Strickler resistance number M ($\text{m}^{1/3}\text{s}^{-1}$), the reciprocal-form roughness coefficient used natively by MIKE Hydro River ($M = 1/n$ in the Manning–Strickler equation), set to 27 for the dry and 32 for the wet year—equivalent to a Manning’s n of about 0.037 and 0.031, respectively, within the earth-channel range Chow [94] tabulates in the corresponding units—the representation of the two upstream control structures (fixed-crest weirs in the dry year versus daily gate operation in the wet year), and the terminal-weir crest level. Because these parameters are conditioned per year rather than held identical, the analysis is an operationally conditioned wet/dry assessment rather than a strict-sense split-sample validation.

The MIKE SHE component runs continuously from 2009 to 2025 (after a 2005–2008 initialization), using the configuration with the best calibration statistics across the iterative sequence. Regional deep discharge, which the MIKE SHE drainage module did not resolve, is represented by a lumped horizontal-conductivity free-outflow proxy; the multiplier was selected on the basin-wide head MAE (the Moriasi standard for regional groundwater models), which improves to its optimum while the streamflow-oriented Kling–Gupta efficiency degrades over the same range, so the head MAE is the calibration objective and the proxy is disclosed as a structural workaround rather than a calibrated process. Initial heads are interpolated from the observed 1 January depth-to-water at the 132 wells, and first-day (day 1) metrics are excluded to avoid initial-condition circularity.

Calibration is reported with the Moriasi performance-rating suite [95,96]: percent bias, Nash–Sutcliffe efficiency, RSR, mean absolute error, Pearson r , and, for the wells, the Kling–Gupta efficiency [97,98]. Annual mass-balance closure is computed for the three canal sections from the explicit water-balance identity (Equation (1)) [99]. Percent bias is the primary balance criterion for canal discharge, and the head MAE is the pri-

mary skill criterion for the regional groundwater model, with NSE, RSR, KGE and r as complementary diagnostics.

$$P + Q_{in} = ET_a + Q_{out} + \Delta S \quad (1)$$

where P is precipitation, Q_{in} and Q_{out} are the section inflow and outflow, ET_a is actual evapotranspiration and ΔS is the change in storage over the accounting interval, signed positive for a storage increase and negative for a storage decrease (so a drawdown interval adds to the apparent outflow side of the balance and a filling interval subtracts from it).

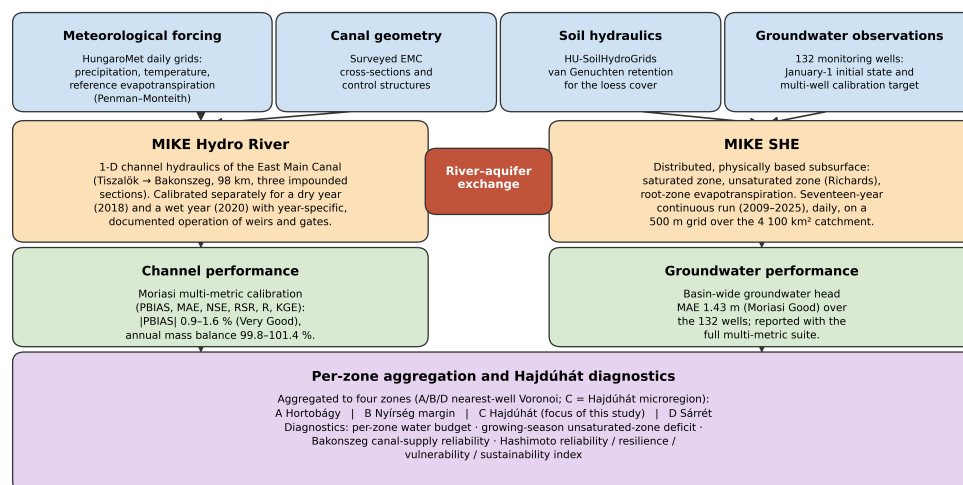


Figure 2. Coupled model architecture: a MIKE Hydro River model of the EMC (1-D channel hydraulics), calibrated separately for the dry (2018) and wet (2020) years, coupled through river–aquifer exchange to a MIKE SHE model of the distributed saturated zone, unsaturated zone and evapotranspiration. The forcing data, boundary conditions, calibration targets and the per-zone aggregation used for the Hajdúhát diagnostics are indicated.

2.3. Hajdúhát Supply Diagnostics

Four diagnostics are derived from the calibrated output, all aggregated to four zones on the SHE grid: zones A, B and D by a nearest-well Voronoi tessellation, and the Hajdúhát loess plateau by its microregion boundary (the Hajdúhát and Dél-Hajdúhátság microregions of the national landscape cadastre [100]).

The first is the per-zone water budget. Seventeen-year mean annual and April–September fluxes, precipitation, actual evapotranspiration, infiltration, recharge to the saturated zone, baseflow, and the unsaturated-zone deficit state are integrated per zone from the evapotranspiration, unsaturated-zone and saturated-zone-flow outputs of the groundwater simulation.

The second is the growing-season deficit. The April–September mean unsaturated-zone deficit per cell, averaged over the model period, is used as a model-derived indicator of the potential net supplemental-water requirement for the Hajdúhát loess plateau, framed as a net-irrigation-requirement analog of the climatic water balance $P - ET_0$ [8].

The third is canal-supply reliability. The EMC discharge at the plateau terminus (Bakonszeg) is extracted from the daily simulated series of the dry-year and wet-year canal configurations; the number of summer (June–August) days below an irrigation-relevant threshold of $0.5 \text{ m}^3 \text{ s}^{-1}$ defines a severe low-supply count, following the deficit-fraction logic of Beça et al. [45]. The $0.5 \text{ m}^3 \text{ s}^{-1}$ value is a plausibility-based estimate of the approximate minimum continuous withdrawal below which a typical tertiary off-take on the EMC secondary network—a small gravity intake or low-lift pump station of the kind implied by the Hungarian irrigation water-demand norms [101]—can no longer maintain a serviceable head

and delivery rate; below it, deliveries become intermittent regardless of nominal demand. This is a reasoned judgment call rather than a documented design specification, and we have not yet been able to source a dedicated operational standard for it; a formal sensitivity of the no-flow-day count and the sustainability index to this choice has, however, been carried out and is reported in Section 3.5: the below-threshold-day count is invariant across $0.3\text{--}1.0\text{ m}^3\text{s}^{-1}$.

The fourth is a set of sustainability metrics. For a sweep of candidate irrigation withdrawal levels ($1\text{--}6\text{ m}^3\text{s}^{-1}$, treated as decision variables rather than measured demand) we compute the Hashimoto reliability $Rel = P[\text{supply} \geq \text{demand}]$, the resilience Res (the conditional recovery rate after a failure day), the vulnerability Vul (the mean normalized shortfall) [41], and the Loucks/Sandoval-Solis sustainability index (Equation (2)) [42,43]:

$$SI = \sqrt[3]{Rel \cdot Res \cdot (1 - Vul)} \quad (2)$$

Inspired by prior reference-scenario comparisons, each option is judged against a study-defined wet-year (2020) reference rather than against an absolute optimum.

The Hashimoto withdrawal sweep is anchored to the physical demand implied by the Zone C April–September unsaturated-zone deficit. Over the Zone C (Hajdúhát) microregion area of 1623.5 km^2 (6494 cells of 0.25 km^2 on the 500 m model grid)—not the full 4100 km^2 HaHo model domain—a 314 mm seasonal deficit converts to a total volume of about $510 \times 10^6\text{ m}^3$ per growing season, equivalent to an average of roughly $32\text{ m}^3\text{s}^{-1}$ over the 183-day April–September window if the entire plateau were irrigated. Realistic irrigation fractions on the loess plateau are far lower; the $3\text{ m}^3\text{s}^{-1}$ illustrative point used in the sweep therefore corresponds to about 9% of this full-plateau requirement, i.e., to irrigating roughly one tenth of the plateau, broadly consistent with the modest fraction of cropland actually irrigated in the Tiszántúl. This provides an order-of-magnitude physical anchor, but empirical demand or permit data are still needed to justify the selected scenario.

2.4. Decision Variables and Evaluation Metrics

The supply assessment is framed as a choice among management options defined by three decision variables: the irrigation withdrawal rate Q_d ($1\text{--}6\text{ m}^3\text{s}^{-1}$, with $3\text{ m}^3\text{s}^{-1}$ as an illustrative case unless supported by observed demand or permit data), the local storage capacity C ($0\text{--}200,000\text{ m}^3$, bracketing the existing $39,213\text{ m}^3$ Vezér Street reservoir on the plateau, rounded to $40,000\text{ m}^3$ in the sweep grid), and the groundwater top-up cap $Q_{gw,max}$ ($0\text{--}2\text{ m}^3\text{s}^{-1}$). The daily canal discharge at Bakonszeg, $Q_c(t)$, is derived from the calibrated dry- and wet-year channel configurations.

The design maps model diagnostics onto decision metrics. Canal discharge is expressed as below-threshold service days and reliability-resilience-vulnerability metrics; the unsaturated-zone deficit is converted into net seasonal supplemental-water volume; storage is evaluated as short-term buffering capacity; and groundwater is treated as a capped residual source that requires drawdown and recovery checks.

For the surface-only option the delivered supply is simply the discharge taken up to demand,

$$S_{surf}(t) = \min[Q_c(t), Q_d] \quad (3)$$

For the hybrid option, a transparent daily mass-balance routing fills storage from any above-demand excess, draws it down to cover deficits, and meets the residual from the capped groundwater top-up:

$$U_{surf}(t) = \min[Q_c(t), Q_d], \quad E(t) = \max[Q_c(t) - Q_d, 0] \quad (4)$$

$$D_{stor}(t) = \min[Q_d - U_{surf}(t), V(t)], \quad (5)$$

$$V(t+1) = \min[\max(V(t) + E(t) - D_{stor}(t), 0), C]$$

$$U_{gw}(t) = \min \left[\max \left(Q_d - U_{surf}(t) - D_{stor}(t), 0 \right), Q_{gw,max} \right] \quad (6)$$

$$S(t) = U_{surf}(t) + D_{stor}(t) + U_{gw}(t) \quad (7)$$

A day counts as a failure when $S(t) < Q_d$. The augmented daily supply series is then scored with the same Hashimoto reliability, resilience, and vulnerability measures and the Loucks/Sandoval-Solis sustainability index from Equation (2) as the surface-only option, so that the two options are compared on an identical footing.

2.5. Canal Water-Distribution Model and Continuous Validation

The regional coupled model above resolves the catchment water balance and the imported supply at the plateau terminus, but the reach-by-reach distribution of the conveyed water among competing sectors, and its year-round operational reliability, call for a focused canal model at the operating scale. We therefore complement the regional MIKE Hydro River/MIKE SHE coupling with a one-dimensional unsteady hydraulic model of the 98 km EMC reach built in HEC-RAS 6.6 (US Army Corps of Engineers, scripted headlessly via the ras-commander v0.98.2 Python 3.12.6 interface), from 97 surveyed cross-sections and the documented control-structure operation, and calibrated against measured daily inflow and stage from the OVF national hydrological archive (<https://www.vizugy.hu>, accessed 15 September 2025). Using a second, independent hydraulic code for this operating-scale model, rather than extending the MIKE Hydro River model itself, lets the reach-split result below be cross-checked against the regional model's own near-zero reach-II net abstraction as an out-of-sample consistency test between two independently implemented solvers, rather than a single code's internal consistency. Canal geometry was reconstructed from the EMC's maximum operating bed storage and verified against the construction design, reproducing the design reach capacities and the maximum stored volume of about $6.9 \times 10^6 \text{ m}^3$ with a volume error of 0% to the reported precision [21,23]. Lateral abstraction was configured as a fixed fraction of inflow, $A = \alpha \cdot Q_{in}$, with $\alpha = 0.81$; a 50-point Latin-hypercube and a 44-run one-at-a-time sensitivity sweep confirm α is the single dominant control on the discharge balance (Spearman $\rho = -1.000$ and a first-order Sobol index of ≈ 0.96 between α and the discharge percent-bias, consistent across all three calibration years, 2018/2020/2022) and identify a Moriasi-conform stable region of $\alpha \in [0.766, 0.810]$ across the calibration years, and the reach split (about 0.49/0.05/0.46) follows the measured off-takes and is independently cross-checked against the near-zero reach-II net abstraction of the regional river model, tying the two canal representations together.

Model evaluation followed the differential split-sample philosophy [35]: the abstraction fraction and the Manning's n (HEC-RAS convention) were fitted on the dry summer of 2018 (percent-bias -0.8% , water-surface-elevation Nash–Sutcliffe efficiency, WSE-NSE, 0.994) and held frozen for the wet year (2020: bias -23.9% , WSE-NSE 0.690) and for 2022 (bias $+0.2\%$, WSE-NSE 0.635), scored with the Moriasi [95] discharge-bias thresholds and the Nash–Sutcliffe efficiency [102]. For year-round operational scheduling, the single coefficient was replaced by a seasonal monthly profile $\alpha(\text{month})$ calibrated during 2018–2021, with winter values clustering near 0.59–0.69 and a July–August peak of about 0.86; all geometry, roughness and structure rules were unchanged. This continuous model is headless-stable over nearly four years (maximum absolute stage error about 0.7 m) and was validated against freshly published OVF discharge to 15 September 2025, as reported in the Results.

2.6. Sectoral Allocation and Scenario Decision-Support

Beyond the reach-terminus reliability of the imported supply, the framework also resolves where the delivered water goes and how alternative management responses compare. The summer canal inflow is routed down the three impounded reaches as an inflow-

proportional withdrawal, and the per-reach total is disaggregated by sector—ecological base flow, fish-pond replenishment, irrigation, municipal drinking water, industrial cooling, and the trans-valley Körös transfer (water exported across the basin divide to the neighboring Körös river system)—by iterative proportional fitting that fuses measured off-takes, the calibrated channel net abstractions, operator permits and statutory allocations, with each cell constrained to the measured reach boundaries and closed to a near-zero marginal residual. Irrigation demand follows the Hungarian irrigation water-demand standards [101]. The reconciled reach $\times$ sector matrix and the cubic-metre cascade are reported in Section 3.6.

Management responses are evaluated for four canonical inflow scenarios—a historical drought (S1), an RCP4.5 mid-century case (S2), an RCP8.5 end-of-century lower edge (S3), and an industrial-expansion demand case (S4)—under three intervention strategies: status quo with no compensation (A), a no-regret package combining demand saving, temporal bed-storage transfer, mobilization of inland excess water and demand de-synchronization (B), and an integrated package that adds a structural Tisza-intake/Körös-transfer increase via the Civaqua scheme (a planned Debrecen-area programme conveying Tisza water westward to recharge the Hajdúság) (C); these management strategies A/B/C, which combine demand- and supply-side measures, are distinct from the surface-only and hybrid supply options assessed above. Where a reach falls into deficit, five compensation sources are applied in cost order, each capped at its seasonal delivery rate: bed-storage re-timing, inland-excess-water storage in the Hortobágy–Berettyó system (a lowland canal-and-floodplain network storing surplus inland water), urban rainwater harvesting, industrial grey-water reuse, and the Civaqua inter-basin transfer. Allocation follows the statutory abstraction-priority order [103], which protects ecological base flow and drinking water before irrigation in every scenario.

The three strategies are ranked by two complementary multi-criteria methods. A Leopold impact matrix [88] scores each strategy on nine sub-indicators across ecology, economy and society, and an analytic hierarchy process [89] with a three-level hierarchy derives criterion weights by the eigenvector method, anchored on the statutory priority order and comparable water-allocation studies [90,104]; consistency was acceptable at every level ($CR < 0.10$). Robustness was tested against a legal-anchored weight set, an $N = 10,000$ Monte-Carlo draw, and $\pm 20\%$ perturbations of each criterion weight. Coupling a Leopold impact matrix to an AHP weighting stage is itself a precedented two-stage design—impact-matrix scores generated first, a separate method supplying weights and the final ranking second—previously applied to water-reuse allocation [66,67,90]; the present study extends this architecture to a regulated, multi-sector irrigation district and, critically, derives the Leopold magnitude scores from the calibrated model's reach-level and scenario-level outputs (the reconciled reach $\times$ sector balance, the sustainability-index screening and the MOWA re-timing result) rather than from expert elicitation alone, so double counting between the ecological, economic and social sub-indicators is limited by construction: each sub-indicator maps to a distinct, model-derived quantity (e.g., ecological base-flow shortfall, irrigation/Körös-transfer curtailment, compensation cost) rather than to overlapping qualitative judgments, following the criteria-independence principle for combined MCDA methods [76].

Table 1 reports the framework in full. Each sub-indicator is scored on the Leopold magnitude scale from -3 (strongly adverse) through 0 (neutral) to $+3$ (strongly favorable). The sign convention is embedded at the scoring stage—for the two intrinsically cost-directed sub-indicators (water-quality risk and investment and operating cost), a higher burden receives a more negative score—so that a single “higher is better” convention applies to all nine, and the decision matrix is then normalized sub-indicator by sub-indicator with a min–max transformation across the three strategies,

$$\tilde{x}_{ij} = \frac{x_{ij} - \min_k x_{kj}}{\max_k x_{kj} - \min_k x_{kj}} \in [0, 1], \quad (8)$$

where x_{ij} is the Leopold score of strategy i on sub-indicator j (a sub-indicator with zero range is assigned 1.0 for all strategies). The global weight of each sub-indicator is the product of its pillar weight and its within-pillar local weight, renormalized to $\sum_j w_j = 1$; both are eigenvector weights of the corresponding Saaty pairwise-comparison matrix, and the consistency ratio is acceptable at every level (criterion level CR = 0.000; ecology CR = 0.000; economy and society CR = 0.008; all $\ll 0.10$). The aggregate score of each strategy is $S_i = \sum_j w_j \tilde{x}_{ij}$. The resulting alternative-performance matrix is reported with the ranking results in Section 3.6.

Table 1. Complete specification of the nine Leopold/AHP sub-indicators: definition, the model-derived quantity each is scored from, the rubric mapping that evidence onto a score, benefit/cost direction, and the AHP weights. Pillar weights: ecology 0.4286, economy 0.2857, society 0.2857.

Sub-Indicator	Definition and Model-Derived Scoring Evidence	Dir.	w_{local}	w_{global}
Ecology pillar (weight 0.4286)				
1. Ecological low-flow	Maintenance of the ecological base flow at the Kadarcs minimum and of the Körös-transfer obligation under drought; scored from the reach-level residual remaining after the statutory priority allocation (Section 3.6). <i>Rubric:</i> neither obligation held under drought $\rightarrow -2$; both held but a reach-III residual remains $\rightarrow +1$; both held with the residual closed $\rightarrow +2$.	B	0.5000	0.2143
2. Water table and biodiversity	Direction of the shallow water-table response to bed-storage retention and inter-basin transfer, referenced to the national river-basin management plan objectives; scored from the MIKE SHE Zone C head trend. <i>Rubric:</i> decline continues unchecked $\rightarrow -2$; bed-storage retention arrests the decline $\rightarrow +1$; retention plus inter-basin transfer reverses it $\rightarrow +2$.	B	0.2500	0.1071
3. Water quality	Quality risk introduced by mobilizing inland excess water and industrial grey water as compensation sources; the integrated package alone carries this risk; scored based on which compensation sources each strategy mobilizes. <i>Rubric:</i> no additional source mobilized $\rightarrow 0$; inland excess water and industrial grey water brought into the supply $\rightarrow -1$.	C	0.2500	0.1071
Economy pillar (weight 0.2857)				
4. Investment and operating cost	Capital and operating cost of the intervention package; the structural conveyance component of the integrated package dominates. Scored cost-negative. <i>Rubric:</i> no capital outlay beyond current operation $\rightarrow +2$; demand-side and re-timing measures only $\rightarrow -1$; structural conveyance investment (of the order of 4–5 million HUF ha ⁻¹) $\rightarrow -3$.	C	0.1634	0.0467
5. Return and yield	Irrigation gross-margin gain on the served area and the stabilizing effect of guaranteed compensation delivery; scored from the served irrigated area under each strategy combined with the documented irrigation gross-margin gain of 500–700 thousand HUF ha ⁻¹ in the regional agricultural-economic record. <i>Rubric:</i> irrigation demand left unserved in drought $\rightarrow -2$; served through the compensation package $\rightarrow +1$; served with delivery guaranteed by the structural component $\rightarrow +2$.	B	0.2970	0.0848
6. Supply security	Mean share of the seasonal reach-III deficit compensated across the four inflow scenarios (A 0.0%, B 39.1%, C 55.1%), mapped linearly onto the Leopold scale (0% $\rightarrow -3$; 100% $\rightarrow +2$).	B	0.5396	0.1542
Society pillar (weight 0.2857)				
7. Equitable access	Protection of the downstream reach III and of drinking-water access when curtailment is imposed; scored from the spatial incidence of the residual deficit. <i>Rubric:</i> the whole residual deficit falls on the downstream reach $\rightarrow -2$; it is reduced but not removed $\rightarrow +1$; it is closed $\rightarrow +2$.	B	0.5396	0.1542
8. Rural employment	Employment effect of the irrigated area sustained under each strategy, referenced to the national irrigated area of about 60–70 thousand ha and the 65.8 billion HUF CAP irrigation-support envelope. <i>Rubric:</i> served irrigated area contracts $\rightarrow -1$; is sustained $\rightarrow +1$; expands $\rightarrow +2$.	B	0.1634	0.0467
9. Social acceptance	Stakeholder acceptance of the package, anchored on the 97% farmer support for sustainable irrigation reported for Hungary [105]; the integrated option carries the acceptance sensitivity of a structural scheme that the no-regret package avoids. <i>Rubric:</i> no response to a recognized problem $\rightarrow -1$; measures with documented farmer support and no structural component $\rightarrow +2$; the same support but with the acceptance risk of a large structural scheme $\rightarrow +1$.	B	0.2970	0.0848
Sum				0.9999 ^a

Note(s): All sub-indicators are scored on the same Leopold magnitude scale (−3 to +3, dimensionless); the *Rubric* clause in each row states the evidence-to-score mapping actually applied, so every entry of the performance matrix reported in Section 3.6 can be traced back to the condition that produced it. Italics mark the Rubric sub-label within each cell; bold rows are pillar group headings. B = benefit direction (higher is better); C = cost direction (higher is worse, sign embedded at scoring); the cost direction of sub-indicators 3 and 4 is embedded in the sign of their scores, so a uniform “higher is better” min–max normalization applies to all nine (Equation (8)). Local weights are within-pillar; global weights are the renormalized product of pillar and local weights. ^a The unrounded global weights sum to exactly 1.0000; the printed four-decimal values sum to 0.9999 because of rounding.

The scenario layer treats the critical summer as a single simultaneous peak, yet operational practice decides when water is delivered as much as how much: during the 2025 drought, the TIKEVIR-wide coordination allocated water against daily-reported demands in eight-hour scheduling units, narrowed to four-hour units as reserves fell, expressly to reduce the simultaneity of demands [106]. To give this time dimension a formal method, we adapted the multi-objective land-allocation procedure that Tamás [107] applied to the reallocation of finite land between competing objectives—fuzzy-standardized factors, weights,

and an iterative resolution of the conflict zone along the 45° decision line [108,109]. The water analog, here termed multi-objective water allocation (MOWA), replaces raster pixels with (reach $\times$ month) allocation cells and the two land-use objectives with two conflicting decision objectives: time suitability, whether a sectoral abstraction is agronomically and operationally appropriate in a given month, and quantity suitability, whether water remains for it after all higher-ranked statutory uses. Both are standardized to the 0–255 fuzzy scale of the original procedure, combined with equal weight by default (a 0.3–0.7 sweep is reported), and constrained by the statutory abstraction priority order [103] and the hydraulic capacity envelope as Boolean masks. The single re-timable component is fish-pond filling— $8.57 \times 10^6 \text{ m}^3$, whose status-quo March–May window has an out-of-season October–February alternative proposed half a century ago by Bocz [110]—and any re-timed winter withdrawal must stay within the proven winter operating envelope. The heuristic is benchmarked against the linear-programming optimum of the same placement problem.

2.7. Trend Statistics

For the Zone C groundwater trend, we report, alongside the ordinary least-squares slope, the non-parametric Mann–Kendall test and Sen’s slope, and a Newey–West heteroskedasticity- and autocorrelation-consistent (HAC) correction of the OLS standard error, so that trend uncertainty is reported with serial-correlation-aware diagnostics for the seventeen-year series. A dedicated gate-driving experiment tested whether the MIKE Hydro River component can be made to track a supplied daily gate schedule: the Balmazújváros gate crest level was driven directly by a synthetic daily series taken from the observed headwater water-level signal (standard deviation 0.16 m), and the driven gate level itself tracked this input series exactly, as intended. The downstream simulated water level, however, did not correspondingly recover the observed variability: across every tested configuration—open-loop time-series-driven and closed-loop PID gate control alike—the simulated water-level standard deviation at the Balmazújváros gauge remained in the 0.78–1.0 m range, well above the observed 0.16 m. The experiment therefore shows that the gate schedule itself can be reconstructed and imposed on the model, but that supplying it alone is not sufficient to recover the interior dynamic amplitude; some further process (structure geometry, local storage, or an unmodeled control rule) also contributes to the gap, a more conservative reading than a simple missing-schedule explanation.

3. Results

3.1. Coupled-Model Calibration

Table 2 reports the calibration of both model components. Because the two annual configurations differ not only in climate forcing but in Manning roughness and the year-specific representation of the canal control structures, the wet/dry comparison developed below is operationally conditioned rather than a parameter-identical split-sample; the contrast therefore reflects both the climatic regime and the documented seasonal canal operation, as the limitations detail. On the EMC, the dry-year (2018) and wet-year (2020) configurations reach a mean $|PBIAS|$ of 1.59% and 0.86% across the canal gauges, with annual mass-balance closure of near 100% in both years (Table 2). The upstream Tisza inflow boundary is reproduced almost exactly, and at the plateau terminus (Bakonszeg) the seasonal-mean discharge bias is near zero in both years (Table 2). The seventeen-year MIKE SHE groundwater run attains a basin-wide head MAE of 1.431 m and $|PBIAS| = 1.32\%$ over the 132 wells. The negative Nash–Sutcliffe values at the internal canal water-level gauges are a documented consequence of the undocumented daily gate-operation schedule, a dynamic-validation limitation rather than a demonstrated process failure; the bias-and-balance criterion, which is the relevant metric for the wet/dry supply comparison, is met at Very Good

level. Table 3 tabulates this limitation explicitly: NSE is strongly negative and RSR far above the unity benchmark at every interior water-level gauge in both years, while $|PBIAS|$ at the same gauges stays within 0.08–2.00%, confirming that the dynamic (day-to-day) skill, not the mean bias or balance, is what the undisclosed gate schedule limits. The gate-driving experiment (Section 2.7) is included in the same table for direct comparison: it shows the gate level itself can be driven to match the observed input exactly, but the downstream simulated water level does not correspondingly recover the observed dynamic range. The Kling–Gupta efficiency is reported as a complementary diagnostic; for this regional groundwater application, the Moriasi head-MAE and bias thresholds remain the calibration objective.

Table 2. Calibration of the coupled model: the EMC MIKE Hydro River component (dry-2018 and wet-2020, operationally conditioned) and the seventeen-year MIKE SHE groundwater run. Moriasi class refers to the $|PBIAS|$ thresholds of [95].

Component/Metric	2018 (Dry)	2020 (Wet)	Groundwater	Threshold	Class
Mean $ PBIAS $ (%)	1.59	0.86	1.32	<10	Very Good
Annual mass balance (%)	101.4	99.8	—	≈ 100	—
Bakonszeg Q bias (m^3s^{-1})	−0.08	−0.01	—	$\rightarrow 0$	—
Upstream BC fidelity (R)	0.999	0.991	—	—	structural
Basin-wide head MAE (m)	—	—	1.431	<1.5	Good
Wells (n)	—	—	132	—	—

Table 3. Interior canal water-level gauge dynamic skill (MIKE Hydro River, dry-2018 and wet-2020 configurations), and the gate-driving experiment (Section 2.7), reported because bias-and-balance metrics alone (Table 2) do not show the magnitude of the dynamic-validation limitation. NSE and RSR use the Nash–Sutcliffe/RMSE-observations-standard-deviation convention; KGE is the Gupta et al. [97] decomposition computed from the same r , $\alpha = \sigma_{sim}/\sigma_{obs}$ and $\beta = \mu_{sim}/\mu_{obs}$ underlying the other columns. Years in parentheses denote the calibration year of the model configuration (dry 2018, wet 2020), not a literature citation.

Gauge (Year)	NSE	RSR	KGE	$ PBIAS $ (%)	r
Tiszavásvári WL (2018)	−167.0	12.94	−1.99	1.60	0.146
Bakonszeg WL (2018)	−2.66	1.91	−0.08	0.23	0.007
Tiszavásvári WL (2020)	−1298.5	36.00	−5.05	1.95	−0.310
Balmazújváros upstream WL (2020)	−21.1	4.70	−1.16	0.66	0.364
Balmazújváros downstream WL (2020)	−4.98	2.44	−0.81	0.08	0.489
Bakonszeg WL (2020)	−448.3	21.17	−1.50	2.00	0.091
Gate-driving experiment (Balmazújváros upstream WL, 2020, driven by observed headwater series):					
Driven-gate run	−30.8	5.63	n/a	0.46	0.374

Observed versus simulated groundwater heads at representative wells are shown in Figure 3. The simulated canal water-level long profile reproduces the impounded-section structure between Tiszalök and Bakonszeg, with the largest residual at the downstream Bakonszeg water-level gauge, where the Berettyó-side boundary condition dominates a short terminal reach.

Beyond the wet/dry calibration, the continuous year-round canal model was validated on an uninterrupted multi-year run to test its operational skill (Figure 4). On the 2018–2021 fitting window, it reaches a WSE-NSE of 0.639 and a discharge bias of +1.4%. Over the independent 2022–2025 window—extended to 15 September 2025—the aggregate outlet-discharge bias is −7.7% (Moriasi Very Good; WSE-NSE 0.558). The year-by-year decomposition (annotated in Figure 4) is dominated by 2023 as an operating outlier of the

same character as the wet-year under-bias, while 2025 (January–September) is the best validation year on record. A constant annual abstraction fraction would leave a -33.5% year-round bias, so the single seasonal-monthly adjustment improves the operational bias by more than 25 percentage points, and the model supports year-round scheduling as well as summer scenario screening.

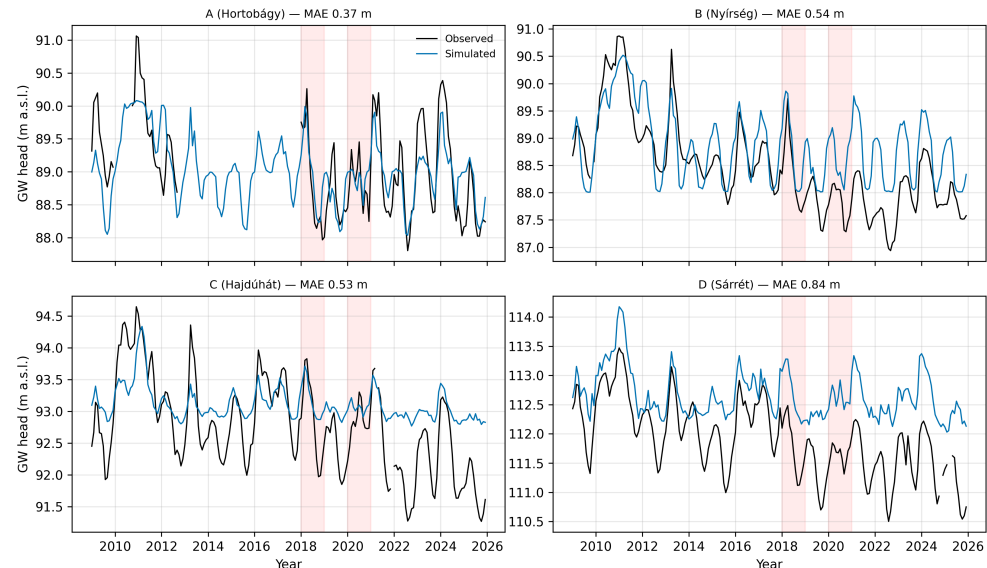


Figure 3. Observed versus simulated groundwater head (m above sea level) at one representative monitoring well of each zone, 2009–2025, shown as monthly means; the per-panel mean absolute error is computed on the daily series. The close agreement (zone MAE 0.37–0.84 m) is consistent with the basin-wide head MAE of 1.43 m. Red shading marks the calibration years (2018, 2020). Breaks in the observed line correspond to periods without measurements at the given well (longest: 2012–2017 at the Zone A well); these gaps were left unfilled.

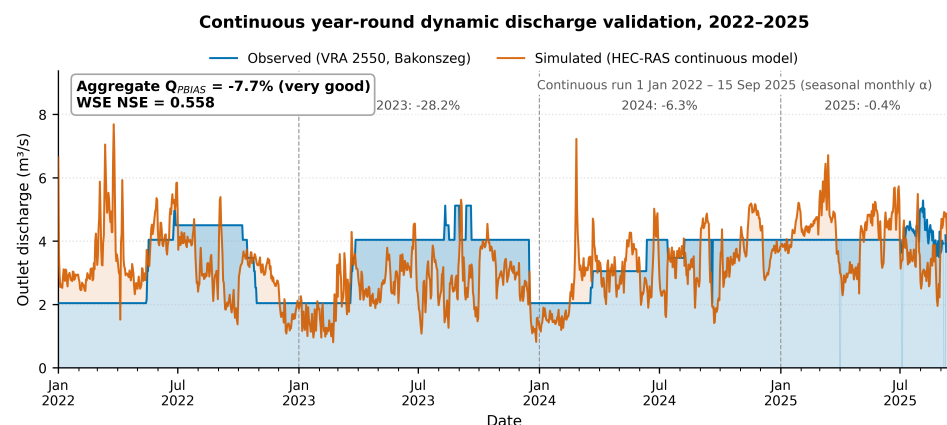


Figure 4. Continuous year-round canal-discharge validation against measured outlet discharge at Bakonszeg, 2022–2025 (extended to 15 September 2025). The aggregate discharge bias is -7.7% (Moriassi Very Good); per-year biases are annotated. The seasonal monthly abstraction profile replaces the constant fraction used for the summer calibration; the 2018 and 2020 single-year calibrations are shown separately in Section 3.5.

3.2. Per-Zone Water Budget

On the loess plateau, precipitation (548 mm yr^{-1}) is almost entirely returned to the atmosphere as actual evapotranspiration, with recharge and baseflow each only $\sim 57 \text{ mm yr}^{-1}$ (Table 4), confirming a strongly evapotranspiration-dominated, recharge-poor loess system. Critically, in the April–September growing season, Zone C actual evapotranspiration

(448 mm) exceeds precipitation (309 mm) by 139 mm, with the water being drawn from unsaturated-zone storage, the physical origin of the irrigation requirement quantified below. The annual-mean unsaturated-zone deficit of this zone is 311 mm (Table 4); the larger growing-season (April–September) figure of 314 mm and the 139 mm climatic ET–P gap are distinct quantities; the unsaturated-zone deficit integrates antecedent soil-profile drawdown rather than only the seasonal balance.

Table 4. Seventeen-year (2009–2025) mean annual water budget per zone (mm yr^{−1}). The UZ deficit row is the annual-mean state; the distinct growing-season (April–September) Zone C deficit of 314 mm, reported below, is a different quantity. Aggregated per zone from the MIKE SHE groundwater outputs (Zone C by its microregion boundary). Actual evapotranspiration is the unsaturated-zone actual-ET output only (see text); ΔS is the residual of the same closure identity ($\Delta S = P - ET_a - S_{base} + S_{leak}$). Zones A and D do not close to a physically plausible residual (see text); this is disclosed rather than resolved.

Flux Component	A (Hortobágy)	B (Nyírség)	C (Hajdúhát)	D (Sárrét)
Precipitation	551	548	548	555
Actual evapotranspiration (UZ)	306	547	547	88
Infiltration to UZ	266	361	515	95
Recharge to SZ	−13	−118	57	19
Baseflow (S_{base})	32	40	57	2
Downward leakage (S_{leak})	7	18	29	1
UZ deficit (annual mean)	249	238	311	456
ΔS (closure residual)	+220	−21	−27	+466

“Actual evapotranspiration” in Table 4 is the MIKE SHE unsaturated-zone actual-ET output only; it excludes the model’s separate direct evaporation-from-saturated-zone term, which is material where the water table is shallow. For Zone A (Hortobágy) that excluded term amounts to about 123 mm yr^{−1}, so the total modeled actual ET is about 429 rather than 306 mm yr^{−1}—consistent with an alluvial lowland zone with a shallow water table—and this is the principal reason Zone A’s closure below improves once the term is included. (The diagnostic that isolates the two terms was run on the nine-year subset for which the separate output was archived, where they are 316 and 123 mm yr^{−1}; the increment, not the nine-year base value, is what we carry over to the seventeen-year total tabulated here.) The identical 547 mm figure for Zones B and C is confirmed as a genuine coincidence of two independently computed values (546.6 and 547.2 mm) rather than a transcription error. Applying the same closure identity ($\Delta S = P - ET_a - S_{base} + S_{leak}$) to the components above, with the leakage term S_{leak} now shown explicitly, gives a small, physically plausible residual for Zones B and C (−21 and −27 mm yr^{−1}) but a large, implausible apparent storage gain for Zones A and D (+220 and +466 mm yr^{−1}); using the corrected Zone A actual-ET total (429 mm yr^{−1}) reduces its residual by the same 123 mm yr^{−1}, to +97 mm yr^{−1}—better, but still not closing exactly. Zone D’s (Sárrét) low actual evapotranspiration (88 mm yr^{−1}) is not explained by the same excluded-term effect—the direct saturated-zone evaporation term is itself small there (~6 mm yr^{−1})—so the model is simulating a genuinely dry unsaturated zone in this, the smallest of the four zones; whether this reflects the documented post-drainage history of the historically marshy Sárrét landscape or an artefact of the sparse well coverage used to define the zone could not be established from the present analysis and is disclosed as an open question rather than resolved.

An independent remote-sensing cross-check supports the zone budget to which the model is calibrated. Zone C (Hajdúhát), the microregion that anchors the 314 mm growing-season deficit, is the model’s calibration target; Zones A (Hortobágy), B (Nyírség margin) and D (Sárrét) enter the coupled model as neighborhood domains supplying the regional groundwater context rather than as independently calibrated local water budgets, and

representative water-balance models purpose-built for those environments are available in the literature [111]. We compared the tabulated zonal ET_a against the MODIS MOD16A2GF actual-evapotranspiration product (Collection 6.1, 500 m) [112], aggregated to the four zones over 2009–2024 (Table 5; per-year values available from the corresponding author on request). Because the tabulated ET_a is the model’s unsaturated-zone term only, whereas MOD16 reports total actual ET, the two are expected to agree where the water table is deep and to diverge, MODIS-high, where saturated-zone and open-water evaporation are significant. Accordingly, the MODIS-minus-model difference is only -29 and -38 mm yr⁻¹ on the deep loess plateau (Zones C and B), rising to $+194$ mm yr⁻¹ in the alluvial Zone A and $+493$ mm yr⁻¹ in the clay-floored Sárrét (Zone D). For the calibrated Zone C, the MODIS mean (518 mm yr⁻¹) reproduces the tabulated 547 mm yr⁻¹ to within the product’s inter-annual range, so the total from which the central deficit is derived is independently supported. In Zone A, the positive gap is consistent with the excluded saturated-zone evaporation identified above. Zone D is not diagnostic in this comparison—the tabulated unsaturated-zone term and a surface-driven satellite product represent very different parts of a complex, layered soil-water system there—and for a representative Sárrét/Berettyó-vidék water balance, we refer the reader to the purpose-built regional model of Tran et al. [111].

Table 5. Zonal actual evapotranspiration: model (unsaturated-zone term, Table 4) versus the MODIS MOD16A2GF total-ET product (2009–2024 mean, inter-annual range in brackets). Zones A, B and D are neighborhood/boundary zones (regional context, not calibration targets); C is the calibrated core. Zone D is non-diagnostic (see text). All values mm yr⁻¹.

Zone	Model ET _a (UZ)	MODIS ET (Mean [Range])
A (Hortobágy)	306	500 [399–573]
B (Nyírség margin)	547	509 [409–574]
C (Hajdúhát, calibrated)	547	518 [407–572]
D (Sárrét)	88	581 [507–624]

The wet/dry contrast at the annual scale is summarized in Table 6. For the entire HaHo catchment, the wet year (2020) leaves a much larger annual storage gain than the dry year (2018) ($+253$ vs. $+101$ mm; Table 6). On the loess plateau, the dry-year annual balance shows a net storage loss ($\Delta S \approx -111$ mm), while in the wet year, there is a $+53$ mm storage gain (Table 6). The zone-by-zone breakdown additionally shows the strong wet/dry buffering in Zone D (Sárrét) and the recharge deficit in Zone B.

3.3. Water-Table Conditions and Irrigation Requirement on the Hajdúhát Loess Plateau

The end-of-growing-season (31 August) depth-to-water—the operationally relevant peak-drawdown state—contrasts markedly between the dry and wet years. The catchment-mean depth-to-water is 3.02 m in 2018 and 2.49 m in 2020; for the Hajdúhát, it is 4.08 m and 3.02 m, respectively, a 1.1 m shallower water table in the wet year, consistent with the contrasting annual storage change (Table 6). This recovery is partial: multi-year memory means a single wet year does not fully erase preceding-drought deficits, as the Discussion develops.

3.4. Spatial Pattern of the Growing-Season Deficit

Aggregated to a zone mean, the 314 mm growing-season unsaturated-zone deficit (Section 3.2) conceals substantial within-plateau spatial structure. Figure 5 maps the seventeen-year (2009–2025) April–September deficit at the native 500 m grid resolution across the Hajdúhát (Zone C) boundary and its surroundings. Over the plateau area, the per-cell deficit ranges up to 576 mm, with the 90th percentile at 548 mm, and 20% of the plateau area exceeds 400 mm—concentrated along the eastern margin of the zone,

adjacent to the EMC corridor, where the shallower regional water table and the loess-to-sand transition combine to leave the largest residual unsaturated-zone drawdown. The north-western part of the plateau, by contrast, carries a markedly smaller deficit, consistent with its position closer to the Nyírség-margin recharge zone (Zone B). This spatial indicator is the direct fulfilment of aim (ii); it is the same per-cell field whose zone mean (314 mm) is reported in Table 4 and whose area-weighted 20% tail underpins the corresponding Conclusions statement.

Table 6. Annual water balance for the dry (2018) and wet (2020) calibration years, aggregated for the entire HaHo catchment (A+B+C+D) and for the Hajdúhát separately, integrated from the MIKE SHE groundwater outputs. P = precipitation; ET_a = actual evapotranspiration; R_{ch} = net recharge to the saturated zone; S_{base} = baseflow (SZ $\rightarrow$ overland); S_{leak} = downward leakage (overland $\rightarrow$ SZ); ΔS = residual storage change = $P - ET_a - (S_{base} - S_{leak})$. All values in mm yr⁻¹ (area-mean per zone).

Component	HaHo (A+B+C+D)			Zone C (Hajdúhát)		
	2018 Dry	2020 Wet	Δ	2018 Dry	2020 Wet	Δ
P (precipitation)	484	618	+134	490	623	+133
ET _a (actual ET)	357	347	−10	567	550	−17
R _{ch} (net recharge to SZ)	−50	+29	+79	+26	+120	+94
S _{base} (baseflow)	43	27	−16	69	34	−35
S _{leak} (downward leakage)	16	8	−8	35	14	−21
ΔS (storage)	+101	+253	+152	−111	+53	+164

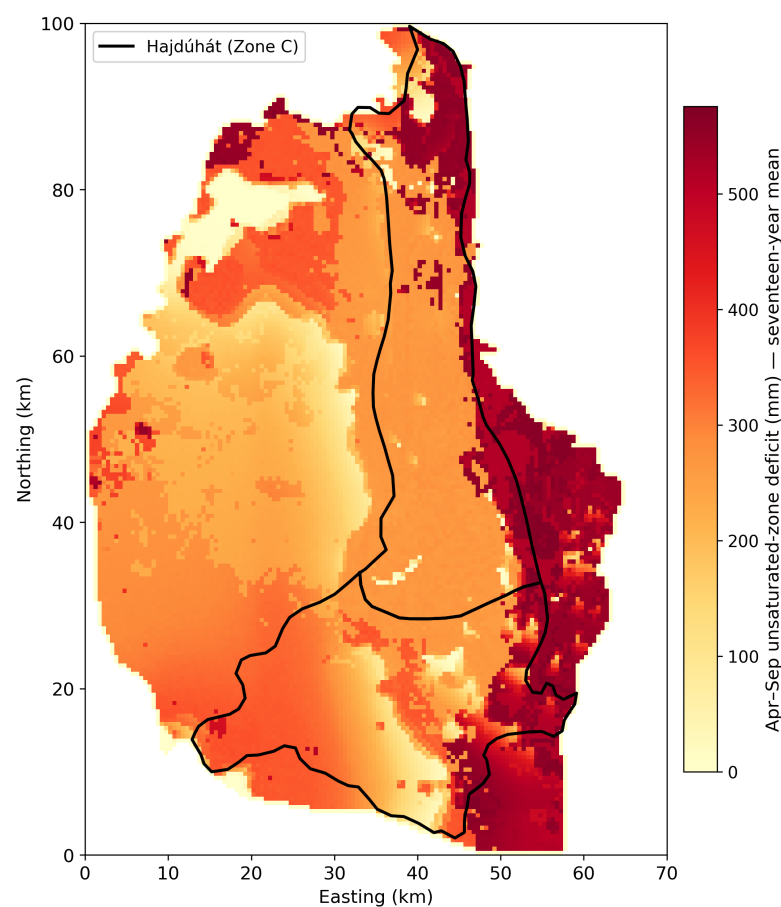


Figure 5. Seventeen-year (2009–2025) mean April–September unsaturated-zone deficit (mm) at native 500 m grid resolution across the HaHo domain; the Hajdúhát (Zone C) boundary is outlined in black. Twenty percent of the Zone C area exceeds 400 mm (90th percentile 548 mm; maximum 576 mm), concentrated along the zone’s eastern margin adjacent to the EMC corridor.

3.5. Canal-Supply Reliability and Option Ranking

Table 7 summarizes the discharge regime of the imported supply from the East Main Canal (EMC) at the plateau terminus; the reliability metrics are organized as a supply-option-by-metric matrix after Beça et al. [45] in Table 8. In the dry year (2018), the June–August 25th-percentile discharge at Bakonszeg falls to zero and 34 of 92 summer days lie below the $0.5 \text{ m}^3 \text{ s}^{-1}$ irrigation threshold, whereas the wet year (2020) has no no-flow days (Table 7, Figure 6a). This count is insensitive to the specific threshold: sweeping it from 0.3 to $1.0 \text{ m}^3 \text{ s}^{-1}$ leaves the dry-year count at 34 and the wet-year count at 0 throughout, because the dry-year low-supply days carry essentially zero conveyed flow—the next-lowest daily value is $1.23 \text{ m}^3 \text{ s}^{-1}$ —and the wet-year minimum is $1.51 \text{ m}^3 \text{ s}^{-1}$, so the dry/wet reliability contrast does not depend on the $0.5 \text{ m}^3 \text{ s}^{-1}$ value.

Table 7. Hajdúhát EMC surface-conveyance discharge statistics at Bakonszeg for the dry and wet years. No-flow = June–August days below $0.5 \text{ m}^3 \text{ s}^{-1}$; the corresponding Hashimoto reliability metrics at a $3 \text{ m}^3 \text{ s}^{-1}$ withdrawal are given in Table 8 (Option A).

Metric	Surface-Only, Dry 2018	Surface-Only, Wet 2020
Jun–Aug median Q ($\text{m}^3 \text{ s}^{-1}$)	4.33	4.82
25th percentile Q ($\text{m}^3 \text{ s}^{-1}$)	0.00	3.71
No-flow days (of 92)	34	0

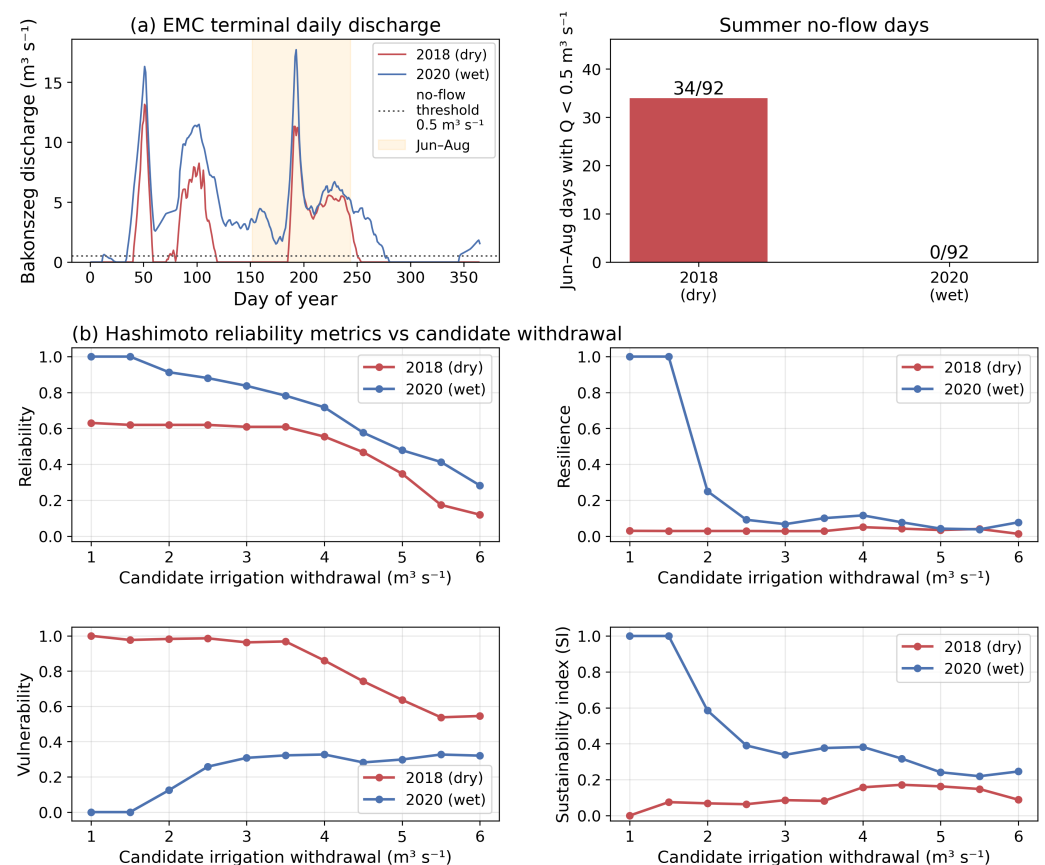


Figure 6. EMC supply reliability at Bakonszeg. (a) Daily discharge for the dry (2018) and wet (2020) years and the number of June–August days below the $0.5 \text{ m}^3 \text{ s}^{-1}$ irrigation threshold (34 of 92 in the dry year; none in the wet year). (b) Hashimoto reliability, resilience, vulnerability, and the Loucks/Sandoval-Solis sustainability index versus candidate withdrawal level; the dry-year sustainability index remains low across the range.

Translating this into Hashimoto metrics (Figure 6b), at a representative $3 \text{ m}^3\text{s}^{-1}$ withdrawal, the dry-year surface-only supply gives only a Loucks sustainability index of 0.09, improving to 0.34 in the wet year (component reliability, resilience and vulnerability values in Table 8). Judged against the wet-year reference [44], surface conveyance alone fails to provide a sustainable dry-year supply at any withdrawal above about $2 \text{ m}^3\text{s}^{-1}$.

Applying the Option C hybrid routing offline to the calibrated Bakonszeg supply series—an option-screening calculation, not a coupled re-run—estimates the achievable gain (Figure 7, Table 8). Local storage alone, sized at the existing Vezér Street reservoir ($40,000 \text{ m}^3$), barely improves the dry-year SI, because dry-year discharges leave little above-demand excess to buffer; a $100,000 \text{ m}^3$ reservoir plus a capped $1.0 \text{ m}^3\text{s}^{-1}$ groundwater top-up (Option C4) doubles the dry-year SI to 0.18 and lifts the wet-year SI to 0.59. The wet-year 0.59 crosses the study-defined benchmark ($\text{SI} \geq 0.5$), whereas the dry-year 0.18, though double the surface-only 0.09, stays in the index’s low, drought-stressed range [43]. Storage capacity alone is therefore insufficient on the loess plateau, and the capped groundwater contribution is the decisive lever; a coupled simulation of the preferred configuration remains a required confirmatory step.

Table 8. Quantified hybrid (Option C) variants at the $3 \text{ m}^3\text{s}^{-1}$ representative withdrawal, evaluated by Hashimoto metrics on the post-processed Bakonszeg supply series. Reservoir capacities and the groundwater cap are decision variables. The $40,000 \text{ m}^3$ row is the rounded sweep-grid value corresponding to the existing $39,213 \text{ m}^3$ Vezér Street reservoir.

Scenario	2018 (Dry)				2020 (Wet)			
	Rel	Res	Vul	SI	Rel	Res	Vul	SI
Option A (surface only)	0.61	0.03	0.96	0.09	0.84	0.07	0.31	0.34
Option C1 (40k tank, no GW)	0.61	0.03	0.96	0.09	0.85	0.07	0.32	0.35
Option C2 (100k tank, no GW)	0.61	0.03	0.95	0.09	0.86	0.08	0.33	0.35
Option C3 (40k + $0.5 \text{ m}^3/\text{s}$ GW)	0.62	0.03	0.82	0.15	0.88	0.09	0.21	0.40
Option C4 (100k + $1.0 \text{ m}^3/\text{s}$ GW)	0.62	0.03	0.64	0.18	0.91	0.25	0.08	0.59

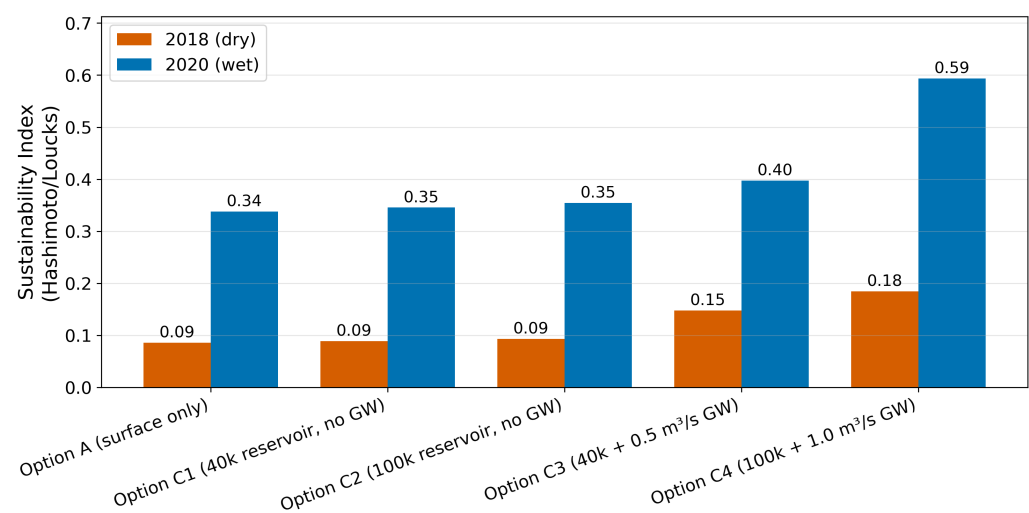


Figure 7. Loucks sustainability index for the surface-only baseline (Option A) and the four hybrid configurations (Option C1–C4) at the $3 \text{ m}^3\text{s}^{-1}$ representative withdrawal, for the dry (2018) and wet (2020) calibration years. Adding a capped groundwater top-up is the main screening improvement; the $100,000 \text{ m}^3 + 1.0 \text{ m}^3\text{s}^{-1}$ hybrid approaches the Sandoval-Solis sustainable band in the wet year.

Over the seventeen-year groundwater record, the loess plateau’s shallow-water-table trend is weakly downward but statistically inconclusive: OLS and Sen slopes are both

$\approx -0.02 \text{ m yr}^{-1}$, but neither the OLS ($p = 0.10$) nor Mann–Kendall ($p = 0.20$) test reaches significance, and the HAC-corrected result is only borderline ($p = 0.05$). With seventeen annual values, the record is therefore still underpowered to confirm a robust decline, even though the downward direction is consistent with the regional multi-decadal pattern [13,15]. Groundwater therefore offers a buffer but not a guaranteed long-term substitute.

3.6. Water Distribution and Decision-Support Ranking

Routing the July-peak inflow down the three-reach cascade produces a $3.30 \text{ m}^3\text{s}^{-1}$ reach-III outflow, of the same order as the measured Bakonszeg seasonal mean ($\approx 2.87 \text{ m}^3\text{s}^{-1}$), which is the independent field quantity available for comparison at the outlet (Figure 8). The cascade itself closes to $\approx 1.3\%$: the abstraction implied by its endpoints (intake minus outlet, $18.45 - 3.30 = 15.15 \text{ m}^3\text{s}^{-1}$) exceeds the sum of the three per-reach withdrawals ($7.30 + 0.75 + 6.90 = 14.95 \text{ m}^3\text{s}^{-1}$, which is the inflow-proportional total $\alpha \times Q_{in} = 0.81 \times 18.45$) by $0.20 \text{ m}^3\text{s}^{-1}$, or 1.3% of the routed abstraction; this same $0.20 \text{ m}^3\text{s}^{-1}$ rounding-and-allocation residual is why the inter-reach discharges printed in Figure 8 (11.10 and $10.30 \text{ m}^3\text{s}^{-1}$) are not the exact arithmetic differences in the printed withdrawals. The 1.3% is a closure statistic of the routing, not a validation error against the Bakonszeg mean. Table 9 and Figure 8 deliberately report two different accountings of the same cascade, and we reconcile them explicitly here. Table 9 (reach totals $4.30/0.30/4.00 \text{ m}^3\text{s}^{-1}$, $8.60 \text{ m}^3\text{s}^{-1}$ overall) is the metered and licensed sectoral backbone: the ecological, drinking-water, industrial and licensed-irrigation/Körös-transfer off-takes for which a measured or permitted volume exists, reconciled against the measured reach boundaries. Figure 8 ($7.30/0.75/6.90 \text{ m}^3\text{s}^{-1}$, $14.95 \text{ m}^3\text{s}^{-1}$ overall, $= \alpha \times Q_{in} = 0.81 \times 18.45$) is the full inflow-proportional hydraulic-routing cascade, which additionally includes the named branch-canal and fish-pond-filling withdrawals not separately metered against a sector license: in reach I, the Kadarcs and Nyugati-főcsatorna-rendszer branch off-takes plus an estimated fish-pond-filling term; in reach II, a smaller fish-pond term added to the metered drinking/industrial off-takes; and in reach III, the Hamvas/Sárréti/Körös branch deliveries ($\approx 2.9 \text{ m}^3\text{s}^{-1}$) alongside the Kösely/K-VII off-take ($4.02 \text{ m}^3\text{s}^{-1}$), the latter being the routed counterpart of the $4.00 \text{ m}^3\text{s}^{-1}$ metered reach-III total in Table 9. The $\approx 6.35 \text{ m}^3\text{s}^{-1}$ difference between the two totals is exactly this set of branch-canal and fish-pond volumes, named only in Figure 8. It is not distributed evenly: the per-reach gaps are 3.00 , 0.45 and $2.90 \text{ m}^3\text{s}^{-1}$ for reaches I, II and III respectively, so the unmetered component is concentrated in the two reaches carrying the large branch-canal off-takes and is almost negligible in reach II, where the metered drinking-water and industrial licenses account for nearly all of the withdrawal. Table 9 is the subset of the cascade that closes against an audited sector license or meter, and the “balance-closed” claim refers to that reconciled subset closing against the measured reach boundaries, not to the two figures summing to the same total. The reconciled reach $\times$ sector matrix (Table 9) closes against the measured reach boundaries on this metered/licensed basis. Reach II carries the highest supply-security load—drinking water and industrial cooling—on the smallest flow, whereas reach III is dominated by irrigation ($1.60 \text{ m}^3\text{s}^{-1}$) and the Körös transfer ($1.50 \text{ m}^3\text{s}^{-1}$), the two statutory low-priority uses curtailed first under drought. Moving fish-pond filling off the July irrigation peak cuts the combined simultaneous peak from 11.8 to $9.3 \text{ m}^3\text{s}^{-1}$ (a 21% reduction) without reducing any sector’s annual volume. This seasonal-scale de-synchronization result was obtained against the nearest surplus window available in the July-peak accounting, the March spring refill; the finer (reach $\times$ month) MOWA analysis in Section 3.7 then shows that the spring window is itself a conflict zone, and identifies the October–February winter band as the placement that delivers the same peak relief without creating a new spring

deficit. The 21% figure therefore quantifies the size of the de-synchronization lever; the winter band, not the spring refill, is the placement the method selects for this system.

Under status-quo strategy A the seasonal deficit, computed on the seasonal compensation engine (the basis used throughout this subsection; the monthly MOWA accounting in Section 3.7 is a separate pipeline and gives slightly different totals), is $4.38 \times 10^6 \text{ m}^3$ in the historical-drought scenario S1 and $22.83 \times 10^6 \text{ m}^3$ in the RCP8.5 lower-edge scenario S3, while S2 and S4 carry zero deficit (Figure 9); all deficit falls on reach III, and the ecological minimum and drinking water carry zero residual in every scenario (Figure 9). The no-regret strategy B closes the deficit to zero in S1, S2 and S4 and reduces the S3 residual to $4.51 \times 10^6 \text{ m}^3$ (80.2% compensated); the integrated strategy C closes S3 as well. The S3 compensation pool ($23.15 \times 10^6 \text{ m}^3$) exceeds the deficit by volume, so the binding constraint is the seasonal delivery-rate cap of the compensation infrastructure rather than the stored volume—a finding insensitive to the sourced 10–25% mobilizable fraction of the Hortobágy–Berettyó inland-excess store.

The analytic hierarchy process ranks the integrated strategy C first, the no-regret strategy B second and the status quo A last under the statutory-priority default weights (Figure 10). The ordering is robust: $C > B > A$ holds under ecology-, economy- and society-dominant perspectives and under a legal-anchored weight set (consistent, $CR = 0.046$), the Monte-Carlo analysis ranks A last in 93% of draws, and no rank reversal occurs across any $\pm 20\%$ weight perturbation. The single exception is objective entropy weighting, which marginally prefers B to C (0.745 vs. 0.727). A second, more material caveat concerns the nine sub-indicators themselves rather than the pillar weights: three of them (the ecological low-flow, supply-security and equitable-access sub-indicators) are near-perfectly correlated (Pearson $r \geq 0.999$ across the fifteen-member scenario ensemble, $r = 1.0$ to three decimals for most pairs) in the present scoring, because each is currently driven by the same underlying reach-III deficit signal; collapsing or removing these collinear sub-indicators reverses the ranking to $B > C > A$. The headline $C > B > A$ ordering is therefore robust to weight perturbation but not yet to this scoring redundancy, and disaggregating the three collinear sub-indicators onto genuinely independent evidence is identified as a priority methodological refinement rather than a settled result. We also note that the statutory-priority default weights are the authors' own construction, anchored on the legal priority order and the comparable studies cited above, and do not yet reflect an external, independently elicited expert judgment; the elicitation instrument for such a validation exists (a structured pairwise-comparison template) but has not yet been completed by a domain expert external to the author team, and we report this as an open validation step rather than a completed one. The converged reading is nonetheless three-tiered: the status quo is unambiguously dominated, the no-regret package suffices for every scenario except the RCP8.5 end-of-century edge, and the integrated transfer is required specifically for that most severe future. The full alternative-performance matrix underlying this ranking—the raw Leopold score and the normalized value of every strategy on every sub-indicator, together with the global weights and the resulting aggregate—is given in Table 10, so that the ranking can be recomputed directly from the reported numbers.

An isolating canal test underpins this verdict: with the level-control structures holding their set-points and no abstraction, the canal conveys and holds operating water levels stably down to $6 \text{ m}^3 \text{ s}^{-1}$. Reach III (the Hajdúszoboszló–Bakonszeg section) turns to deficit only when the $\approx 81\%$ sectoral withdrawal is imposed on diminished flow. The drought deficit is therefore a demand-side allocation problem, not a conveyance limit, and active enforcement of the statutory priority order resolves the spatial mis-routing of deficits at no hydraulic cost.

Table 9. Reconciled reach $\times$ sector withdrawal matrix at the summer (July) peak (m^3s^{-1} ; iterative-proportional-fitting balance-closed, multi-source fusion). Dashes denote sectors absent from a reach; the rightmost column gives annual volumes. Values from the companion EMC operational analysis. The reconciliation with the full inflow-proportional cascade of Figure 8 is given in Section 3.6.

Reach	Ecological	Fish-Pond	Irrigation	Drinking	Industrial	Körös Transfer	Total	Annual (10^6 m^3)
I	1.49	2.45	0.18	—	—	0.18	4.30	≈ 38.5
II	—	0.02	0.05	0.126	0.065	0.04	0.30	≈ 10.0
III	0.10	0.80	1.60	—	—	1.50	4.00	≈ 30.0

Table 10. Alternative-performance matrix of the Leopold/AHP ranking: raw Leopold magnitude scores (-3 to $+3$) and min-max normalized values (Equation (8)) of the three management strategies on the nine sub-indicators defined in Table 1, with the global weights and the resulting aggregate scores $S_i = \sum_j w_j \tilde{x}_{ij}$. A = status quo, B = no-regret package, C = integrated package. The three collinear sub-indicators discussed in the text (1, 6 and 7) are marked †. Aggregates are computed from the unrounded weights, so recomputing them from the four-decimal w_j printed here can differ in the last digit (strategy B: 0.7715 unrounded, 0.7714 from the rounded weights).

Sub-Indicator	w_j	Leopold Score			Normalized		
		A	B	C	A	B	C
1. Ecological low-flow †	0.2143	−2	+1	+2	0.000	0.750	1.000
2. Water table and biodiversity	0.1071	−2	+1	+2	0.000	0.750	1.000
3. Water quality	0.1071	0	0	−1	1.000	1.000	0.000
4. Investment and operating cost	0.0467	+2	−1	−3	1.000	0.400	0.000
5. Return and yield	0.0848	−2	+1	+2	0.000	0.750	1.000
6. Supply security †	0.1542	−3.00	−1.05	−0.25	0.000	0.709	1.000
7. Equitable access †	0.1542	−2	+1	+2	0.000	0.750	1.000
8. Rural employment	0.0467	−1	+1	+2	0.000	0.667	1.000
9. Social acceptance	0.0848	−1	+2	+1	0.000	1.000	0.667
Aggregate S_i	0.9999				0.154	0.772	0.818

EMC (Keleti-főcsatorna) discharge cascade ($\text{m}^3 \text{s}^{-1}$) (July demand peak)

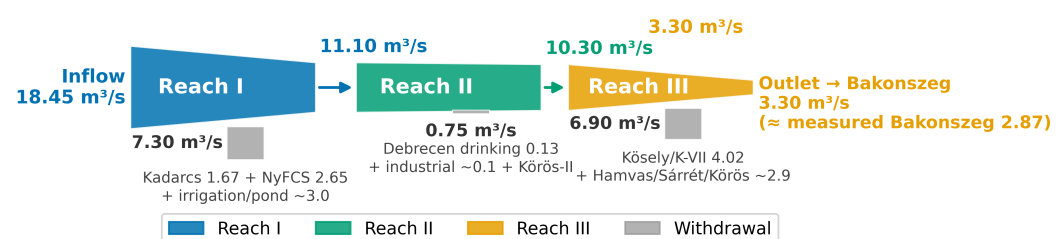


Figure 8. EMC discharge cascade (m^3s^{-1}) and per-reach sectoral water distribution at the July demand peak: canal inflow ($18.45 \text{ m}^3\text{s}^{-1}$) is routed down the three impounded reaches (11.10 and $10.30 \text{ m}^3\text{s}^{-1}$ between reaches) to a $3.30 \text{ m}^3\text{s}^{-1}$ outflow at Bakonszeg, with reach-level sectoral withdrawals shown below each reach. The outlet validates against the measured Bakonszeg mean ($\approx 2.87 \text{ m}^3\text{s}^{-1}$). The figure's per-reach withdrawal totals ($7.30/0.75/6.90 \text{ m}^3\text{s}^{-1}$) are the full inflow-proportional off-take, including branch-canal deliveries (Kadarcs, NyFCS, Köseley/K-VII, Hamvas/Sárrét/Körös); Table 9 reports the subset reconciled to named end-use sectors ($4.30/0.30/4.00 \text{ m}^3\text{s}^{-1}$), see the Results (Section 3.6) for the reconciliation between the two accountings.

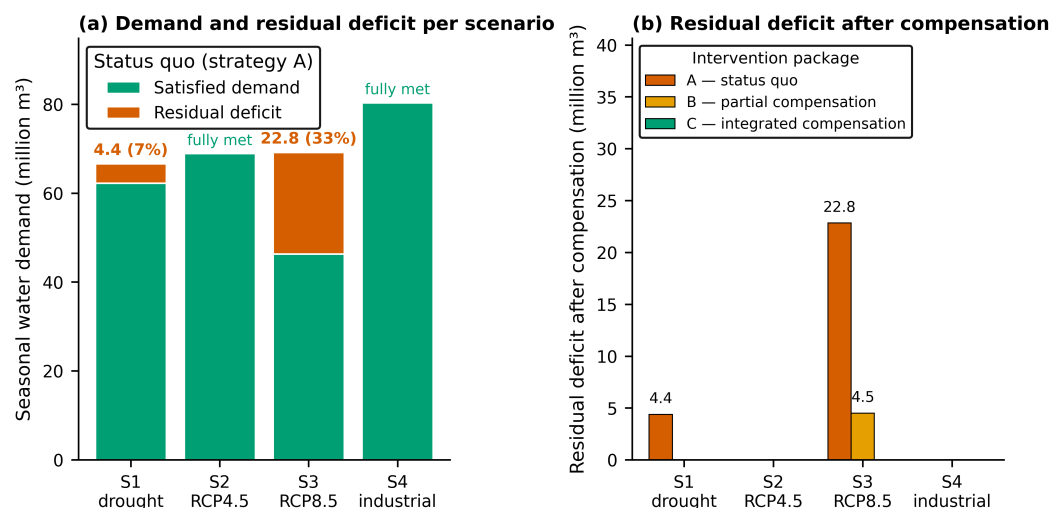


Figure 9. Status-quo seasonal water balance and residual deficit after compensation, by scenario. (a) Total seasonal demand under status-quo strategy A for the four scenarios (S1 drought, S2 RCP4.5, S3 RCP8.5, S4 industrial), split into the satisfied volume and the residual deficit (S1 4.38 and S3 22.83×10^6 m³, i.e., 7% and 33%; S2 and S4 are fully satisfied); the deficit falls on the downstream reach III and on the statutory low-priority uses, while the ecological minimum and drinking water carry zero residual in every scenario. (b) Residual deficit after the no-regret (B) and integrated (C) compensation strategies; B closes every scenario except S3 (residual 4.51×10^6 m³), which C closes fully. The legend entry for strategy C has no visible bar in (b) because C leaves zero residual deficit in every scenario.

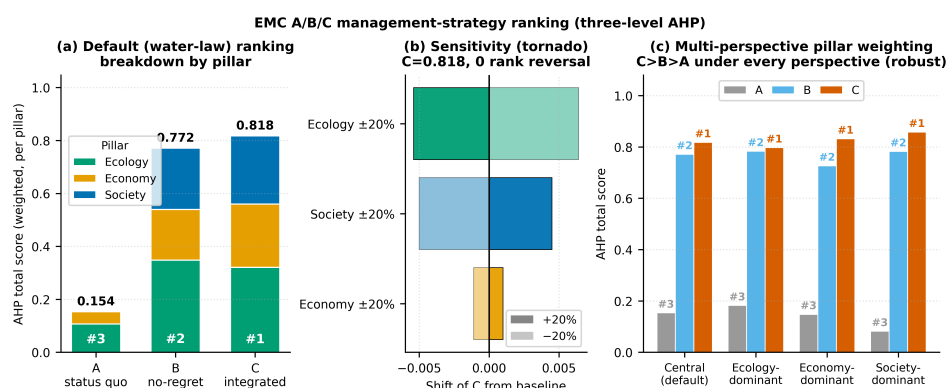


Figure 10. EMC A/B/C management-strategy ranking by the three-level analytic hierarchy process. (a) Default statutory-priority ranking by pillar (C 0.818 > B 0.772 > A 0.154). (b) Sensitivity tornado ($\pm 20\%$ criterion-weight perturbation; zero rank reversal); each bar keeps the colour of its pillar from (a), with the saturated bar the +20% and the pale bar the −20% perturbation, so the grey legend keys indicate shade only, not bar colour. (c) Ranking under central, ecology-, economy- and society-dominant perspectives: C > B > A under every perspective.

3.7. Time–Quantity Allocation of the Seasonal Deficit

Resolving the seasonal scenario balance into (reach $\times$ month) cells exposes a conflict structure that the seasonal aggregate hides (Figure 11). Every deficit cell lies in the downstream reach, but the deficits split into a spring band (April–May), driven by the simultaneity of fish-pond filling, the irrigation ramp-up and reservoir refill, and a summer band (June–October), driven by the climatic peak. In the decision space, the spring filling cells sit in the conflict zone—high time suitability but low marginal quantity suitability—while the October–February cells form an unexploited headroom zone, with water available at the proven winter operating envelope and near-zero competing demand.

Re-timing the fish-pond filling volume (8.57×10^6 m³) from the March–May window into the October–February band, within the winter envelope and served through the

documented winter side-gate operation, eliminates the spring deficit completely in the historical-drought scenario S1 and cuts it by 63% in the RCP8.5 end-of-century scenario S3, reducing the annual deficit in both cases (Table 11). The placement is insensitive to the objective weighting (identical for $w_t = 0.3\text{--}0.7$) and attains the linear-programming optimum of the same problem exactly, so no better schedule exists under the stated constraints. Under a conservative winter basis (the 10th-percentile climatology) about 84–85% of the volume still fits and the spring deficit is still eliminated in S1, whereas in the industrial-expansion scenario the year-round demand consumes the winter envelope and only $0.43 \times 10^6 \text{ m}^3$ fits—an honest signal that industrial growth competes with re-timing flexibility, not only with summer supply. The summer deficit is deliberately reported unchanged: re-timing resolves the spring simultaneity conflict, while the summer climatic deficit remains the domain of the compensation module and the integrated strategy, so the two levers are complementary rather than substitutes. The method re-derives, with a transparent two-objective rule, the out-of-season principle that Bocz [110] formulated for soil-reservoir irrigation, and it illustrates the monthly scale decision rule that the 2025 scheduling practice currently lacks [106].

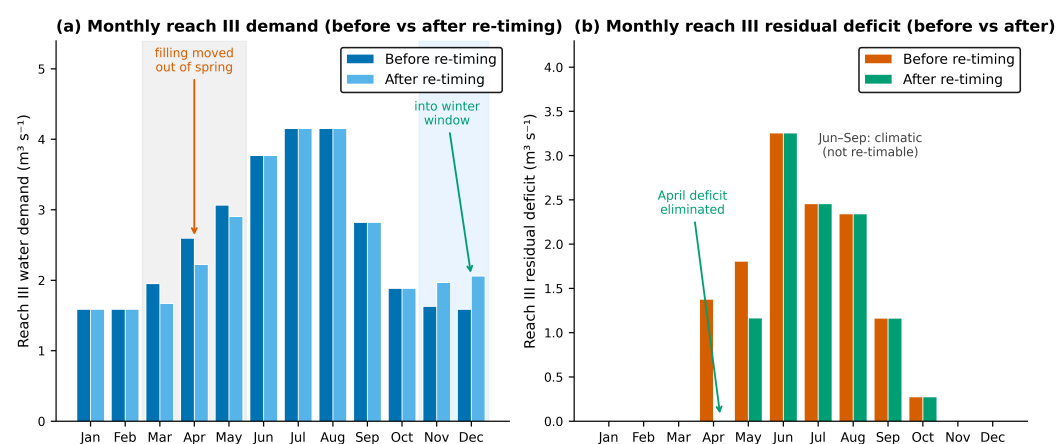


Figure 11. Monthly water demand and residual deficit on the critical downstream reach (reach III) for the RCP8.5 scenario, before and after re-timing the fish-pond filling (the MOWA two-objective time–quantity allocation). (a) Monthly reach-III water demand: the $8.57 \times 10^6 \text{ m}^3$ fish-pond filling is shifted out of the spring window (March–May) into the winter operating window (November–December), conserving the annual volume. (b) Monthly reach-III residual deficit: re-timing eliminates the April deficit and reduces May, while the June–September deficit is climatic and not re-timable; reaches I and II carry no residual deficit in any month.

Table 11. Two-objective time–quantity (MOWA) re-timing result (100% movable fish-pond filling, equal objective weights, mean winter basis; deficits in 10^6 m^3). LP = linear-programming optimum of the same placement problem. Deficits here are computed on the monthly (reach $\times$ month) MOWA demand accounting and are therefore not numerically identical to the seasonal-aggregate scenario deficits of Section 3.6, which are computed on the coarser seasonal compensation engine; the two pipelines agree on direction and on which scenarios carry deficit, not to the last decimal.

Scenario	Filling Re-Timed	Spring Deficit Before $\rightarrow$ After	JJA Deficit (Unchanged)	Annual Deficit Before $\rightarrow$ After	LP Optimum
S1 drought	8.57	0.52 $\rightarrow$ 0.00	3.32	3.84 $\rightarrow$ 3.32 (−13.5%)	3.32
S2 RCP4.5 2050	8.57	0.00 $\rightarrow$ 0.00	0.00	0.00 $\rightarrow$ 0.00	—
S3 RCP8.5 2100	8.57	8.41 $\rightarrow$ 3.13 (−63%)	21.29	33.46 $\rightarrow$ 28.17 (−15.8%)	28.17
S4 industrial	8.57	0.00 $\rightarrow$ 0.00	0.00	0.00 $\rightarrow$ 0.00	—

4. Discussion

4.1. Bias-and-Balance Calibration Quality

The mean $|PBIAS|$ of 1.59% (2018) and 0.86% (2020) with mass-balance closure of 101.4% and 99.8% places the coupled model in the upper range of comparable lowland canal–aquifer applications: the Danish national MIKE SHE setup reports 5–10% PBIAS on a far larger domain [32] and the classic Karup application 3–8% [33]. We report the full Moriasi suite rather than a single headline figure, since single-metric calibration can mask compensating errors and parameter non-uniqueness [38,98]; the 1.431 m basin-wide head MAE meets the Moriasi Good threshold for regional groundwater models [96]. The only Hungarian peer-reviewed application overlapping our domain [113], on a neighboring sub-catchment (Berettyó/Kálló-ér) that shares the Bakonszeg gauge, reports MIKE Hydro River NSE 0.665–0.99 and confirms that the same operational-schedule limitation prevents interior-structure cross-validation, independently supporting our disclosure; an earlier Hungarian Great Plain lowland-catchment precedent [114] documents the characteristic low-flow overestimation consistent with our risk-aware tail disclosure.

4.2. Dynamic Skill as a Data and Dynamic-Validation Limitation Rather than a Demonstrated Process Failure

The EMC is an artificial, operator-regulated watercourse: gate, weir and pump operations set reach-scale levels and discharges on a daily schedule that is not publicly released. Classical streamflow metrics, built for natural rainfall-runoff transposability [35], lose interpretability on regulated reaches, where ignoring operational infrastructure yields a deceptively good NSE through parameter compensation [36] and multi-site, multi-variable calibration becomes necessary [37]. The Pannonian setting compounds this: lowland Tisza maxima are declining [115], regional discharges and shallow groundwater are trending downward [2,13], and flow intermittency is emerging in small streams [116]. Following precedents from data-scarce managed basins and the Danish national MIKE SHE practice [32–34,39,117], we calibrate on reach-mean discharge, multi-well heads and zone-wise water balance, and disclose that interior water-level NSE is not the appropriate primary skill metric here.

The negative Nash–Sutcliffe efficiency at the interior water-level gauges reflects, at least in part, the open-loop simulation of operator-controlled structures whose daily schedule is not public. A gate-driving experiment tested this directly: the Balmazújváros gate crest was driven by a synthetic series matched to the observed headwater signal (standard deviation 0.16 m), and the driven gate level tracked the input series exactly, confirming the schedule itself can be reconstructed and imposed. The downstream simulated water level, however, did not correspondingly recover the observed variability: across every configuration tested, open-loop and closed-loop PID gate control alike, the simulated standard deviation remained in the 0.78–1.0 m range. We therefore read the residual dynamic gap more conservatively than a missing-schedule explanation alone would suggest: the unavailable daily schedule is a necessary but evidently not sufficient condition for the mismatch, and some further process—structure geometry, local storage capacity, or an unmodeled control rule at the gauge—also contributes [40,95]; a hybrid process–machine-learning approach [118] remains a plausible route to recovering the interior dynamics, but in the present evidence, it is not established that the schedule alone would suffice. The 2020 amplitude suppression at the wells is similarly structural—a wet, saturated aquifer damps the observed variability itself [13]. The basin-wide head MAE (1.431 m) is comparable to the median per-well annual fluctuation amplitude (~1.1 m), while the per-zone temporal MAE of 0.37–0.84 m (Figure 3) is only 33–74% of that amplitude, so the model resolves seasonal dynamics and the larger aggregate mainly reflects absolute-datum offsets between

zones. The allocation layer is likewise one-way—demand is imposed as a decision variable and is not throttled by real-time canal availability—so supply-to-demand feedbacks await a fully two-way coupling.

4.3. Internal-State Diagnostics and the Drainage-Module Proxy

Following the principle that internal-state constraints improve process realism at modest cost to a single fit metric [40], we report the per-zone water budget (Table 4), the Zone C flux partition and the seasonal groundwater cycle as process diagnostics alongside the head MAE; these show a recharge-poor, evapotranspiration-dominated loess system consistent with the region's sandy-loess hydraulics [93]. These internal fluxes are model diagnostics rather than independently validated quantities—the simulated recharge was not cross-checked against independent observations, though the simulated evapotranspiration is now cross-checked against the MODIS MOD16A2GF product (Table 5)—so the evidence guards against parameter equifinality without fully excluding it. As an independent cross-check, GRACE/GRACE-FO gravimetry corroborates the simulated storage: the CSR mascon solution (NASA JPL GRACE/GRACE-FO Data Analysis Tool, land water-equivalent-thickness anomaly, single native mascon cell of about $3^\circ \times 3^\circ$ (~ 330 km) centered near 47.66° N, 21.15° E covering the Hajdúhát/Debrecen area, monthly values from April 2002 to March 2026) shows regional terrestrial water storage lower in 2018 (-9.2 cm) than in 2020 (-7.2 cm) and falling from a 2009–2021 mean of about -4.1 cm to about -11.1 cm of water-equivalent thickness over 2022–2025 [119,120], matching the wet/dry contrast and the post-2022 decline; the coarse, single-cell resolution of this product means it corroborates the regional storage trend only, not the zone-level pattern. The regional deep discharge unresolved by the drainage module is represented by a lumped horizontal-conductivity free-outflow proxy whose sensitivity is monotonic and saturates at the chosen optimum, selected on the basin-wide head MAE ($1.543 \rightarrow 1.431$ m) rather than KGE ($0.35 \rightarrow 0.16$); we disclose this as a structural workaround rather than a calibrated process [38].

The diagnostics rank three supply options [45]: the growing-season deficit of 314 mm, with evapotranspiration exceeding precipitation (448 vs. 309 mm), establishes a structural irrigation requirement comparable to regional maize needs [8,10]; the end-of-season water table is 1.1 m shallower in the wet year (3.02 vs. 4.08 m; Section 3.3) and the requirement matches Central European irrigation-requirement projections [121], but multi-year memory means one wet year does not erase the deficit, so a single-year assessment would mislead [15,17]. Surface conveyance, the stakeholder-preferred option, is adequate in the wet year but collapses in the dry one—34 of 92 summer days below threshold and a near-zero sustainability index—because the Tisza source itself enters drought [29], mirroring the central finding of Haro-Monteagudo et al. [44] that the obvious supply-side measure is insufficient alone; groundwater-only abstraction can buffer the shortfall but the shallow aquifer is drought-sensitive and its seventeen-year trend, while directionally declining, is underpowered to rule out depletion [13].

A hybrid therefore screens best: canal conveyance as the primary source, buffered by local storage and complemented by a strictly capped groundwater top-up. The offline screening sweep (Table 8, Figure 7) shows local storage alone is insufficient on the loess plateau, whereas a $100,000 \text{ m}^3$ reservoir with a $1.0 \text{ m}^3 \text{ s}^{-1}$ groundwater cap doubles the dry-year sustainability index ($0.09 \rightarrow 0.18$) and brings the wet-year value (0.59) into the Sandoval-Solis sustainable band ($\text{SI} \geq 0.5$). A back-of-the-envelope check— $1.0 \text{ m}^3 \text{ s}^{-1}$ sustained over the 183-day season, distributed over the Zone C area—must be converted to head change with specific yield and pumping geometry before comparison with regional

decline [13], which is exactly what the cap is meant to bound. Securing dry-year supply is thus less a question of canal capacity than of storage and conjunctive-use management [25].

4.4. Comparison with Previous Irrigation-District Studies

Benchmarked against comparable studies, the framework's outputs and design choices read consistently with, and in places extend, the published record. The Sandoval-Solis sustainability index used here (Equation (2)) has been applied to an actual canal-fed irrigation district competing with urban demand under a legally structured allocation regime, Irrigation District DR-014 on the Mexican Colorado River [85], and at basin scale in the water-stressed Rio Verde Grande basin, Brazil [86]; in both cases, as here, the index is low under scarcity and improves once demand-side or storage measures are added, supporting its transferability across very different regulated systems. A 62-district Irrigation Sustainability Index screening of the Segura basin, Spain [87], found aquifer overexploitation among the principal drivers of unsustainable districts, paralleling the weakly declining, still-underpowered Zone C groundwater trend reported here (Section 3.5)—though that study screens 62 districts against our single, deeply instrumented one, a scope trade-off worth stating explicitly. At the reach scale, a spatial risk assessment of drought-induced operational failure in interconnected canals [122] resolves a comparable reach-level failure-propagation problem to the reach $\times$ sector cascade reported here (Table 9, Figure 8), though by a spatial-risk rather than a deficit-cascade-with-compensation-ladder approach. Among European, publicly managed, canal-conveyance analogs, a climate-resilience framework for a Portuguese collective irrigation system [55], a comparison of three Venetian reclamation consortia [123], and the 2022–2023 Po Valley drought assessment [124] all attribute a material share of performance variation to organizational and institutional capacity rather than to hydraulic design alone, consistent with this study's emphasis on disciplined, priority-ordered allocation as the binding lever rather than added conveyance. For the surface-only-versus-hybrid comparison, a conjunctive-use framework coupling surface-water operations to a MODFLOW groundwater model [125] reports reduced downstream irrigation-deficit ratios and damped reservoir depletion from a groundwater top-up of comparable character to the capped $1.0 \text{ m}^3\text{s}^{-1}$ top-up evaluated here (Table 8), giving an independent, published benchmark for the reliability gain such a top-up should deliver. For the time–quantity allocation, MOWA is best read as complementary to, rather than competing with, established multi-objective canal-allocation formulations that optimize continuous quantity or gate-control variables by evolutionary algorithms [126,127]: MOWA is a time-placement heuristic operating under a statutory-priority Boolean mask and benchmarked against the linear-programming optimum of the same placement problem, whereas these formulations optimize quantity and hydraulic-control variables directly, and the two could in principle be nested in a future iteration. Finally, and to state plainly what this study does not attempt: classical adequacy and equity delivery-performance indicators for canal-served schemes [128] operate at the field or turnout scale, a resolution this reach-and-sector-scale framework does not resolve.

4.5. Illustrative Management Implications of the Demonstration

For operators and the authority alike, in this case, the framework yields an operating-rule template, not a guarantee. In that template, canal discharge remains the first source, local storage buffers only short interruptions, and groundwater serves as a capped residual top-up, triggered by service deficits and curtailed when sentinel heads, seasonal recovery or water-quality thresholds are breached; the wet-year sustainability index of 0.59 provides a reference benchmark for holding served demand at or above the $\text{SI} \geq 0.5$ band [43]. The

cap matters as much as the volume, because an uncapped draw would turn a seasonal deficit into a structural one [13].

The scheme treats groundwater as a strictly capped withdrawal, yet the same conjunctive logic admits a proactive complement. Managed aquifer recharge, which banks wet-year surplus for recovery in dry years, is increasingly applied to drought-sensitive aquifers worldwide [129], and on the loess plateau, the wet-year storage gain the model already resolves (a +53 mm Zone C gain in 2020; Table 6) is exactly the surplus such a scheme would capture. Integrating recharge into the conjunctive plan, rather than treating the aquifer only as a source to draw down, is therefore a natural extension that the capped-withdrawal design used here does not yet represent, and one worth carrying into a future iteration of the framework.

The capped top-up is a no-regret measure only in buffering acute deficits: against the long-term, climate-driven decline of Great-Plain shallow groundwater projected through mid-century [130] and the over-abstraction pressure documented for irrigating farmers in Hungary [105]—consistent with the post-2021 decline resolved here and corroborated by GRACE/GRACE-FO and Szanyi et al. [17]—it is a mitigation tactic, not a sustainable substitute for demand restraint, and must be curtailed on sentinel heads and seasonal recovery. These supply- and allocation-side levers are therefore complementary to, not a replacement for, demand- and landscape-side measures: nature-based, landscape-scale water retention and soil-structure restoration are increasingly advocated for the Hungarian lowland to raise the recharge-poor loess system's own moisture-holding capacity [131–133], data-driven drought-risk tools are emerging regionally [134], and precision and variable-rate irrigation guided by high-resolution soil mapping can lower the baseline requirement itself [135], easing the simultaneity conflict that the re-timing strategy targets.

A drought contingency follows from the same logic. When the Tisza source itself enters low flow—increasingly the late-summer norm [31]—surface conveyance cannot be the swing supply, and stored volume plus the capped top-up must carry the peak-demand weeks. This steers the regional plan toward demand management and managed storage rather than new abstraction, in line with the integrated Tiszántúl strategy [27] and the wider Hungarian move to retain water in the landscape [136]; the Debrecen Civaqua programme, conveying Tisza water westward to recharge the Hajdúság, illustrates this direction and complements the conjunctive scheme.

Transferability is a design property of the framework rather than an incidental possibility: none of its components is site-specific, and re-implementation requires only a calibrated supply series, a sectoral demand structure and a statutory priority order. Regulated-canal lowlands with thin, drought-sensitive aquifers face analogous constraints, and the reliability–resilience–vulnerability and sustainability metrics used here give water authorities a common currency for ranking options; the European reporting infrastructure that now standardizes drought and water-status information across member states [6,7] makes such comparisons increasingly tractable beyond the TIKEVIR system, which serves here as the design's first demonstration.

Finally, the sectoral allocation makes the operating-rule template spatially explicit. Because every modeled drought deficit falls on reach III and on the two statutory low-priority uses (irrigation and the Körös transfer), while the ecological minimum and drinking water are protected in all scenarios, the binding management lever is not additional conveyance but disciplined, priority-ordered allocation augmented by demand de-synchronization and capped compensation; the multi-criteria ranking confirms this, with the no-regret package, the robust default for all but the most extreme end-of-century scenario, for which the integrated Tisza/Körös transfer becomes necessary.

5. Limitations and Future Work

Because the dry-year and wet-year canal configurations differ not only in Manning roughness but also in the year-specific representation of the upstream control structures (fixed-crest weirs in the dry year versus daily gate operation in the wet year) and in the Bakonszeg terminal-weir crest, the assessment is an operationally conditioned wet/dry comparison rather than a strict-sense Klemeš split-sample validation: the performance contrast reflects both the climatic regime and the documented seasonal canal operation. A fully parameter-identical split-sample would test a different question from the operationally conditioned comparison used here.

The daily gate regulation schedule for the three EMC control structures is not public, which caps the interior-gauge dynamic skill; the same schedule limitation has been disclosed independently on the neighboring Berettyó system [113], so it is a regional rather than a site-specific data-availability constraint, and acquiring the schedule, or hybridizing the physical model with a learning component [118], would recover the interior water-level dynamics. The lumped free-outflow proxy used here is a documented workaround for the MIKE SHE 2022 drainage limitation, and a corrected drainage formulation would remove the need for it. The Tiszalök upstream boundary currently under-feeds the designed inflow, and the Hortobágy–Berettyó pumping stations are not explicitly represented; sourcing the observed Tiszalök discharge and the pump network would sharpen the conveyance estimate.

The 2009–2025 record spans the 2022 drought and the subsequent lower-storage years, with 2018 retained as the strong but not worst-case dry-year calibration, so the hybrid's dry-year robustness should be read against an intensifying regional drought regime [18]; the simulated post-2021 decline is corroborated by GRACE/GRACE-FO storage and by the post-2022 groundwater modeling of Szanyi et al. [17] for the neighboring Nyírség. Finally, the unsaturated-zone parameters use the 100 m national HU-SoilHydroGrids product [93]; plateau-specific field measurements would reduce the deficit-estimate uncertainty. The zonal actual-evapotranspiration totals in Table 4 have now been cross-checked against the MODIS MOD16A2GF remote-sensing product (Table 5): the calibrated Zone C total is reproduced to within the product's inter-annual range, and the divergences in the neighborhood zones are consistent with the unsaturated-zone-only definition of the tabulated term. A fully independent, ground-based ET dataset for the plateau remains a useful further step, and the marshland Zone D is better represented by purpose-built regional models than by this Hajdúhát-calibrated coupling [111]. The $0.5 \text{ m}^3\text{s}^{-1}$ irrigation-relevant threshold used in Section 2.3 is a reasoned engineering estimate rather than a documented operational standard; a formal sensitivity analysis, now reported in Section 3.5, shows the below-threshold-day count to be invariant across $0.3\text{--}1.0 \text{ m}^3\text{s}^{-1}$, and the sustainability index is evaluated at the withdrawal demand rather than at this threshold, so neither the dry/wet reliability contrast nor the sustainability result depends on the specific value; sourcing the operational minimum-delivery specification directly from TIVIZIG remains the outstanding item.

6. Conclusions

This study set out a coupled hydrological–multi-criteria design in which the scores, weights and allocation masks of the decision layer are derived from a calibrated physical model rather than elicited independently of it, and demonstrated that design on the TIKEVIR East Main Canal and the Pannonian Hajdúhát loess plateau by coupling a wet-/dry-conditioned MIKE Hydro River model with a seventeen-year MIKE SHE groundwater model under a dry (2018) and a wet (2020) year. The conclusions are led by the design contribution; the findings that follow are the demonstration of that design on this system.

- The principal contribution is the closure of the loop between hydrological modeling and multi-criteria decision support: the impact scores, reliability metrics and allocation masks are propagated deterministically from the calibrated model, so the decision output remains testable against the physics rather than resting on expert consensus alone. Because no component of the design is site-specific, the framework is transferable to other regulated canal–aquifer systems; the findings below demonstrate it for TIKEVIR.
- The coupled model reaches Moriasi Very Good bias-and-balance quality on the canal (mean $|PBIAS| < 1.6\%$) and a 1.431 m basin-wide head MAE over 132 wells (Table 2), an adequate basis for exploratory scenario screening under the disclosed data limitations.
- The Hajdúhát loess plateau has a structural, rather than occasional, growing-season irrigation requirement: the seventeen-year April–September unsaturated-zone deficit averages 314 mm, with evapotranspiration exceeding precipitation across the growing season, and the spatial pattern (Figure 5) shows 20% of the plateau area exceeding 400 mm, concentrated along the eastern canal-side margin.
- Imported canal supply is reliable in wet years but fails in dry ones: 34 of 92 summer days fall below the irrigation threshold and the sustainability index drops to 0.09 (against 0.34 in the wet year). Surface conveyance alone is therefore not a dependable dry-year source.
- A hybrid of canal supply, a 100,000 m³ local reservoir and a capped 1.0 m³s^{−1} groundwater top-up roughly doubles the dry-year sustainability index (to 0.18) and lifts the wet-year value to 0.59; storage alone is insufficient on the loess plateau, and the capped groundwater contribution is the decisive lever.
- The deeper wet-year initial water table relative to the dry year is consistent with multi-year groundwater memory, so supply security must be judged in a multi-year rather than a single-year frame.
- For this system, the demonstration identifies disciplined, priority-ordered allocation—not added conveyance—as the binding management lever: the no-regret package suffices for every scenario but the most severe end-of-century one, which alone requires the integrated Tisza/Körös transfer, and re-timing 8.57×10^6 m³ of fish-pond filling into the proven winter window would remove the spring deficit at no new infrastructure cost.

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Data Availability Statement: The complete decision-support layer of this study—a documented reference implementation of the AHP, Leopold-matrix, MOWA and robustness procedures, together with the criterion weights, the alternative-performance matrix, all decision-layer input and output tables reported in the paper, and a blank expert-elicitation template—is archived at Zenodo under a CC BY 4.0 license (<https://doi.org/10.5281/zenodo.21815553>). These materials allow all rankings, sensitivity results and decision-layer figures to be independently recomputed. The MIKE SHE, MIKE Hydro River and HEC-RAS model configurations are specified in the Materials and Methods and associated parameter tables at a level of detail sufficient for independent re-implementation. The model

files themselves cannot be publicly deposited: they were developed under a DHI Thesis Research Licence and constitute institutional intellectual property, and the underlying hydrometeorological and discharge records are owned by third parties (the Trans-Tisza Water Directorate, TIVIZIG, and the National Water Authority, OVF) and relate to an ongoing national water-resources planning process. These materials are available from the corresponding author, János Tamás (tamas@agr.unideb.hu), upon reasonable request for collaborative research.

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References

1. Crocetti, L.; Forkel, M.; Fischer, M.; Jurečka, F.; Grlj, A.; Salentinig, A.; Trnka, M.; Anderson, M.C.; Ng, W.-T.; Kokalj, Ž.; et al. Earth observation for agricultural drought monitoring in the Pannonian Basin. *Reg. Environ. Change* **2020**, *20*, 123. [CrossRef]
2. Jánosi, I.M.; Bíró, T.; Lakatos, B.O.; Gallas, J.A.C.; Szöllősi-Nagy, A. Changing water cycle under a warming climate: Tendencies in the Carpathian Basin. *Climate* **2023**, *11*, 118. [CrossRef]
3. Mohammed, S.; Alsafadi, K.; Enaruvbe, G.O.; Bashir, B.; Elbeltagi, A.; Széles, A.; Alsalman, A.; Harsanyi, E. Assessing the impacts of agricultural drought (SPI/SPEI) on maize and wheat yields across Hungary. *Sci. Rep.* **2022**, *12*, 8838. [CrossRef]
4. International Commission for the Protection of the Danube River (ICPDR). *Danube Facts and Figures: Hungary*; ICPDR: Vienna, Austria, 2020. [CrossRef] [PubMed]
5. Csáki, P.; Szinétár, M.M.; Herceg, A.; Kalicz, P.; Gribovszki, Z. Climate change impacts on the water balance, case studies in Hungarian watersheds. *Időjárás* **2018**, *122*, 81–99. [CrossRef]
6. European Commission, Joint Research Centre. European Drought Observatory (EDO), Copernicus Emergency Management Service. Available online: <https://drought.emergency.copernicus.eu/> (accessed on 15 September 2025). [CrossRef]
7. European Environment Agency. *Water Information System for Europe (WISE)*; European Environment Agency: Copenhagen, Denmark, 2024.
8. Busschaert, L.; de Roos, S.; Thiery, W.; Raes, D.; De Lannoy, G.J.M. Net irrigation requirement under different climate scenarios using AquaCrop over Europe. *Hydrol. Earth Syst. Sci.* **2022**, *26*, 3731–3752. [CrossRef]
9. Szabó, A.; Tamás, J.; Nagy, A. Evaluation of new pivoting linear-move precision irrigation machine. *Irrig. Drain.* **2023**, *72*, 922–933. [CrossRef]
10. Nxumalo, G.S.; Magyar, T.; Tamás, J.; Nagy, A. Modelling soil moisture content with Hydrus 2D in a continental climate for effective maize irrigation planning. *Agriculture* **2024**, *14*, 1340. [CrossRef]
11. Rónai, A. A Nyírség, Hajdúság és Hortobágy talajviszonyai [Soil conditions of the Nyírség, Hajdúság and Hortobágy regions]. *Hidrológiai Közlöny* **1955**, *35*, 252–273. (In Hungarian) [CrossRef]
12. Flores, Y.G.; Eid, M.H.; Szűcs, P.; Szőcs, T.; Fancsik, T.; Szanyi, J.; Kovács, B.; Markos, G.; Újlaki, P.; Tóth, P.; et al. Integration of geological, geochemical modelling and hydrodynamic condition for understanding the geometry and flow pattern of the aquifer system, Southern Nyírség–Hajdúság, Hungary. *Water* **2023**, *15*, 2888. [CrossRef]
13. Garamhegyi, T.; Kovács, J.; Pongrácz, R.; Tanos, P.; Hatvani, I.G. Investigation of the climate-driven periodicity of shallow groundwater level fluctuations in a Central-Eastern European agricultural region. *Hydrogeol. J.* **2018**, *26*, 677–688. [CrossRef]
14. Kløve, B.; Ala-Aho, P.; Bertrand, G.; Gurdak, J.J.; Kupfersberger, H.; Kværner, J.; Muotka, T.; Mykrä, H.; Preda, E.; Rossi, P.M.; et al. Climate change impacts on groundwater and dependent ecosystems. *J. Hydrol.* **2014**, *518*, 250–266. [CrossRef]
15. Rakonczai, J.; Fehér, Z. A klímaváltozás szerepe az Alföld talajvízkészleteinek időbeli változásaiban [The role of climate change in temporal changes of groundwater resources on the Great Hungarian Plain]. *Hidrológiai Közlöny* **2015**, *95*, 2–16. [CrossRef]
16. Kovács, A.; Jakab, A. Modelling the impacts of climate change on shallow groundwater conditions in Hungary. *Water* **2021**, *13*, 668. [CrossRef]
17. Szanyi, J.; Abdulhaq, H.A.; Hegyi, R.; Gál, T.; Szabó, É.; Lossos, L.; Tóth, E. Assessment of changes in groundwater resources due to climate change for the purpose of sustainable water management in Hungary. *Water* **2026**, *18*, 724. [CrossRef]

18. Kis, A.; Szabó-Takács, B.; Pongrácz, R. Analysis of detected and future drought conditions, a case study for the Great Hungarian Plain. *Theor. Appl. Climatol.* **2025**, *156*, 303. [\[CrossRef\]](#)
19. Wu, W.-Y.; Lo, M.-H.; Wada, Y.; Famiglietti, J.S.; Reager, J.T.; Yeh, P.J.-F.; Ducharne, A.; Yang, Z.-L. Divergent effects of climate change on future groundwater availability in key mid-latitude aquifers. *Nat. Commun.* **2020**, *11*, 3710. [\[CrossRef\]](#)
20. Kumar, R.; Samaniego, L.; Thober, S.; Rakovec, O.; Marx, A.; Wanders, N.; Pan, M.; Hesse, F.; Attinger, S. Multi-model assessment of groundwater recharge across Europe under warming climate. *Earth Future* **2025**, *13*, e2024EF005020. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Szigyártó, Z. A Keleti-főcsatorna rekonstrukciójának alapelvei [Principles for the reconstruction of the East Main Canal]. *Hidrológiai Közlöny* **1976**, *56*, 282–287. (In Hungarian) [\[CrossRef\]](#)
22. Bordás, C. A Keleti-főcsatorna keletkezés- és építéstörténete [Origin and construction history of the East Main Canal]. In Proceedings of the Magyar Hidrológiai Társaság Országos Vándorgyűlése, Szeged, Hungary, 2–4 July 2014; pp. 713–729. (In Hungarian)
23. Tömöri, F. A Keleti-főcsatorna múltja, jelene és jövője [Past, present and future of the East Main Canal]. In Proceedings of the Magyar Hidrológiai Társaság Országos Vándorgyűlése, Nyíregyháza, Hungary, 6–8 July 2022; pp. 1712–1726.
24. Radácsi, G. A Keleti-főcsatorna üzemrendjének sajátosságai szélsőséges vízgazdálkodási helyzetekben [Operational characteristics of the East Main Canal under extreme water-management conditions]. In Proceedings of the Magyar Hidrológiai Társaság Országos Vándorgyűlése, Szombathely, Hungary, 1–3 July 2015; pp. 1612–1645.
25. Cselőtei, L. Az öntözés története Magyarországon (1935–2005)—Fejlesztés, fejlődés, jövőkép [The history of irrigation in Hungary, 1935–2005: Development, progress and future outlook]. *Hidrológiai Közlöny* **2005**, *85*, 310–313. (In Hungarian)
26. Lovas, A.; Horváth, B.; Virágné Kóházi-Kis, E. A Közép-Tisza vidék, a Jászság és a Nagykunság vízkészlet-hasznosítási stratégiája [Water-resource utilization strategy of the Middle Tisza region, Jászság and Nagykunság]. In Proceedings of the Magyar Hidrológiai Társaság Országos Vándorgyűlése, Gödöllő, Hungary, 3–5 July 2013; pp. 77–98. (In Hungarian)
27. Tamás, J.; Nagy, A. A Tiszántúl területi integrált vízgyűjtőgazdálkodási problémáinak és megoldási lehetőségeinek azonosítása a TIKEVIR hatásterületén [Identification of regional integrated water-management problems and solution options in the Tiszántúl within the TIKEVIR impact area]. *Hidrológiai Közlöny* **2023**, *103*, 64–67. (In Hungarian)
28. Pásztor, D.; Fehér, Z.Z.; Tamás, J. Integrált vízgazdálkodás a természeti és társadalmi folyamatok tükrében a Tisza-Körös völgyi Együttműködő Vízgazdálkodási Rendszer területén [Integrated water management in light of natural and social processes in the Tisza-Körös Valley Cooperating Water Management System]. *Hidrológiai Közlöny* **2024**, *104*, 30–47. (In Hungarian) [\[CrossRef\]](#)
29. Leščešen, I.; Dolinaj, D.; Pantelic, M.; Telbisz, T.; Varga, G. Hydrological drought assessment of the Tisza river. *J. Geogr. Inst. Jovan Cvijic SASA* **2020**, *70*, 89–100. [\[CrossRef\]](#)
30. Közép-Tisza-vidéki Vízügyi Igazgatóság (KÖTIVIZIG). *Vízgyűjtő-Gazdálkodási Terv—Jelentős Vízgazdálkodási Kérdések: Tisza Részvízgyűjtő (Vitaanyag)*; Közép-Tisza-vidéki Vízügyi Igazgatóság: Szolnok, Hungary, 2020. [\[CrossRef\]](#)
31. Országos Vízügyi Főigazgatóság (OVF). *Magyarország Negyedik Vízgyűjtő-Gazdálkodási Terve—Jelentős Vízgazdálkodási Kérdések (Vitaanyag)*; Országos Vízügyi Főigazgatóság: Budapest, Hungary, 2025.
32. Henriksen, H.J.; Trolborg, L.; Nyegaard, P.; Sonnenborg, T.O.; Refsgaard, J.C.; Madsen, B. Methodology for construction, calibration and validation of a national hydrological model for Denmark. *J. Hydrol.* **2003**, *280*, 52–71. [\[CrossRef\]](#)
33. Refsgaard, J.C. Parameterisation, calibration and validation of distributed hydrological models. *J. Hydrol.* **1997**, *198*, 69–97. [\[CrossRef\]](#)
34. Thompson, J.R.; Sørensen, H.R.; Gavin, H.; Refsgaard, A. Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. *J. Hydrol.* **2004**, *293*, 151–179. [\[CrossRef\]](#)
35. Klemes, V. Operational testing of hydrological simulation models. *Hydrol. Sci. J.* **1986**, *31*, 13–24. [\[CrossRef\]](#)
36. Vu, D.T.; Dang, T.D.; Pianosi, F.; Galelli, S. Calibrating macroscale hydrological models in poorly gauged and heavily regulated basins. *Hydrol. Earth Syst. Sci.* **2023**, *27*, 3485–3504. [\[CrossRef\]](#)
37. Sheikh, M.R.; Coulibaly, P. Hydrologic model calibration approaches for highly regulated river basin: A comprehensive assessment. *J. Hydrol. Reg. Stud.* **2025**, *58*, 102198. [\[CrossRef\]](#)
38. Cinkus, G.; Mazzilli, N.; Jourde, H.; Wunsch, A.; Liesch, T.; Ravbar, N.; Chen, Z.; Goldscheider, N. When best is the enemy of good, critical evaluation of performance criteria in hydrological models. *Hydrol. Earth Syst. Sci.* **2023**, *27*, 2397–2411. [\[CrossRef\]](#)
39. Koch, H.; Yangouliba, G.I.; Liersch, S. From data scarcity to solutions: Hydrological and water management modeling in a highly managed river basin. *Water* **2025**, *17*, 823. [\[CrossRef\]](#)
40. Talbot, F.; Sylvain, J.-D.; Drolet, G.; Arsenaault, R. Enhancing physically based and distributed hydrological model calibration through internal state variable constraints. *Hydrol. Earth Syst. Sci.* **2025**, *29*, 6549–6576. [\[CrossRef\]](#)
41. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [\[CrossRef\]](#)
42. Loucks, D.P. Quantifying trends in system sustainability. *Hydrol. Sci. J.* **1997**, *42*, 513–530. [\[CrossRef\]](#)
43. Sandoval-Solis, S.; McKinney, D.C.; Loucks, D.P. Sustainability index for water resources planning and management. *J. Water Resour. Plan. Manag.* **2011**, *137*, 381–390. [\[CrossRef\]](#)

44. Haro-Montegudo, D.; Palazón, L.; Zoumides, C.; Begueria, S. Optimal implementation of climate change adaptation measures to ensure long-term sustainability on large irrigation systems. *Water Resour. Manag.* **2023**, *37*, 2909–2924. [\[CrossRef\]](#)
45. Beça, P.; Rodrigues, A.C.; Nunes, J.P.; Diogo, P.; Mujtaba, B. Optimizing reservoir water management in a changing climate. *Water Resour. Manag.* **2023**, *37*, 3423–3437. [\[CrossRef\]](#)
46. Sandoval, A.; Requelme, N.; Cachipuendo, C. Multi-criteria decision making (MCDM) methodology for the prioritization of technical irrigation projects. *Water Policy* **2025**, *27*, 804–822. [\[CrossRef\]](#)
47. Bayat, F.; Roozbahani, A.; Hashemy Shahdany, S.M. Performance evaluation of agricultural surface water distribution systems based on water-food-energy nexus and using AHP-Entropy-WASPAS technique. *Water Resour. Manag.* **2022**, *36*, 4697–4720. [\[CrossRef\]](#)
48. Radmehr, A.; Bozorg-Haddad, O.; Loáiciga, H.A. Developing strategies for agricultural water management of large irrigation and drainage networks with fuzzy MCDM. *Water Resour. Manag.* **2022**, *36*, 4885–4912. [\[CrossRef\]](#)
49. Qu, S.; Chen, H.; Shen, Z.; Ma, H. The performance evaluation of management mode of small water resources projects. *PLoS ONE* **2023**, *18*, e0282357. [\[CrossRef\]](#)
50. Jiang, M.; Zhang, C. The index system for the implementation effect evaluation of water-saving renovation of key medium-sized irrigation districts: A case study. *PLoS ONE* **2024**, *19*, e0296953. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Neissi, L.; Albaji, M.; Boroomand Nasab, S. Site selection of different irrigation systems using an analytical hierarchy process integrated with GIS in a semi-arid region. *Water Resour. Manag.* **2019**, *33*, 4955–4967. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Orojloo, M.; Hashemy Shahdany, S.M.; Roozbahani, A. Developing an integrated risk management framework for agricultural water conveyance and distribution systems within fuzzy decision making approaches. *Sci. Total Environ.* **2018**, *627*, 1363–1376. [\[CrossRef\]](#)
53. Wei, S.; Zhai, L.; Liu, C.; Wang, K.; Li, J. Resilience assessment of irrigation district infrastructure: Indicators, modeling, and empirical application. *Water* **2025**, *17*, 1214. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Fan, X.; Qin, J.; Lv, M.; Jiang, M. An evaluation system of the modernization level of irrigation districts with an analysis of obstacle factors: A case study for North China. *Agronomy* **2024**, *14*, 538. [\[CrossRef\]](#)
55. Esteves, R.; Calejo, M.J.; Rolim, J.; Teixeira, J.L.; Cameira, M.R. Framework for assessing collective irrigation systems resilience to climate change—The Maiorga case study. *Agronomy* **2023**, *13*, 661. [\[CrossRef\]](#)
56. Mahmoodian, M.; Shahrivar, F.; Li, C. Maintenance prioritisation of irrigation infrastructure using a multi-criteria decision-making methodology under a fuzzy environment. *Sustainability* **2022**, *14*, 14791. [\[CrossRef\]](#)
57. Talbi, A.; Karimi, P.; Waalewijn, P.; Onimus, F.; Jsbrand de Jong, I.; Zaveri, E.D.; Li, R. Climate-resilient irrigation: Essential changes to balance food production and water security on a livable planet. *Irrig. Drain.* **2024**, *73*, 1723–1730. [\[CrossRef\]](#)
58. Gutiérrez-Martín, C.; Gómez-Limón, J.A.; Montilla-López, N.M. Priority water rights for irrigation at the river basin level. Do they improve economic efficiency during drought periods. *Water Resour. Manag.* **2022**, *36*, 3737–3758. [\[CrossRef\]](#)
59. Gómez-Limón, J.A.; Gutiérrez-Martín, C.; Montilla-López, N.M. Agricultural water allocation under cyclical scarcity: The role of priority water rights. *Water* **2020**, *12*, 1835. [\[CrossRef\]](#)
60. de Oliveira Castro, G.; Costa Morais, D. Multi-criteria sorting model for water resource allocation in drought regions. *Water Resour. Manag.* **2026**, *40*, 207. [\[CrossRef\]](#)
61. Golfam, P.; Ashofteh, P.-S.; Rajaei, T.; Chu, X. Prioritization of water allocation for adaptation to climate change using multi-criteria decision making (MCDM). *Water Resour. Manag.* **2019**, *33*, 3401–3416. [\[CrossRef\]](#)
62. Rudberg, P.M. Water allocation for drought adaptation: A review of practical options. *Front. Water* **2026**, *8*, 1803379. [\[CrossRef\]](#)
63. Martínez-Dalmau, J.; Gutiérrez-Martín, C.; Kahil, T.; Berbel, J. Impact of alternative water policies for drought adaptation in the Guadalquivir Mediterranean river basin, southern Spain. *J. Hydrol. Reg. Stud.* **2023**, *47*, 101444. [\[CrossRef\]](#)
64. Kim, W.; Choi, S.; Kang, S.; Woo, S. Assessment of future water security under climate change: Practical water allocation scenarios in a drought-prone watershed in South Korea. *Water* **2024**, *16*, 2933. [\[CrossRef\]](#)
65. Liu, X.; Tang, Q.; Zhao, Y.; Wang, P. Persistent water scarcity due to high irrigation demand in arid China: A case study in the north slope of the Tianshan Mountains. *Earth Future* **2024**, *12*, e2024EF005070. [\[CrossRef\]](#)
66. Fooladi Dehaghi, B.; Khoshfetrat, A. Optimal allocation of water reuse using modified TODIM-GP approach with considering the Leopold matrix outputs. *Water Resour. Manag.* **2020**, *34*, 3823–3854. [\[CrossRef\]](#)
67. Rahimi, N.; Khoshfetrat, A. Modified VIKOR-GP approach by considering the Leopold matrix for optimal water reuse allocation. *Urban Water J.* **2024**, *21*, 757–773. [\[CrossRef\]](#)
68. Valizadeh, S.; Hakimian, H. Evaluation of waste management options using rapid impact assessment matrix and Iranian Leopold matrix in Birjand, Iran. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 3337–3354. [\[CrossRef\]](#)
69. Wang, L.; Zu, Q.; Zhang, Q. A procedure for risk assessment of check dam systems: A case study of Wangmaogou watershed. *PLoS ONE* **2023**, *18*, e0287750. [\[CrossRef\]](#)
70. Janjua, S.; Hassan, I. Fuzzy AHP-TOPSIS multi-criteria decision analysis applied to the Indus Reservoir system in Pakistan. *Water Supply* **2020**, *20*, 1933–1949. [\[CrossRef\]](#) [\[PubMed\]](#)

71. Mandal, P.; Mukhopadhyay, A.; Mukherjee, S.; Mukhopadhyay, U.; Bhattacharya, S.; Paul, S. Assessing the suitability of a reservoir site in a water-stressed area in Purulia, India, using AHP-TOPSIS. *Sustain. Water Resour. Manag.* **2023**, *9*, 74. [\[CrossRef\]](#)
72. Tu, Y.; Chen, K.; Wang, H.; Li, Z. Regional water resources security evaluation based on a hybrid fuzzy BWM-TOPSIS method. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4987. [\[CrossRef\]](#)
73. Natarajan, N.; Vasudevan, M.; Dineshkumar, S.K.; Anuja, R. Comparison of analytic hierarchy process (AHP) and fuzzy analytic hierarchy process (f-AHP) for the sustainability assessment of a water supply project. *J. Inst. Eng. India Ser. A* **2022**, *103*, 1029–1039. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Geng, G.; Wardlaw, R. Application of multi-criterion decision making analysis to integrated water resources management. *Water Resour. Manag.* **2013**, *27*, 3191–3207. [\[CrossRef\]](#)
75. Cinelli, M.; Coles, S.R.; Kirwan, K. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecol. Indic.* **2014**, *46*, 138–148. [\[CrossRef\]](#)
76. Marttunen, M.; Lienert, J.; Belton, V. Structuring problems for multi-criteria decision analysis in practice: A literature review of method combinations. *Eur. J. Oper. Res.* **2017**, *263*, 1–17. [\[CrossRef\]](#)
77. Hajkowicz, S.; Collins, K. A review of multiple criteria analysis for water resource planning and management. *Water Resour. Manag.* **2007**, *21*, 1553–1566. [\[CrossRef\]](#)
78. Magnabosco, R.; Godoy, V.A.; Gómez-Hernández, J.J. Review of multi-sectoral water management simulation–optimization approaches. *Sustain. Water Resour. Manag.* **2026**, *12*, 19. [\[CrossRef\]](#)
79. Fetene, D.T.; Lohani, T.K.; Mohammed, A.K. Application of coupled MIKE SHE/MIKE HYDRO on streamflow dynamics under climate change in Lake Tana sub basin, Abay Basin, Ethiopia. *World Water Policy* **2024**, *11*, 250–273. [\[CrossRef\]](#)
80. Dung, T.T.; Thai, T.H.; Tri, D.Q.; Hong, N.V.; Minh, N.H. A coupled MIKE SHE–MIKE 11 framework for simulating surface–groundwater connectivity and water quality to support sustainable water management in the Cau River Basin. *Sustainability* **2026**, *18*, 7089. [\[CrossRef\]](#)
81. Chung, E.-S.; Hong, W.-P.; Lee, K.S.; Burian, S.J. Integrated use of a continuous simulation model and multi-attribute decision-making for ranking urban watershed management alternatives. *Water Resour. Manag.* **2011**, *25*, 641–659. [\[CrossRef\]](#)
82. Subagadis, Y.H.; Schütze, N.; Grundmann, J. A fuzzy-stochastic modeling approach for multiple criteria decision analysis of coupled groundwater-agricultural systems. *Water Resour. Manag.* **2016**, *30*, 2075–2095. [\[CrossRef\]](#)
83. Jolfan, M.H.; Hashemy Shahdany, S.M.; Javadi, S.; Milan, S.G.; Neshat, A.; Berndtsson, R.; Tork, H. Modernization in agricultural water distribution system for aquifer storage and recovery—A case study. *Agric. Water Manag.* **2023**, *282*, 108270. [\[CrossRef\]](#)
84. Liu, J.; Liu, Y. Integrating performance indicators and simulation model for assessing operational performance of water distribution pipe system (WDPS) in irrigation district. *Water* **2026**, *18*, 299. [\[CrossRef\]](#)
85. Hernández-Cruz, A.; Sandoval-Solís, S.; Mendoza-Espinosa, L.G.; Ramírez-Hernández, J.; Medellín-Azuara, J.; Daesslé, L.W. Assessing water management strategies under water scarcity in the Mexican portion of the Colorado River Basin. *J. Water Resour. Plan. Manag.* **2023**, *149*, 04023042. [\[CrossRef\]](#)
86. Vieira, E.O.; Sandoval-Solis, S. Water resources sustainability index for a water-stressed basin in Brazil. *J. Hydrol. Reg. Stud.* **2018**, *19*, 97–109. [\[CrossRef\]](#)
87. Cánovas-Molina, A.; García-Frapolli, E.; Ruggerio, C.A. A proposal of an Irrigation Sustainability Index for agricultural basins: Application in a semi-arid river basin. *Irrig. Sci.* **2023**, *41*, 173–182. [\[CrossRef\]](#)
88. Leopold, L.B.; Clarke, F.E.; Hanshaw, B.B.; Balsley, J.R. *A Procedure for Evaluating Environmental Impact*; US Geological Survey Circular 645; US Geological Survey: Washington, DC, USA, 1971. [\[CrossRef\]](#)
89. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*; McGraw-Hill: New York, NY, USA, 1980.
90. Fooladi Dehaghi, B.; Khoshfetrat, A. AHP-GP approach by considering the Leopold matrix for sustainable water reuse allocation: Najafabad case study, Iran. *Period. Polytech. Civ. Eng.* **2020**, *64*, 485–499. [\[CrossRef\]](#)
91. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998. [\[CrossRef\]](#)
92. Lakatos, M.; Weidinger, T.; Hoffmann, L.; Bihari, Z.; Horváth, Á. Computation of daily Penman-Monteith reference evapotranspiration in the Carpathian Region. *Adv. Sci. Res.* **2020**, *16*, 251–259. [\[CrossRef\]](#)
93. Szabó, B.; Mészáros, J.; Laborci, A.; Takács, K.; Szatmári, G.; Bakacsi, Z.; Makó, A.; Pásztor, L. From EU-SoilHydroGrids to HU-SoilHydroGrids: A leap forward in soil hydraulic mapping. *Sci. Total Environ.* **2024**, *921*, 171258. [\[CrossRef\]](#)
94. Chow, V.T. *Open-Channel Hydraulics*; McGraw-Hill: New York, NY, USA, 1959. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **2007**, *50*, 885–900. [\[CrossRef\]](#)
96. Moriasi, D.N.; Gitau, M.W.; Pai, N.; Daggupati, P. Hydrologic and water quality models: Performance measures and evaluation criteria. *Trans. ASABE* **2015**, *58*, 1763–1785. [\[CrossRef\]](#)
97. Gupta, H.V.; Kling, H.; Yilmaz, K.K.; Martinez, G.F. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* **2009**, *377*, 80–91. [\[CrossRef\]](#)

98. Knoben, W.J.M.; Freer, J.E.; Woods, R.A. Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 4323–4331. [\[CrossRef\]](#)
99. Bibok, A. Vízmérleg számítás pontosságának határai [Limits of the accuracy of water-balance calculation]. In Proceedings of the Magyar Hidrológiai Társaság Országos Vándorgyűlése, Mosonmagyaróvár, Hungary, 5–7 July 2017; pp. 895–918. (In Hungarian) [\[CrossRef\]](#)
100. Dövényi, Z. *Magyarország Kistájainak Katasztere [Cadastral of the Microregions of Hungary]*, 2nd ed.; Hungarian Academy of Sciences, Geographical Research Institute: Budapest, Hungary, 2010.
101. Csanádi, M.; Koltai, I.; Somogyi, T. Öntözési víznormák [Irrigation water norms]. *Hidrológiai Közöny* **1977**, *57*, 224–232.
102. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [\[CrossRef\]](#)
103. Hungarian Parliament. *Act LVII of 1995 on Water Management, §15: Abstraction Priority Order*; Hungarian Parliament: Budapest, Hungary, 1995. [\[CrossRef\]](#)
104. Radmehr, A.; Bozorg-Haddad, O.; Loáiciga, H.A. Integrated strategic planning and multi-criteria decision-making framework with its application to agricultural water management. *Sci. Rep.* **2022**, *12*, 8406. [\[CrossRef\]](#)
105. Gaál, M.; Becsákné Tornay, E. Drought events in Hungary and farmers' attitudes towards sustainable irrigation. *Időjárás* **2023**, *127*, 143–165. [\[CrossRef\]](#) [\[PubMed\]](#)
106. Lovas, A.; Ungvári, G.; Vizi, D.; Kiss, A.; Harsányi, G. Víz-szakpolitikai innovációk és továbbfejlesztési lehetőségeik a 2025-ös aszályvédekezés tapasztalatai alapján [Water-policy innovations from the 2025 drought-response experience]. *Hidrológiai Közöny* **2026**, *106*, 4–17. (In Hungarian) [\[CrossRef\]](#)
107. Tamás, J. A Talaj és a Környezet Térinformatikai értékelése az Alföldön [Geoinformatic Evaluation of Soil and Environment on the Great Hungarian Plain]. Doctoral Dissertation (DSc), Hungarian Academy of Sciences, Budapest, Hungary, 2005; Section 5.1.4, pp. 51–57. [\[CrossRef\]](#)
108. Eastman, J.R.; Jin, W.; Kyem, P.A.K.; Toledano, J. Raster procedures for multi-criteria/multi-objective decisions. *Photogramm. Eng. Remote Sens.* **1995**, *61*, 539–547.
109. Voogd, H. *Multicriteria Evaluation for Urban and Regional Planning*; Pion: London, UK, 1983.
110. Bocz, E. *Az Idényen Kívüli öntözés [Out-of-Season Irrigation]*; Mezőgazdasági Kiadó: Budapest, Hungary, 1978.
111. Tran, H.Q.; Fehér, Z.Z.; Túri, N.; Rakonczai, J. Climate change as an environmental threat on the central plains of the Carpathian Basin based on regional water balances. *Geogr. Pannonica* **2022**, *26*, 184–199. [\[CrossRef\]](#)
112. Mu, Q.; Zhao, M.; Running, S.W. Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sens. Environ.* **2011**, *115*, 1781–1800. [\[CrossRef\]](#)
113. Tran, Q.H. Két alföldi kisvízgyűjtő éves vízmérlegének meghatározása mért és modellezett adatok alapján [Determination of the annual water balance of two lowland small catchments from measured and modelled data]. *Hidrológiai Közöny* **2023**, *103*, 54–63. (In Hungarian) [\[CrossRef\]](#)
114. Právetz, T.; Sipos, G.; Benyhe, B.; Blanka, V. Modelling runoff on a small lowland catchment, Hungarian Great Plains. *J. Environ. Geogr.* **2015**, *8*, 49–58. [\[CrossRef\]](#)
115. Jánosi, I.M.; Zsuffa, I.; Bíró, T.; Lakatos, B.O.; Szöllősi-Nagy, A.; Hetesi, Z. The dynamics of lowland river sections of Danube and Tisza in the Carpathian Basin. *Front. Earth Sci.* **2025**, *13*, 1391458. [\[CrossRef\]](#)
116. B-Béres, V.; Kókai, Z.; Várbiro, G.; Mustazhapova, G.; Csabai, Z.; Pernecker, B.; Borics, G.; Bácsi, I.; Boda, P. Flow intermittence drives the benthic algal composition, biodiversity and diatom-based quality of small hilly streams in the Pannonian ecoregion, Hungary. *Front. Ecol. Evol.* **2022**, *10*, 834548. [\[CrossRef\]](#)
117. Hrachowitz, M.; Savenije, H.H.G.; Blöschl, G.; McDonnell, J.J.; Sivapalan, M.; Pomeroy, J.W.; Arheimer, B.; Blume, T.; Clark, M.P.; Ehret, U.; et al. A decade of Predictions in Ungauged Basins (PUB)—A review. *Hydrol. Sci. J.* **2013**, *58*, 1198–1255. [\[CrossRef\]](#)
118. Liu, J.; Koch, J.; Stisen, S.; Troldborg, L.; Schneider, R.J.M. A national-scale hybrid model for enhanced streamflow estimation. *Hydrol. Earth Syst. Sci.* **2024**, *28*, 2871–2893. [\[CrossRef\]](#)
119. Tapley, B.D.; Bettadpur, S.; Ries, J.C.; Thompson, P.F.; Watkins, M.M. GRACE measurements of mass variability in the Earth system. *Science* **2004**, *305*, 503–505. [\[CrossRef\]](#)
120. Save, H.; Bettadpur, S.; Tapley, B.D. High-resolution CSR GRACE RL05 mascons. *J. Geophys. Res. Solid Earth* **2016**, *121*, 7547–7569. [\[CrossRef\]](#) [\[PubMed\]](#)
121. Potopová, V.; Trnka, M.; Vizina, A.; Semerádová, D.; Balek, J.; Chawdhery, M.R.A.; Musiolková, M.; Pavlík, P.; Možný, M.; Štěpánek, P.; et al. Projection of 21st century irrigation water requirements for sensitive agricultural crop commodities across the Czech Republic. *Agric. Water Manag.* **2022**, *262*, 107337. [\[CrossRef\]](#)
122. Bidabadi, M.; Hashemy Shahdany, S.M.; Mashal, M. Spatial risk assessment of drought-induced operational failures in interconnected irrigation canals: Application to the Mahyar–Jarghooye district, Iran. *Irrig. Sci.* **2026**, *44*, 55. [\[CrossRef\]](#)
123. Salmaso, F.; Cogato, A.; Bortolini, L. Climate-adaptive irrigation management in Venetian reclamation consortia (Italy). *Sustainability* **2025**, *17*, 10251. [\[CrossRef\]](#)

124. Monteleone, B.; Borzì, I. Drought in the Po Valley: Identification, impacts and strategies to manage the events. *Water* **2024**, *16*, 1187. [[CrossRef](#)]
125. Wu, C.; Chou, F.N.-F.; Chen, Y.-W. Conjunctive-use frameworks driven by surface water operations: Integrating concentrated and distributed strategies for groundwater recharge and extraction. *Water* **2026**, *18*, 130. [[CrossRef](#)]
126. Mai, Z.; He, Y.; Feng, C.; Han, C.; Shi, Y.; Qi, W. Multi-objective modeling and optimization of water distribution for canal system considering irrigation coverage in artesian irrigation district. *Agric. Water Manag.* **2024**, *301*, 108959. [[CrossRef](#)]
127. Cai, Q.; Xu, X.; Li, M.; Ye, X.; Liu, W.; Lian, H.; Zhou, Y. Multi-objective optimization for irrigation canal water allocation and intelligent gate control under water supply uncertainty. *Water* **2025**, *17*, 3585. [[CrossRef](#)]
128. Kharrou, M.H.; Le Page, M.; Chehbouni, A.; Simonneaux, V.; Er-Raki, S.; Jarlan, L.; Ouzine, L.; Khabba, S.; Chehbouni, G. Assessment of equity and adequacy of water delivery in irrigation systems using remote sensing-based indicators in semi-arid region, Morocco. *Water Resour. Manag.* **2013**, *27*, 4697–4714. [[CrossRef](#)]
129. Dillon, P.; Stuyfzand, P.; Grischek, T.; Lluria, M.; Pyne, R.D.G.; Jain, R.C.; Bear, J.; Schwarz, J.; Wang, W.; Fernandez, E.; et al. Sixty years of global progress in managed aquifer recharge. *Hydrogeol. J.* **2019**, *27*, 1–30. [[CrossRef](#)]
130. Koncsos, L.; Murányi, G. A multi-scenario multi-model analysis of regional climate projections in a Central–Eastern European agricultural region: Assessing shallow groundwater table responses using an aggregated vertical hydrological model. *Appl. Water Sci.* **2024**, *14*, 42. [[CrossRef](#)]
131. Tímár, G.; Jakab, G.; Székely, B. A step from vulnerability to resilience: Restoring the landscape water-storage capacity of the Great Hungarian Plain—an assessment and a proposal. *Land* **2024**, *13*, 146. [[CrossRef](#)]
132. Báder, L.; Szilágyi, J. Widening gap of land evaporation to reference evapotranspiration implies increasing vulnerability to droughts in Hungary. *Period. Polytech. Civ. Eng.* **2023**, *67*, 1028–1037. [[CrossRef](#)]
133. Balatonyi, L.; Lengyel, B.; Berger, Á. Nature-based solutions as water management measures in Hungary. *Mod. Geogr.* **2022**, *17*, 73–85. [[CrossRef](#)]
134. Birinyi, E.; O. Lakatos, B.; Belényesi, M.; Kristóf, D.; Hetesi, Z.; Mrekva, L.; Mikus, G. Contribution of data-driven methods to risk reduction and climate change adaptation in Hungary and beyond. *Időjárás* **2023**, *127*, 421–446. [[CrossRef](#)]
135. Szabó, A.; Juhász, C.; Gálya Farkasné, B.; Kövesdi, Á.; Tamás, J.; Nagy, A. Combined traffic control of irrigation on heterogeneous field. *Acta Agrar. Debreceniensis* **2022**, *1*, 187–190. [[CrossRef](#)]
136. Láng, I. Teret a folyóknak! A nagyvízi mederkezelés szerepe a hazai árvízvédelemben [Make room for rivers: The role of high-water riverbed management in Hungarian flood protection]. *Biztosítás és Kockázat* **2017**, *4*, 42–59. [[CrossRef](#)] [[PubMed](#)]

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