

SMART IRRIGATION AND DRAINAGE SYSTEM TO ENHANCE THE NORDIC AGRICULTURE RESILIENCE UNDER CLIMATE CHANGE

SYSTÈME INTELLIGENT D'IRRIGATION ET DE DRAINAGE POUR AMÉLIORER LA RÉSISTANCE DE L'AGRICULTURE NORDIQUE FACE AU CHANGEMENT CLIMATIQUE

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ABSTRACT

Climate change is intensifying summer droughts in traditionally rainfed boreal agricultural regions, creating water management challenges that existing frameworks. In such landscapes, extensive subsurface drainage infrastructure designed to remove excess water during wet periods can be strategically repurposed by integrating rainwater harvesting reservoirs, creating dual-purpose irrigation-drainage systems that enhance agricultural resilience without requiring new water source development. This study develops a spatially explicit optimization framework for sizing integrated reservoir systems across the Temmesjoki River Basin in Northern Finland, using 43 years of daily gridded climate data (1981–2023) and crop-specific water requirements for potato cultivation. A daily water balance model was applied to determine minimum reservoir capacities satisfying three agronomically grounded reliability thresholds: zero, ≤ 5 , and ≤ 7 consecutive deficit days. Results show that basin-mean optimized capacities range from 757 to 863 m³ ha⁻¹ across the three scenarios, with the ≤ 5 to ≤ 7 consecutive deficit day window offering the most cost-effective design standard given potato crop physiology. A consistent north–south gradient in required storage reflects underlying climatic heterogeneity, reinforcing the need for spatially differentiated rather than uniform infrastructure standards. Temporal analysis reveals a pronounced upward trend in required capacity over the most recent decade, indicating that water balance conditions are actively shifting rather than fluctuating around a stable mean. These findings provide agricultural planners and policymakers with a quantitative framework for transforming existing drainage networks into climate-resilient irrigation infrastructure across boreal agricultural regions.

Keywords: Smart irrigation and drainage system; rainwater harvesting reservoirs; infrastructure standards; Temporal analysis; water balance.

RESUME

Le changement climatique accentue de plus les sécheresses estivales des régions agricoles boréales traditionnellement pluviales, créant des défis de gestion de l'eau qui dépassent les cadres existants. Dans de tels paysages, de vastes infrastructures de drainage souterrain conçues pour éliminer l'eau excédentaire pendant les périodes humides peuvent être stratégiquement réutilisées grâce à l'intégration des réservoirs de collecte des eaux de pluie, en créant ainsi un système mixte irrigation-drainage qui améliorent la résistance agricole sans l'exigence du développement de nouvelles sources

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d'eau. Cette étude développe un cadre d'optimisation spatialement explicite pour juger des systèmes de réservoirs intégrés à travers le bassin versant de Temmesjoki en Finlande du Nord, en utilisant 43 années de données climatiques quotidiennes maillées (1981–2023) et les besoins en eau spécifiques aux cultures pour la culture de pommes de terre. Un modèle de bilan hydrique quotidien a été appliqué pour déterminer les capacités minimales des réservoirs tout en satisfaisant trois seuils de fiabilité basés sur les critères agronomiques : zéro, ≤ 5 et ≤ 7 jours de déficit consécutifs. Les résultats montrent que les capacités optimisées moyennes du bassin vont de 757 à 863 m³ ha⁻¹ selon les trois scénarios, avec une possibilité de ≤ 5 à ≤ 7 jours consécutifs de déficit offrant la norme de conception la plus rentable compte tenu de la physiologie des cultures de pommes de terre. Un gradient nord–sud cohérent dans le stockage requis reflète l'hétérogénéité climatique sous-jacente, ce qui renforce la nécessité de normes d'infrastructure spatialement différenciées plutôt qu'uniformes. L'analyse temporelle constate une tendance à la hausse plus prononcée de la capacité requise au cours de la dernière décennie, ce qui indique que les conditions du bilan hydrique évoluent de manière active plutôt que de fluctuer autour d'une moyenne stable. Ces résultats fournissent aux planificateurs et décideurs agricoles un cadre quantitatif pour transformer les réseaux de drainage existants en infrastructures d'irrigation résistantes au climat dans les régions agricoles boréales.

Mots-clés : Système intelligent d'irrigation et de drainage; Réservoirs de collecte des eaux de pluie; Normes d'infrastructure; Analyse temporelle; Bilan hydrique.

INTRODUCTION

Climate change is fundamentally altering the hydrological conditions that boreal agriculture has historically relied upon. Across northern Europe, growing seasons are becoming warmer and more evapotranspiration-intensive, while summer precipitation is increasingly unreliable, generating seasonal water deficits in regions that have traditionally required little or no supplemental irrigation (Felsche et al., 2024; Ducros et al., 2024). For water-sensitive crops such as potato, even brief periods of moisture stress during critical developmental stages can trigger substantial yield and quality losses, making reliable water supply a prerequisite for stable agricultural production (Adekanmbi et al., 2024). This emerging vulnerability in traditionally rainfed boreal systems has created an urgent need for locally appropriate, cost-effective water storage solutions that can bridge the gap between seasonal precipitation surplus and growing-season deficit.

Rainwater harvesting coupled with on-farm reservoir storage represents one of the most accessible pathways for building this resilience. By capturing excess drainage water during wet periods and releasing it as supplemental irrigation during dry spells, such systems can substantially improve crop water availability without dependence on centralized infrastructure (Garg et al., 2022). In boreal agricultural with established subsurface drainage networks existing infrastructure provides a ready-made collection mechanism that lowers implementation costs considerably (Virtanen et al., 2015). The central engineering challenge therefore shifts from infrastructure installation to reservoir sizing: determining the minimum storage capacity that reliably meets crop water demand across the full range of climatic variability, without excessive over-investment in rarely utilized capacity.

Reservoir sizing optimization has been widely studied in arid and semi-arid contexts, where water scarcity is chronic and the economic case for storage is self-evident (Di Francesco et al., 2022; Baah-Kumi et al., 2024). However, boreal systems present a structurally different optimization problem. Water deficits are seasonal rather than permanent, and the tolerable deficit threshold is defined not by absolute scarcity but by crop-specific physiological sensitivity. Standard frameworks developed for arid regions do not translate directly to these conditions, and dedicated computational approaches for temperate drainage-fed systems remain scarce (Beça et al., 2023). Furthermore, most existing studies adopt single-location approaches, overlooking the spatial heterogeneity in water demand that determines whether a given storage capacity performs adequately across an entire agricultural landscape (Semaan et al., 2020).

This study addresses these gaps by applying a spatially explicit optimization framework to determine minimum reservoir storage capacities across a Nordic river basin, using 43 years of daily climate data and crop-specific water demand parameters for potato cultivation. The optimization targets three agronomically grounded reliability thresholds defined by maximum tolerable consecutive deficit days, enabling direct linkage between storage design and crop vulnerability. By evaluating both the spatial distribution and temporal evolution of optimized capacities, the study provides quantitative guidance for farm-level reservoir investment that accounts for landscape heterogeneity and climatic non-stationarity, increasingly recognized as essential in climate-adaptive water infrastructure planning (Felsche et al., 2024; Beça et al., 2023).

METHODS

Study area and data

The Temmesjoki Basin (1,180.71 km²) in North Ostrobothnia, Finland, serves as the study domain as a subarctic agricultural landscape where potato farming dominates the 209.69 km² of cultivated land. The basin experiences strong seasonal temperature variation (-17 to -13°C in January; 10 to 15°C in July) and moderate annual precipitation of 400-600 mm, much of which falls during the growing season. The study was driven by daily gridded precipitation and potential evapotranspiration data at 1×1 km resolution spanning 1981-2023, sourced from the Finnish Meteorological Institute. Precipitation was interpolated using kriging with external drift (Aalto et al., 2016), while evapotranspiration was estimated following the FAO Penman-Monteith method (Allen et al., 1998; Pirinen et al., 2022).

Reservoir storage optimization

The minimum reservoir storage capacity required to satisfy three reliability standards including zero, ≤5, and ≤7 consecutive deficit days was determined through constrained nonlinear minimization across the full 43-year simulation period. The optimization was formulated as:

$$\begin{aligned} & \text{Min } S_{\text{RHR}} \\ \text{Subject to:} & \\ & g_y(S_{\text{RHR}}) = \min_{t \in T_y} \{D_{\text{cons}}(t, S_{\text{RHR}})\} \leq D_{\text{threshold}} \quad \forall y \in Y \\ & S_{\text{RHR}} \geq 0 \end{aligned}$$

where S_{RHR} is the reservoir storage capacity (m³ ha⁻¹), $g_y(S_{\text{RHR}})$ is the maximum consecutive deficit duration in year y as a function of reservoir capacity, $D_{\text{cons}}(t, S_{\text{RHR}})$ represents the current consecutive deficit duration at day t given capacity S_{RHR} , $D_{\text{threshold}}$ is the operational threshold (0, 5, or 7 consecutive days), Y is the set of all years in the simulation period, and T_y is the set of days in the growing season for year y .

RESULTS

Spatially Optimized Reservoir Capacity

Figure 2 presents the spatial distribution of minimum reservoir storage capacity required to satisfy three irrigation reliability scenarios across the basin over the 1981-2023 period. Moving from the strictest to the most relaxed threshold progressively reduces the required storage, though meaningful spatial gradients persist under all three conditions.

Under the zero-deficit scenario, optimized capacities ranged from 764.6 to 966.8 m³ ha⁻¹, with a basin mean of 862.6 m³ ha⁻¹. Allowing up to five consecutive deficit days reduced these values to a range of 696.3-889.6 m³ ha⁻¹ (mean: 790.4 m³ ha⁻¹), while tolerating up to seven consecutive deficit days brought the range down further to 541.0-857.4 m³ ha⁻¹ (mean: 757.2 m³ ha⁻¹). The transition from zero to seven consecutive tolerated deficit days therefore yields a basin-mean saving of approximately 105 m³ ha⁻¹,

suggesting that even a modest relaxation of the reliability standard translates into tangible reductions in infrastructure demand.

From a crop production perspective, the five- and seven-day thresholds carry agronomic relevance. For potato cultivation, as the dominant crop in the Temmesjoki basin, short moisture deficits of up to five to seven consecutive days during non-critical growth stages are generally tolerable without triggering significant yield penalties. Water stress becomes most damaging during tuber initiation and bulking phases, where prolonged deficits exceeding one week can lead to substantial yield losses and quality deterioration. Designing reservoir capacity around these biologically meaningful thresholds therefore represents a more agronomically grounded and economically efficient approach than targeting complete elimination of all deficit days, which demands considerably larger and costlier infrastructure. The difference in mean optimized capacity between the zero-deficit and five-day scenarios amounts to approximately $72 \text{ m}^3 \text{ ha}^{-1}$, while the further step to the seven-day threshold adds a reduction of roughly $33 \text{ m}^3 \text{ ha}^{-1}$. These incremental savings, though moderate in absolute terms, can meaningfully influence farm-level investment feasibility when multiplied across hundreds of hectares of cultivated land.

Spatially, the western and northern portions of the basin consistently required the largest storage volumes across all three scenarios. The south-eastern parts showed the greatest sensitivity to the chosen reliability threshold, under the seven-day scenario, this area transitions to distinctly lower values approaching the $541 \text{ m}^3 \text{ ha}^{-1}$ minimum, reflecting more favorable local water balance conditions. This spatial gradient underscores that a uniform basin-wide design capacity would either over-invest in lower-demand areas or leave higher-demand zones under-protected, reinforcing the value of spatially explicit optimization for practical reservoir planning across heterogeneous agricultural landscapes.

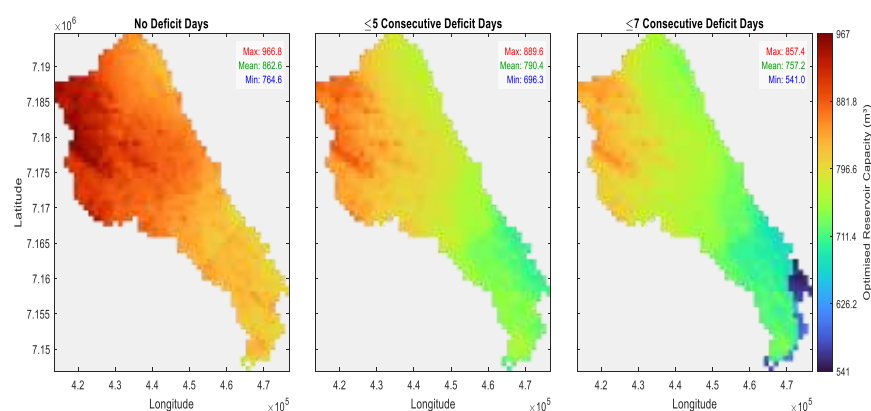


Figure 2. Optimized reservoir capacity under three irrigation reliability scenarios across the basin over 1981-2023

Latitudinal Variation in Optimized Reservoir Capacity

Figure 3 illustrates how the average optimized reservoir capacity varies along the north-south gradient of the basin for all three reliability scenarios. The shaded bands around each curve represent spatial uncertainty across grid cells at each latitude, providing a measure of within-row variability in addition to the latitudinal trend.

Across all three scenarios, a consistent northward increase in required storage capacity is evident, with the curves shifting progressively to higher capacity values as latitude increases. This monotonic trend confirms that northern parts of the basin face structurally more demanding water balance conditions, requiring greater storage investment to achieve any given reliability level. The pattern is coherent and continuous rather than abrupt, suggesting that the underlying drivers including changes in the precipitation-evapotranspiration balance across the basin exert a smooth latitudinal influence on storage requirements.

The three curves are well separated throughout most of the latitudinal range, reinforcing that the choice of reliability threshold has a meaningful and spatially consistent effect on design capacity. The zero-deficit scenario demands the highest storage at every latitude, ranging from approximately 800 m³ in the south to around 950 m³ in the north. The ≤ 5 consecutive deficit days scenario tracks consistently below, spanning roughly 700–870 m³ across the same range. The ≤ 7 consecutive deficit days scenario occupies the lowest position, with values between approximately 560–840 m³, and also exhibits the widest shaded uncertainty band, particularly in the southern portion of the basin. This greater variability at the relaxed threshold reflects the heightened sensitivity of the optimization outcome to local conditions when the constraint is less binding, small differences in the local water balance translate into larger differences in the minimum adequate storage.

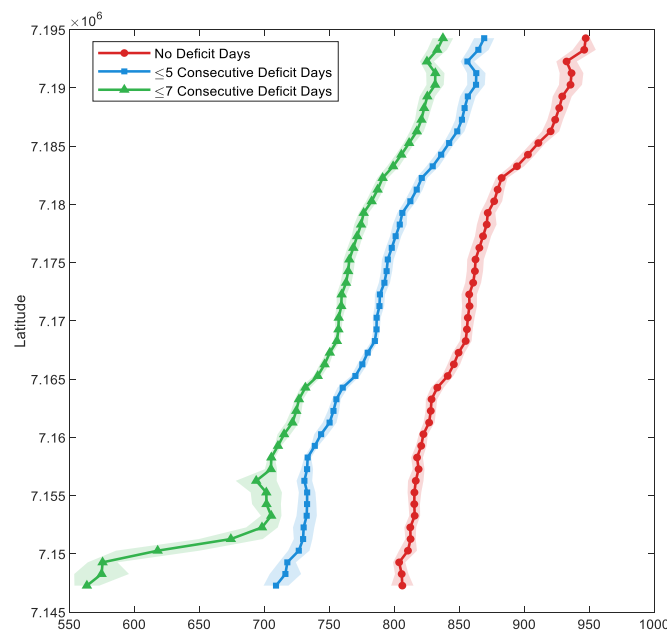


Figure 3. Latitudinal variation in average optimized reservoir capacity (m³)

Temporal Trends in Optimized Reservoir Capacity

Figure 4 reveals considerable interannual variability in spatially averaged optimized reservoir capacity across the 1981–2023 period, with a discernible upward trend emerging particularly from the mid-2010s onward. The shaded band between the zero-deficit and ≤ 7 consecutive deficit day curves captures the design uncertainty envelope, which remains relatively stable in width throughout the record, indicating that the gap between strict and relaxed reliability standards is broadly consistent over time regardless of climatic conditions in any given year.

During the 1980s, required capacities started at moderate-to-high levels (approximately 275 m³ under the zero-deficit scenario) before declining through the late 1980s to early 1990s, a period of comparatively favorable growing season water availability. A gradual recovery in required capacities through the 1990s was followed by a sharp drop around 2000–2001, where all three curves reach some of their lowest values across the entire record, with the ≤ 7 -day scenario falling to around 130 m³. This period appears to reflect a cluster of wetter-than-average growing seasons that temporarily reduced storage requirements across all reliability thresholds.

The most striking feature of the time series is the pronounced dip occurring around 2012–2013, where all three curves simultaneously reach their absolute minima as the zero-deficit scenario drops to approximately 185 m³, while the ≤ 7 -day threshold falls close to 95 m³. This anomalously low period is followed almost immediately by a sustained and steep upward trajectory that continues through to 2023,

with the zero-deficit scenario reaching its record high of approximately 325 m³ by the end of the period. This post-2013 rise is the most consistent and prolonged trend in the entire record and strongly suggests that recent growing seasons have become increasingly more water-demanding, requiring progressively larger storage to maintain any given level of irrigation reliability.

From an agricultural planning perspective, this temporal trajectory carries important implications. Reservoir systems designed based on historical averages from the 1990s or early 2000s would be systematically undersized relative to the demands of the most recent decade. The convergence of all three scenarios toward higher values in the 2020s, regardless of the chosen reliability threshold, points to a structural shift in water deficit conditions rather than simple year-to-year fluctuation. This reinforces the need to incorporate the full length of available climate records, including both wetter and drier decades, when determining design capacities, and supports a forward-looking approach to reservoir sizing that anticipates continued increases in growing-season water demand.

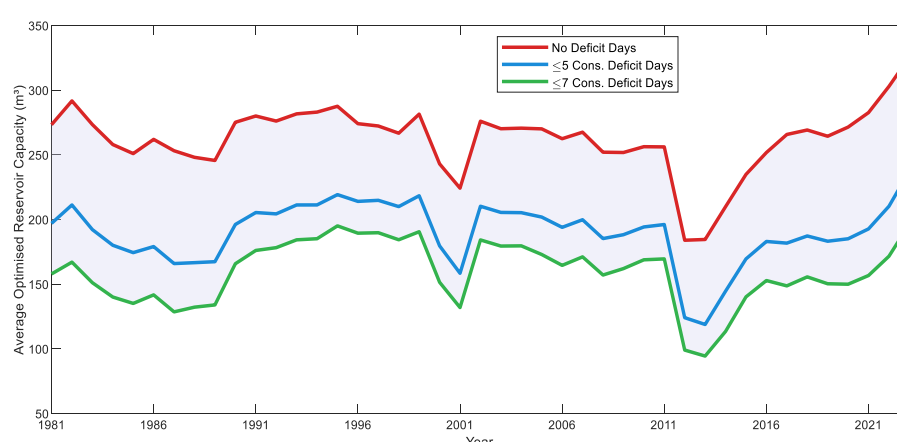


Figure 4. Temporal change in spatially averaged optimized reservoir capacity (m³)

Distributional Shifts in Optimized Capacity Across Decadal Periods

Figure 5 presents the optimized reservoir capacity across three sub-periods (e.g., 1981-1994, 1995-2008, and 2009-2023) for each reliability scenario, revealing how both the central tendency and the distributional shape of storage requirements have evolved over time.

The most striking pattern across all three scenarios is the pronounced peak in required capacity during the 1995-2008 period. The orange violins are consistently the tallest and widest, with median values reaching approximately 850, 800, and 750 m³ under the zero-deficit, ≤5-day, and ≤7-day scenarios respectively. The broad, rounded shape of these distributions indicates that high storage requirements were widespread and relatively uniform across the basin during this period, driven largely by the inclusion of the exceptionally dry 2006 growing season. This mid-period peak confirms that the 1995–2008 window represents the most hydrologically demanding period in the simulation record, placing the greatest strain on reservoir infrastructure regardless of the chosen reliability threshold.

In contrast, the 1981-1994 period shows notably lower and more compact distributions, with medians clustered around 530, 495, and 480 m³ across the three scenarios. The narrow violin shapes reflect a relatively homogeneous set of growing seasons during this earlier period, with limited spread between high and low storage requirements. This suggests that the earlier decades of the record were characterized by more moderate and consistent water balance conditions, where even moderately sized reservoirs would have performed adequately across most years and locations.

In the 2009-2023 period, median values drop noticeably compared to 1995-2008 to approximately 490, 435, and 400 m³ while the violin shapes remain moderately wide, indicating continued year-to-year variability. Alongside the temporal trend in Figure 4, this apparent decline in the 2009–2023 median

reflects the influence of the very low-demand years around 2012-2013 pulling the distribution downward, while the sharp upward trend in the most recent years (2018-2023) is captured in the upper tails of the green violins. This combination of a lower median but an extended upper tail signals an increasingly polarized climate signal, more frequent low-demand years punctuated by increasingly severe high-demand events.

Across all three sub-periods, the consistent ordering of the three reliability scenarios confirms the robustness of the ≤ 5 to ≤ 7 consecutive deficit day window as a design standard: it reliably reduces required capacity relative to the zero-deficit benchmark while remaining responsive to the same temporal and distributional dynamics, making it a stable and practical reference for crop-oriented reservoir planning.

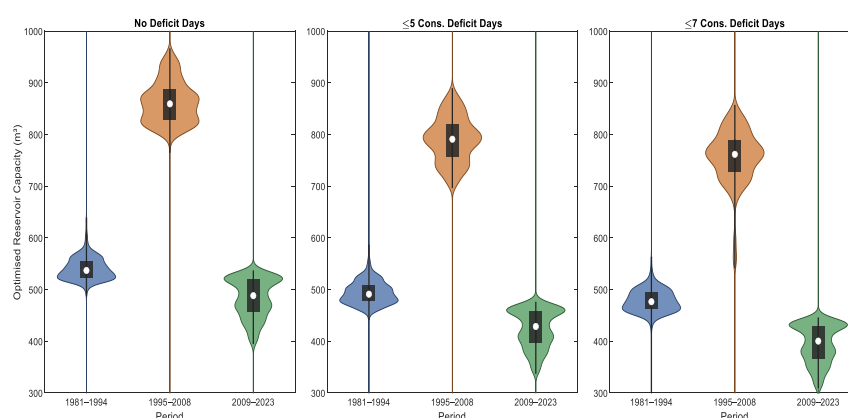


Figure 5. Distributional variation in spatially optimized reservoir capacity across three climatic periods (1981-1994, 1995-2008, and 2009-2023) under three reliability scenarios

DISCUSSION

The choice of reliability threshold in reservoir design is rarely a purely hydrological decision as it is fundamentally an agronomic and economic one. The relatively modest difference in required capacity between the zero-deficit and ≤ 7 consecutive deficit day scenarios suggests that insisting on complete drought elimination carries a disproportionate infrastructure cost for marginal crop protection gains. For potato cultivation, yield penalties become agronomically significant only when moisture stress persists beyond roughly one week during tuber initiation and bulking (Adekanmbi et al., 2024). The ≤ 5 to ≤ 7 consecutive day window therefore represents a more rational design frontier as one that aligns storage investment with actual crop vulnerability rather than with an idealized supply guarantee, consistent with broader arguments for adaptive, threshold-based infrastructure planning (Beça et al., 2023; Di Francesco et al., 2022).

The spatial gradient in required storage raises a broader question about how water infrastructure policy is formulated across heterogeneous landscapes. There is a persistent tendency in regional planning to adopt uniform design standards for administrative simplicity, yet the latitudinal variation identified here illustrates how such approaches systematically disadvantage areas with structurally higher water demand. Northern farms would face chronic under-performance from a basin-average sized reservoir not because of poor management, but because of geography. Spatially explicit optimization offers a practical tool for identifying where infrastructure investment yields the greatest reliability gains per unit of storage capacity, particularly in Nordic systems where coastal evapotranspiration gradients create meaningful within-basin variability (Olesen et al., 2011; Semaan et al., 2020).

Perhaps the most consequential finding from a forward-looking perspective is not the magnitude of required storage at any given moment, but the direction of change over time. The progressive increase in optimized capacity through the most recent decade suggests that the water balance conditions

underpinning reservoir design are themselves shifting rather than fluctuating around a stable mean. This is consistent with the broader northward intensification of summer drought across Scandinavia (Felsche et al., 2024), where warming temperatures are simultaneously lengthening the evapotranspiration season and reducing growing-season precipitation reliability. Infrastructure sized on mid-period historical averages would therefore risk being functionally inadequate before the end of its service life, reinforcing the case for incorporating non-stationarity assumptions into design practice (Baah-Kumi et al., 2024).

Disaggregating the record into sub-periods reveals that this upward pressure on storage demand is neither linear nor uniform but is instead shaped by the statistical weight of rare but climatically decisive events. The elevated storage requirements of the 1995-2008 period, anchored heavily by the 2006 growing season, illustrate how single extreme events can define infrastructure standards for decades. Given that compound heat-drought events are projected to become more frequent across northern Europe (Rousi et al., 2023; Felsche et al., 2024), events of 2006 magnitude may transition from statistical outliers to near-normal conditions within the operational lifetime of reservoirs built today. This reframes the planning question: not whether to design for extremes, but which extremes should serve as the credible design benchmark going forward (Gharib et al., 2023).

Finally, it is worth acknowledging what optimized reservoir sizing alone cannot resolve. Even well-designed storage infrastructure will face residual deficits during the most severe drought years, pointing to the complementary role of irrigation efficiency improvements, drought-tolerant crop variety selection, and demand management as part of a broader climate adaptation portfolio (Georgakakos et al., 2012; Li et al., 2024). The framework developed here provides a quantitative basis for sizing decisions, but its outputs should be interpreted alongside economic feasibility assessments, soil drainage characteristics, and local land use constraints to support well-rounded investment planning.

CONCLUSIONS

This study applied a spatially explicit optimization framework to determine minimum reservoir storage capacities required for reliable irrigation of potato crops across a Nordic river basin, evaluated against three agronomically grounded reliability thresholds over a 43-year simulation period. The results demonstrate that complete elimination of deficit days demands substantially larger infrastructure than tolerating short moisture gaps of five to seven consecutive days as a tolerance range that aligns with the actual drought sensitivity of potato crops during non-critical growth stages. This threshold-based design approach offers a more cost-effective and biologically justified pathway for farm-level reservoir investment than engineering toward zero deficit, particularly in contexts where capital resources are constrained. Spatially, the analysis confirms that a single basin-wide design standard is insufficient. The consistent north-south gradient in optimized capacity, driven by differences in the local precipitation-evapotranspiration balance means that uniform infrastructure standards would systematically under-serve the most drought-vulnerable areas while over-investing elsewhere. Effective planning therefore requires spatially differentiated approaches that reflect the underlying hydrological heterogeneity of the landscape. From a temporal perspective, the findings carry a forward-looking warning. Required storage capacities have trended upward through the most recent decade, and the growing frequency of severe drought years suggests that historical averages from earlier periods no longer provide a reliable basis for infrastructure sizing. Reservoir systems designed today must account for a water balance regime that is actively shifting, not merely variable around a stable long-term average. Collectively, these findings provide agricultural planners and policymakers with a quantitative framework for prioritizing reservoir investments across heterogeneous landscapes under climate change.

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