AIntelia

Optimizing Variable-Rate Linear Move Irrigation Systems Using Edge-AI and Hydrological Modeling: A Case Study of the Danube-Tisa-Danube Canal Basin in Vojvodina

Dušan Radovanović[1], Ivana Bjelić[2], Gracijela Abramenko[3]

[1] *Department of Water Resources and Environmental Engineering, University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia, d.radovanovic@ftn.uns.ac.rs, ORCID: 0009-0004-9292-7897*

[2] *Department of Field and Vegetable Crops, University of Novi Sad, Faculty of Agriculture, Novi Sad, Serbia, i.bjelic@polj.uns.ac.rs, ORCID: 0009-0009-3301-0495*

[3] *M-Inženjering d.o.o, Podgorica, Montenegro,* g.abramenko@m-inzenjering.com*, ORCID: 0009-0009-9864-4747*

Vojvodina, the principal agricultural region of Serbia, faces escalating irrigation demand driven by intensifying summer drought conditions and declining summer precipitation attributable to regional climate change. The Danube-Tisa-Danube (DTD) hydrosystem — a 929 km canal network providing irrigation water to up to 510,000 ha of arable land — is under growing pressure to improve the spatial and temporal precision of water allocation to individual fields. This paper proposes and evaluates an integrated optimisation framework for variable-rate irrigation (VRI) linear move systems supplied from the DTD canal network, combining: (i) a SWAT+ hydrological model of the DTD basin calibrated on 2011–2022 discharge and canal water-level records; (ii) a field-scale LSTM-based soil moisture and reference evapotranspiration (ET_0) prediction module driven by IoT soil moisture sensors and near-real-time weather data; and (iii) an Edge-AI prescription generation engine deployed on an NVIDIA Jetson Nano embedded unit mounted on the linear move machine. The SWAT+ model achieves Nash-Sutcliffe Efficiency (NSE) of 0.81 and R^2 of 0.87 in validation. The LSTM module predicts 48-hour soil moisture with RMSE of 0.028 m^3/m^3. Field trials on maize (Zea mays L.) and sunflower (Helianthus annuus L.) across four trial sites in Bačka demonstrate a 22.4% reduction in seasonal irrigation water application relative to uniform-rate management, with equivalent or improved grain yields (maize +3.1%, sunflower +1.8%), confirming the operational viability of data-driven VRI optimisation in the DTD basin context.

Keywords: *variable-rate irrigation; linear move system; Edge-AI; SWAT+; LSTM; soil moisture prediction; Vojvodina; Danube-Tisa-Danube canal; precision agriculture*

1. Introduction

Irrigation is the single largest consumptive use of freshwater globally, accounting for approximately 70% of total water withdrawals in agricultural economies. In the Pannonian Plain, including Vojvodina — the flat, fertile northern province of Serbia that produces the majority of the country's maize, sunflower, sugar beet, and soybean — summer precipitation deficits create recurring crop water stress that constrains yields below genetic potential. The Danube-Tisa-Danube (DTD) hydrosystem, a 929 km multi-purpose canal network constructed between 1947 and 1977, provides the primary surface-water irrigation source for up to 510,000 ha of agricultural land in Bačka and Banat [1]. However, escalating summer droughts — the hydrological year 2022 was characterised by the worst water scarcity in Vojvodina in 100 years, forcing temporary irrigation bans in parts of the province [2] — are placing unprecedented pressure on the DTD water balance and on the efficiency of irrigation water use.

Conventional fixed-rate irrigation management, in which a linear move or centre-pivot machine applies a spatially uniform water depth on each pass, is inherently inefficient in fields with heterogeneous soil texture, water-holding capacity, and crop stress patterns. Variable-rate irrigation (VRI) technology, which enables the spatial modulation of water application depth across the field through speed control or individual nozzle sector switching, offers a technically mature pathway to improving both water use efficiency (WUE) and yield uniformity [3]. The integration of IoT soil moisture sensing, machine learning-based irrigation scheduling, and edge computing for prescription execution has been identified as the transformative enabler for data-driven VRI at farm scale [4].

Despite the technical readiness of VRI components, their integration with hydrological decision support at the canal network scale — incorporating supply-side water availability constraints from the DTD system alongside demand-side crop water stress estimates — has not been systematically addressed in the literature for the Vojvodina context. This paper presents a three-tier optimisation framework: (i) a SWAT+ basin-scale hydrological model providing 10-day canal water availability forecasts; (ii) a field-scale LSTM neural network predicting 48-hour soil moisture and ET_0 to generate VRI prescriptions; and (iii) an Edge-AI prescription execution engine on a linear move machine. The framework is evaluated in a two-season field trial on maize and sunflower in the northern Bačka sub-region.

2. Literature Review

Variable-rate irrigation enables site-specific water application by modulating system speed or individual nozzle sector flow rates across spatially delineated management zones. Nguyen et al. [5] developed the MOPivot software for automatic management zone delineation for centre pivot VRI, demonstrating that machine-geometry-constrained prescription maps derived from soil data achieve application rate adherence within 5% of target values. Alomari and Alfatlawi [6] reviewed the performance of VRI versus constant rate irrigation across published field trials, concluding that VRI achieves water savings of 10-25% depending on field soil variability and crop type, with yield responses ranging from neutral to +8% compared to uniform management.

For linear move systems — which traverse a rectangular field in a straight path rather than rotating around a fixed pivot point — VRI prescription generation follows the same management zone logic as centre pivot VRI, but field geometry simplifies sector management. Evans et al. [7] documented the adoption trajectory of site-specific variable rate sprinkler irrigation, identifying soil-based zone delineation as the most robust approach for field-scale deployment. The integration of apparent soil electrical conductivity (EC_a) mapping with remote sensing and machine learning for management zone delineation was demonstrated for corn under a centre pivot, achieving a 15% water saving relative to uniform management [8].

Machine learning approaches to irrigation scheduling have developed rapidly, driven by the availability of IoT soil moisture sensor networks and near-real-time weather data. Bwambale et al. [9] reviewed smart irrigation monitoring and control strategies, identifying Long Short-Term Memory (LSTM) recurrent neural networks as the most accurate data-driven approach for multi-step-ahead soil moisture prediction due to their capacity to capture temporal dependencies across diverse time scales. Togneri et al. [10] developed a machine learning-based soil moisture forecast framework tested across eight crop types in twelve fields in Brazil, demonstrating RMSE values of 0.020-0.045 m^3/m^3 for 24-hour-ahead predictions using LSTM architectures — the benchmark against which the present study's performance is calibrated.

The integration of ET_0 prediction with soil moisture forecasting for irrigation prescription generation was addressed by Abioye et al. [11], who reviewed precision irrigation management using machine learning and digital farming solutions, confirming that model-predictive control frameworks that couple ET_0 predictions with soil water balance models outperform fixed-threshold-based scheduling in water use efficiency. Hossain [12] demonstrated advanced machine learning techniques for irrigation optimisation in canal systems, achieving 17.3% water savings relative to conventional scheduling through LSTM-based demand forecasting integrated with supply-side canal management.

The Soil and Water Assessment Tool (SWAT) and its successor SWAT+ are widely applied physics-based semi-distributed hydrological models capable of simulating water balance, crop growth, and irrigation scheduling at basin scale on a daily time step. SWAT+ incorporates structural improvements over the original SWAT in channel routing, reservoir operations, and landscape unit connectivity that are particularly relevant for managed canal networks such as the DTD hydrosystem [13]. The Danube River Basin Management Plan [14] identified hydromorphological alterations and drought/water scarcity as the principal pressures on the DTD and Pannonian Plain water systems, directly motivating basin-scale hydrological modelling for water allocation management.

The application of SWAT to irrigation-dominated basins with complex canal networks requires explicit representation of water diversion structures, irrigation scheduling algorithms, and return flow pathways. Arnold et al. [15] documented SWAT model calibration and validation protocols establishing NSE $\geq$ 0.50 as satisfactory and NSE $\geq$ 0.75 as very good performance for monthly streamflow simulation — criteria used as benchmarks in the present study. Calibration of SWAT to canal water levels rather than streamflow, as required for the DTD system, introduces additional parameter uncertainty that is addressed through multi-site multi-variable calibration.

The deployment of machine learning inference on resource-constrained embedded computing platforms — Edge AI — is increasingly applied in precision agriculture to enable closed-loop sensor-actuator systems without dependence on cloud connectivity. Debauche et al. [16] demonstrated an Edge AI-IoT system for pivot irrigation, plant disease, and pest identification using a Jetson-class embedded GPU, confirming the viability of real-time deep learning inference on field-deployed hardware. The NVIDIA Jetson Nano (472 GFLOPS FP16) provides sufficient compute for LSTM inference at sub-second latency, enabling prescription updates on a per-tower-section basis as the linear move machine traverses the field.

While individual components — VRI zone management, LSTM irrigation scheduling, SWAT basin modelling, and Edge AI — have been individually demonstrated in the literature, their integration into a coherent three-tier framework coupling basin-scale water availability forecasts with field-scale soil moisture predictions and on-machine Edge AI prescription execution has not been evaluated in the Vojvodina/DTD context or in comparable Pannonian Plain agriculture settings. The present work addresses this integration gap, providing a complete system design and two-season field trial evaluation.

3. Methodology

The study area encompasses the northern Bačka sub-region of Vojvodina, covering approximately 3,800 km² between the Danube and Tisa rivers, underlain by Quaternary alluvial deposits with chernozem and calcareous chernozem soils predominating. The DTD canal network provides irrigation water through gravity-fed offtakes and pumping stations, with nominal irrigation capacity of 84 m^3/s for Bačka [1]. The trial fields are located within 5 km of active DTD offtakes in the municipalities of Vrbas and Kula, at elevations of 80-90 m above sea level. The regional climate is continental, with mean annual precipitation of 560-580 mm and a pronounced summer moisture deficit: July-August precipitation averages 60-70 mm against potential ET of 200-220 mm, creating a structural irrigation requirement for summer crops.

The DTD basin SWAT+ model was set up using a 30 m resolution digital elevation model derived from SRTM data, CORINE Land Cover 2018 for land use classification, and the FAO Harmonised World Soil Database (HWSD v1.2) for soil parameterisation. The model domain covers the northern Bačka sub-catchment (3,820 km²) discretised into 47 sub-basins and 312 Hydrological Response Units (HRUs). Canal operations are explicitly represented using SWAT+ reservoir and water rights modules, with diversion structures parameterised from records provided by Vode Vojvodine Public Water Management Company. Daily meteorological inputs (precipitation, maximum and minimum temperature, solar radiation, wind speed, relative humidity) were drawn from four RHMSS (Republic Hydrometeorological Service of Serbia) meteorological stations within or adjacent to the basin for the period 2000-2022.

Model calibration was performed against monthly canal water levels at three gauging stations (Vrbas, Kula, Srbobran) for the period 2011-2019, using the SWAT+ Auto-Calibration tool (SWAT+ Cal) with the Sequential Uncertainty Fitting (SUFI-2) algorithm. Validation was performed for 2020-2022. Sensitive parameters identified by Latin Hypercube One-factor-At-a-Time (LH-OAT) sensitivity analysis include CN2 (curve number), ALPHA_BF (baseflow recession constant), GW_DELAY (groundwater delay), CANMX (maximum canopy storage), and the irrigation diversion efficiency coefficient. Model performance was evaluated using NSE, R^2, and Percent Bias (PBIAS) following Arnold et al. [15].

A field-scale LSTM neural network was trained to predict 48-hour-ahead volumetric soil moisture at 20 cm depth, the primary root-zone monitoring depth for maize and sunflower in the study area. Input features include: (i) soil moisture at t, t-24h, t-48h; (ii) daily maximum and minimum air temperature; (iii) precipitation; (iv) reference evapotranspiration ET_0 computed by the FAO-56 Penman-Monteith method from weather station data; (v) solar radiation; and (vi) day of year as a cyclical encoding. IoT soil moisture sensors (Decagon 5TM capacitance sensors at 20 cm and 40 cm depth) were deployed at 12 field positions across the four trial sites, transmitting data at 30-minute intervals via LoRaWAN to a field-edge gateway.

The LSTM architecture comprises two stacked LSTM layers (hidden dimensions 128 and 64) with dropout regularisation (rate 0.25) and a fully connected output layer. Training data spans 2021-2022 (N = 17,520 hourly records per site), with an 80:10:10 train:validation:test split. The model is trained using the Adam optimiser with initial learning rate 1×10^{-3} and early stopping. ET_0 forecasts are generated using a secondary Random Forest model trained on the same meteorological inputs for 24-48 h ahead prediction, following Bwambale et al. [9]. The trained LSTM model is exported to ONNX format and deployed on the NVIDIA Jetson Nano edge unit for inference at 50 ms per prediction step.

The Edge-AI prescription generation engine runs on an NVIDIA Jetson Nano (4 GB RAM, 472 GFLOPS FP16) mounted in an IP65-rated enclosure on the linear move machine control cabinet. At each 60-second cycle, the engine retrieves current soil moisture readings from the IoT network via LoRaWAN gateway, runs the LSTM inference to project 48-hour soil moisture trajectories for each management zone, computes the irrigation demand as the deficit between field capacity and predicted minimum moisture, and generates a speed-control VRI prescription map. The prescription is transmitted to the linear move SCADA system via Modbus

TCP, modulating section speed relative to the nominal pass speed (range: ±30%) to deliver spatially variable water depths between 12 mm and 38 mm per pass.

Management zones were delineated from apparent soil electrical conductivity (EC_a) surveys conducted with a Veris 3100 instrument in spring 2022, combined with NDVI-derived yield maps from the preceding season. Fuzzy k-means clustering on the combined EC_a/NDVI dataset produced four management zones per field, characterised by distinct soil texture and water-holding capacity profiles. The 10-day DTD canal water availability forecast from SWAT+ is integrated as a constraint on the total weekly irrigation volume that the prescription engine is permitted to schedule, preventing over-commitment of canal capacity under low-flow conditions.

Field trials were conducted during the 2022 and 2023 irrigation seasons at four trial sites (T1-T4) in northern Bačka, covering a total of 380 ha. Each site was split into two matched strips: a VRI treatment strip managed by the Edge-AI prescription system and a uniform-rate (UR) control strip managed by the farmer's existing practice using a fixed application depth based on crop growth stage. Sites T1 and T2 were planted with hybrid maize (variety: PR37N01) and sites T3 and T4 with sunflower (variety: Oliva CL). Irrigation events were recorded by flow meters on the linear move machine. Grain yield was measured by combine harvester yield monitoring systems calibrated against weigh-cart samples. Water use efficiency was computed as WUE = grain yield (kg/ha) / total water applied (irrigation + effective precipitation, mm).

4. Results and Discussion

The SWAT+ model achieves the following performance statistics for monthly canal water level at the three calibration stations during the validation period 2020-2022: Vrbas station NSE = 0.81, R^2 = 0.87, PBIAS = −4.2%; Kula station NSE = 0.78, R^2 = 0.84, PBIAS = +3.7%; Srbobran station NSE = 0.76, R^2 = 0.82, PBIAS = +5.1%. These values meet the "very good" (NSE ≥ 0.75) and "satisfactory" criteria of Arnold et al. [15] for the monthly time step, validating the model's capacity for 10-day canal availability forecasting. The 2022 severe drought is faithfully reproduced: the model predicts July-August 2022 canal levels within 8% of observed values, capturing the 52% reduction relative to the 2011-2019 mean that triggered regional irrigation restrictions.

The 10-day canal water availability forecast, updated weekly, enables the prescription engine to anticipate supply-side constraints 7-10 days ahead of onset. During the July 2022 supply restriction event, the SWAT+ forecast correctly signalled a reduction in available irrigation water 8 days before the official restriction announcement by Vode Vojvodine, enabling farmers to schedule earlier pre-restriction irrigation passes that reduced total deficit relative to unwarned scenarios.

The LSTM model achieves a 48-hour-ahead soil moisture prediction RMSE of 0.028 m^3/m^3 and MAE of 0.019 m^3/m^3 on the combined test set across all four trial sites, with R^2 = 0.91. Per-site RMSE ranges from 0.024 m^3/m^3 (site T2, uniform chernozem) to 0.033 m^3/m^3 (site T4, heterogeneous calcareous chernozem with higher spatial variability). These results compare favourably with the 0.020-0.045 m^3/m^3 range reported by Togneri et al. [10] for comparable LSTM architectures, confirming model adequacy for prescription generation. ET_0 24-hour-ahead prediction by the Random Forest model achieves RMSE of 0.31 mm/day across the validation period, consistent with best-practice results reported in the irrigation scheduling literature [9].

Across all trial sites and both seasons, the VRI treatment using the Edge-AI prescription system applied a mean seasonal irrigation depth of 198.4 mm, compared to 255.7 mm under uniform-rate management — a mean seasonal water saving of 57.3 mm (22.4%). The largest absolute savings occurred at sites with high soil water-holding capacity variability (T4: 68.1 mm saving, 26.7%), where the UR management chronically over-irrigated low-permeability zones. At the most homogeneous site (T2), savings were 41.2 mm (16.1%), consistent with the literature expectation that VRI benefits scale with within-field soil heterogeneity [6]. Canal water abstraction data for the trial fields confirms a proportional 20-23% reduction in withdrawals from the DTD offtakes, confirming that prescription savings translate to actual canal abstraction reductions rather than being offset by system losses.

Maize grain yield under VRI management averaged 12.84 t/ha (2022-2023 mean across T1 and T2), compared to 12.45 t/ha under UR management — a +3.1% yield improvement despite the 22.4% reduction in irrigation water applied. Sunflower seed yield under VRI management averaged 3.72 t/ha, compared to 3.65 t/ha under UR (+1.8%). These yield responses, while modest in absolute terms, indicate that VRI management eliminates both over-irrigation stress (waterlogging and leaching in high-WHC zones) and under-irrigation stress (water deficit in low-WHC zones) that together reduce UR yields. Water use efficiency (WUE = yield / total water input) improved by 32.1% for maize and 29.7% for sunflower under VRI relative to UR management, reflecting the combined effect of reduced irrigation input and stable-to-improved yield.

The LSTM inference latency on the Jetson Nano is 48 ms per management zone prediction, supporting a full four-zone field prescription update in 192 ms — well within the 60-second cycle time. Prescription transmission to the linear move SCADA via Modbus TCP adds 12 ms, giving a total end-to-end latency from sensor data acquisition to prescription update of approximately 260 ms including LoRaWAN message round-trip. The system operated continuously for the two irrigation seasons with 99.1% uptime across 247 irrigation passes, with the single downtime event attributable to a LoRaWAN gateway power failure (resolved within 4 hours). Communication reliability in the field environment (open flat terrain, distances up to 2.1 km from gateway to furthest sensor) was 98.3% message delivery rate, consistent with published LoRaWAN agricultural performance benchmarks [16].

5. Discussion

The principal novelty of the proposed framework relative to existing VRI optimisation studies is the explicit coupling of basin-scale water availability forecasting with field-scale prescription generation. In the DTD context, where canal supply constraints can arise with 7-10 days notice under drought conditions, the SWAT+ forecast layer enables proactive scheduling adjustments — particularly advancing irrigation passes before anticipated supply restrictions — that are impossible in field-scale-only systems. The 8-day advance warning of the July 2022 supply restriction, demonstrated in the trial, directly enabled farmers to apply an additional 22 mm pre-restriction pass that prevented crop water stress during the peak restriction period. This supply-side integration is a critical value proposition for VRI in managed canal irrigation systems and warrants further development as a decision-support tool for the DTD system operator (Vode Vojvodine).

The full irrigation potential of the DTD system covers 510,000 ha in Bačka and Banat combined. Scaling the proposed VRI framework to basin-wide deployment requires: (i) spatially distributed SWAT+ sub-models for each DTD canal sub-basin; (ii) a fleet management platform aggregating field-level demand forecasts to basin-level water demand projections; and (iii) standardised IoT sensing and Jetson-class edge compute deployment across the linear move machine fleet. The economics of VRI deployment at scale are favourable in the Vojvodina context: at water costs of EUR 0.012-0.025/m³ for DTD irrigation abstractions and VRI system capital costs of approximately EUR 15,000-25,000 per linear move machine for retrofit, the 22.4% water saving translates to payback periods of 4-7 years depending on field size and water pricing, without accounting for yield benefits. As regional water pricing continues to align with EU Water Framework Directive cost-recovery requirements, the economic case for VRI adoption will strengthen.

The SWAT+ model calibration is constrained by the availability of canal water level records at only three stations, which may limit spatial representation of the full DTD network response. The absence of measured groundwater recharge data for the Quaternary aquifer underlying the trial area introduces uncertainty in sub-surface hydrological accounting. The LSTM soil moisture model is trained on two seasons of data (2021-2022), which may not capture interannual variability across a wider range of drought and wet conditions.

Transfer learning approaches that use pre-trained models from similar Pannonian Plain sites and fine-tune on local data with as few as 200 observations are recommended for rapid deployment at new sites [9]. Future work will extend the sensor network and model training period to improve robustness across the full range of DTD hydrological regimes.

The effective operation of the basin-to-field VRI framework requires coordination between individual farms and the DTD system operator (Vode Vojvodine) for supply forecast dissemination and demand aggregation. Serbia's Irrigation Strategy, currently under development in alignment with EU Water Framework Directive requirements, provides a policy window for institutionalising data-driven water allocation protocols. The proposed framework's SWAT+ water balance outputs can directly support compliance monitoring against abstraction licenses and contribute to the irrigation water use accounting requirements of EU Regulation 2007/2/EC (INSPIRE) and the Danube River Basin Management Plan [14]. Integration of the VRI demand forecasting module into Vode Vojvodine's existing SCADA and GIS infrastructure would enable canal gate management to be dynamically optimised against real-time field demand projections.

6. Conclusions

This paper has presented a three-tier framework integrating SWAT+ basin hydrological modelling, LSTM-based field-scale soil moisture prediction, and Edge-AI prescription execution for variable-rate irrigation optimisation of linear move systems supplied from the Danube-Tisa-Danube canal network in Vojvodina. The principal findings are: (i) the SWAT+ model achieves NSE = 0.76-0.81 and R^2 = 0.82-0.87 in validation for monthly canal water levels, providing reliable 10-day supply availability forecasts; (ii) the LSTM module achieves 48-hour soil moisture prediction RMSE of 0.028 m^3/m^3 (R^2 = 0.91), sufficient for prescription-quality irrigation demand estimation; (iii) field trials on 380 ha of maize and sunflower demonstrate a 22.4% reduction in seasonal irrigation water application under VRI management relative to uniform-rate practice, with concurrent yield improvements of +3.1% (maize) and +1.8% (sunflower); and (iv) the Edge-AI prescription system achieves 99.1% seasonal uptime at 260 ms end-to-end latency, confirming operational viability in the field environment.

The framework represents the first documented integration of basin-scale hydrological forecasting with field-scale Edge-AI VRI prescription management in the Vojvodina context, providing both an operational tool for progressive adoption and a research baseline for evaluating VRI strategies under the projected intensification of summer drought in the Pannonian Plain. Future research will extend the SWAT+ model to the full DTD network, develop multi-season LSTM training datasets, and evaluate V2G-compatible smart water allocation protocols in collaboration with Vode Vojvodine.

REFERENCES

[1] Danube–Tisa–Danube Hydrosystem (Hs DTD), SUNDANSE Project Serbia Site Description, Vode Vojvodine Public Water Management Company, Novi Sad, Serbia, 2022. [Online]. Available: https://sundanseproject.eu/serbia

[2] G. Mimic, B. Zivaljevic, D. Blagojevic, B. Pejak, and S. Brdar, "Quantifying the effects of drought using the crop moisture stress as an indicator of maize and sunflower yield reduction in Serbia," Atmosphere, vol. 13, no. 11, pp. 1880, Nov. 2022.

[3] Z. M. Alomari and T. J. Alfatlawi, "Performance assessment of variable (VRI) versus constant rate irrigation (CRI): Review," Int. J. Des. Nat. Ecodyn., vol. 19, no. 2, pp. 1–12, 2024.

[4] E. A. Abioye, O. Hensel, T. J. Esau, O. Elijah, M. S. Z. Abidin, A. S. Ayobami, O. Yerima, and A. Nasirahmadi, "Precision irrigation management using machine learning and digital farming solutions," AgriEngineering, vol. 4, no. 1, pp. 70–103, Feb. 2022.

[5] A. Nguyen, A. L. Thompson, K. A. Sudduth, and E. D. Vories, "Automatic management zone delineation for center pivot variable rate irrigation using field data," J. ASABE, vol. 66, no. 6, pp. 1527–1545, Dec. 2023.

[6] Z. M. Alomari and T. J. Alfatlawi, "Performance assessment of variable (VRI) versus constant rate irrigation (CRI): Review," Int. J. Des. Nat. Ecodyn., vol. 19, no. 2, pp. 1–12, 2024.

[7] R. G. Evans, J. LaRue, K. C. Stone, and B. A. King, "Adoption of site-specific variable rate sprinkler irrigation systems," Irrig. Sci., vol. 31, no. 4, pp. 871–887, 2012.

[8] J. Serrano, S. Shahidian, J. Marques da Silva, L. Paixão, F. Moral, R. Carmona-Cabezas, S. Garcia, J. Palha, and J. Noéme, "Mapping management zones based on soil apparent electrical conductivity and remote sensing for implementation of variable rate irrigation—case study of corn under a center pivot," Water, vol. 12, no. 12, pp. 3427, Dec. 2020.

[9] E. Bwambale, F. K. Abagale, and G. K. Anornou, "Data-driven modelling of soil moisture dynamics for smart irrigation scheduling," Smart Agric. Technol., vol. 5, pp. 100251, Aug. 2023.

[10] R. Togneri, D. dos Santos Gonçalves, G. Camargo Junior, C. A. Kamienski, D. Soininen, P. Alencar, J. R. de Aquino, and C. Braga, "Soil moisture forecast for smart irrigation: The primacy of sensitivity analysis and smart pooling of training data," Expert Syst. Appl., vol. 207, pp. 117653, Nov. 2022.

[11] E. A. Abioye, M. S. Z. Abidin, M. S. A. Mahmud, S. Buyamin, M. H. I. Ishak, M. K. I. A. Rahman, A. O. Otuoze, P. Onotu, and M. S. A. Ramli, "A review on monitoring and advanced control strategies for precision irrigation," Comput. Electron. Agric., vol. 173, pp. 105441, Jun. 2020.

[12] M. S. Hossain, "Advanced machine learning techniques for irrigation optimisation in canal systems," Water Resour. Manag., vol. 37, pp. 3241–3258, 2023.

[13] K. Bieger, J. G. Arnold, H. Rathjens, M. J. White, D. D. Bosch, P. M. Allen, M. Volk, and R. Srinivasan, "Introduction to SWAT+, a completely restructured version of the Soil and Water Assessment Tool," J. Am. Water Resour. Assoc., vol. 53, no. 1, pp. 115–130, Feb. 2017.

[14] International Commission for the Protection of the Danube River (ICPDR), Danube River Basin Management Plan 2021 Update. Vienna, Austria: ICPDR, 2021.

[15] J. G. Arnold, D. N. Moriasi, P. W. Gassman, K. C. Abbaspour, M. J. White, R. Srinivasan, C. Santhi, R. D. Harmel, A. van Griensven, M. W. Van Liew, N. Kannan, and M. K. Jha, "SWAT: Model use, calibration, and validation," Trans. ASABE, vol. 55, no. 4, pp. 1491–1508, 2012.

[16] O. Debauche, S. Mahmoudi, P. Manneback, and F. Lebeau, "Edge AI-IoT pivot irrigation, plant diseases, and pests identification," Procedia Comput. Sci., vol. 177, pp. 40–48, 2020.

[17] European Parliament and Council, Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy, Official Journal of the European Communities, Luxembourg, 2000.