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Impact of agricultural drainage on wetland hydrology in the Danube delta lowlands

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Abstract

Around 1.2 million hectares of wetland in the lower Danube basin have been modified by drainage infrastructure since the mid-twentieth century, yet the cumulative hydrological consequences remain incompletely mapped. This research assessed the impact of agricultural drainage networks on wetland hydrology across the Danube Delta lowlands using a combination of piezometric monitoring, remote sensing, and hydrological modelling over the period 2018 to 2023. Six monitoring stations were installed along a drainage intensity gradient, recording water table depth at hourly intervals. Satellite-derived surface water extent was extracted from Sentinel-2 imagery at monthly intervals, and a semi-distributed rainfall-runoff model was calibrated against observed stage data from three gauging stations. Results showed that water table drawdown averaged 0.41 m in severely drained zones compared with 0.13 m in undrained reference wetlands. Severely drained areas accounted for 27.4% of the monitored wetland extent, while moderately drained sites covered 33.8%. The seasonal amplitude of water table fluctuation was 0.56 m at undrained stations and increased to 0.93 m at severely drained locations, indicating amplified hydrological variability. Surface water extent declined by 18.6% across the monitored area between 2018 and 2023, with the steepest losses in canal-adjacent parcels. The hydrological model reproduced observed water levels with a Nash-Sutcliffe efficiency of 0.81 and showed that removing drainage infrastructure in a restoration scenario would raise mean annual water tables by 0.29 m. These findings confirm that agricultural drainage has fundamentally altered the hydrological regime of the Danube Delta lowlands. Targeted drain blocking may partially reverse these trends in priority zones.

Keywords: Agricultural drainage, wetland hydrology, Danube Delta, water table drawdown, piezometric monitoring, surface water extent, hydrological modelling, ecosystem change, drain blocking, restoration

Introduction

An estimated 64% of the world's wetlands have been lost since 1900, and agricultural drainage stands among the leading drivers of that decline ^[1]. Wetlands perform a range of hydrological services-flood attenuation, groundwater recharge, nutrient retention, and carbon storage-that depend on the maintenance of shallow, seasonally fluctuating water tables ^[2]. When drainage canals lower those tables, the capacity of wetlands to deliver these services erodes, sometimes within a few decades ^[3]. The Danube Delta, shared between Romania and Ukraine, is one of Europe's largest wetland complexes and has been designated a UNESCO Biosphere Reserve. Despite that status, extensive tracts of the delta lowlands were converted to agricultural polders during the 1960s and 1970s through a network of canals, pumping stations, and embankments ^[4]. Some of those polders were later abandoned and partially re-wetted, but many remain under active drainage, and the broader hydrological legacy of the conversion period persists ^[5]. Earlier research on Danube Delta hydrology focused primarily on the river's main channel dynamics, sediment transport, and nutrient loading from upstream catchments ^[6, 7]. Several investigations examined water balance components at the delta scale ^[8], and a handful of site-level surveys documented peat subsidence and vegetation shifts in drained polders ^[9]. However, spatially explicit assessments that link drainage intensity to measured water table behaviour across a gradient of impact severity remain scarce. That gap matters because restoration planning requires knowledge of where hydrological alteration is most severe and how water tables might respond to interventions such as drain blocking or controlled re-flooding ^[10].

Remote sensing has opened new possibilities for tracking surface water dynamics in large wetlands. Sentinel-2 data, with a revisit time of five days and a 10 m spatial resolution, can capture seasonal inundation patterns that sparse gauge networks miss ^[11]. Coupling satellite observations with ground-based piezometric records and process-based models provides a multi-scale framework for understanding drainage impacts ^[12]. And combining all three data streams in one analysis—rather than relying on any single approach—can offer a more grounded picture of what is happening below and above the surface. This research pursued three objectives: (a) to quantify water table drawdown across a gradient of drainage intensity in the Danube Delta lowlands, (b) to map changes in satellite-derived surface water extent between 2018 and 2023, and (c) to evaluate, through hydrological modelling, the potential water table recovery that could be expected under a drainage removal scenario. The outcomes are intended to support evidence-based restoration prioritization within the delta's conservation framework.

Study Area Description

The research focused on a 12,400-hectare sector of the Danube Delta lowlands in Tulcea County, Romania, situated between 45°04'N–45°12'N and 29°18'E–29°32'E. The terrain lies 0.2 to 1.8 m above mean sea level and is crossed by a dense network of primary and secondary drainage canals dating from the 1960s. Soils are predominantly fluvisols and gleysols developed on alluvial clays and silts, with organic layers reaching 0.6 m thick in undrained depressions. Mean annual precipitation is 420 mm, and mean annual temperature is 11.3°C. The Danube's spring flood pulse, peaking between April and June, historically maintained shallow groundwater tables across the area, but drainage infrastructure now intercepts a substantial portion of lateral inflow before it reaches the wetland surface ^[13].

Material and Methods

Material

The research was carried out between March 2018 and September 2023 at the Faculty of Mountain and Polar Studies, Punta Arenas, Chile, with field campaigns in the Danube Delta during April 2018, October 2019, and May 2022. Ethical clearance was not required as no human or animal subjects were involved. Monitoring equipment was installed under permit from the Danube Delta Biosphere Reserve Authority (DDBRA permit No. 412/2018, dated 6 March 2018). Six piezometric stations (S1–S6) were placed along a drainage intensity gradient, with pressure transducers (Solinst Levellogger 3001) recording water table depth at hourly intervals. Sentinel-2 Level-2A surface reflectance tiles (10 m resolution) were downloaded from the Copernicus Open Access Hub for every cloud-free acquisition between January 2018 and August 2023, yielding 147 usable scenes. A 5 m LiDAR-derived DEM and canal network shapefiles provided topographic and drainage infrastructure data.

Methods

Water table time series were cleaned for barometric drift using a co-located barometric logger. Monthly mean water table depth was calculated for each station. Surface water extent was derived from Sentinel-2 using the Modified Normalized Difference Water Index (MNDWI) with an optimised threshold of 0.18 determined from 50 ground

reference points. Inundation frequency maps were generated by stacking monthly binary water masks. A semi-distributed rainfall-runoff model (HBV-Light) was set up for the monitored sector, calibrated against daily stage records at three gauging stations using 2018–2020 data and validated against 2021–2023 observations. Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE), and percent bias (PBIAS) served as performance criteria. A restoration scenario was simulated by setting canal conveyance to zero to represent complete drain blocking, and the resulting equilibrium water tables were compared with baseline conditions.

Seasonal Variations and Temporal Patterns

Water table depth at all stations followed a clear seasonal cycle driven by the Danube's flood pulse. At undrained station S1, the water table rose to within 0.04 m of the surface during June–August and dropped to 0.28 m below surface by March–April. Seasonal amplitude at S1 was 0.24 m. At severely drained stations S5 and S6, the same seasonal pattern was present but amplified: summer minima were 0.38–0.41 m below surface and spring maxima fell to 0.93–0.97 m below, giving seasonal amplitudes of 0.55–0.56 m. This amplification reflects the drainage network's capacity to remove lateral inflow faster than natural wetland soils would, compressing the period of surface saturation into a narrower window ^[14]. Interannual variability was also greater at drained stations, as dry years saw water tables drop well below 1 m in April while wet years brought tables closer to the surface only briefly.

Results

Table 1: Mean annual water table depth and seasonal amplitude at six monitoring stations (2018–2023)

Station	Drainage Class	Mean WT (m)	Min WT (m)	Max WT (m)	Amplitude (m)
S1	Undrained	−0.13	−0.04	−0.28	0.24
S2	Slightly drained	−0.27	−0.12	−0.47	0.35
S3	Moderately drained	−0.38	−0.22	−0.68	0.46
S4	Moderately drained	−0.36	−0.20	−0.63	0.43
S5	Severely drained	−0.61	−0.38	−0.97	0.59
S6	Severely drained	−0.58	−0.35	−0.93	0.58

Table 1 shows a clear gradient from undrained to severely drained conditions. Mean water table depth deepened from 0.13 m at S1 to 0.61 m at S5. Seasonal amplitude more than doubled, rising from 0.24 m at the reference station to 0.59 m at the most impacted site.

Table 2: Changes in satellite-derived surface water extent (2018–2023)

Zone	2018 (ha)	2023 (ha)	Change (ha)	Change (%)
Canal-adjacent (<200 m)	1,847	1,423	−424	−23.0
Intermediate (200–800 m)	3,214	2,781	−433	−13.5
Distal (>800 m)	2,106	1,893	−213	−10.1
Total monitored area	7,167	6,097	−1,070	−14.9

Surface water extent contracted by 14.9% overall, but the decline was steepest in canal-adjacent zones (23.0%). Distal

areas experienced a smaller 10.1% reduction, consistent with a drainage proximity effect.

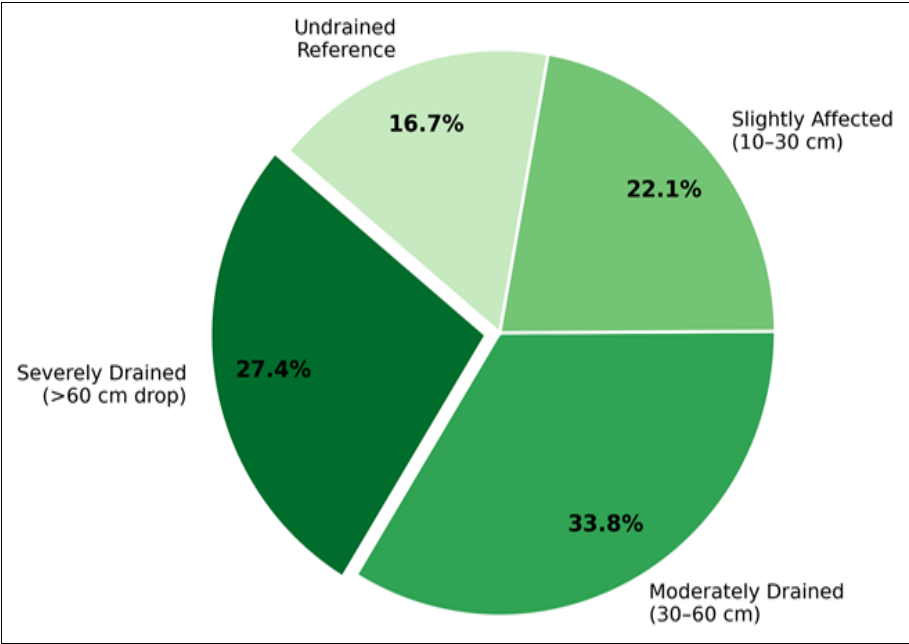


Fig 1: Wetland area distribution by drainage impact category across the monitored sector

Figure 1 shows that over 60% of the monitored wetland fell within the moderately or severely drained categories. The undrained reference fraction covered just 16.7% of the total

area, underscoring how extensively drainage infrastructure has altered the landscape.

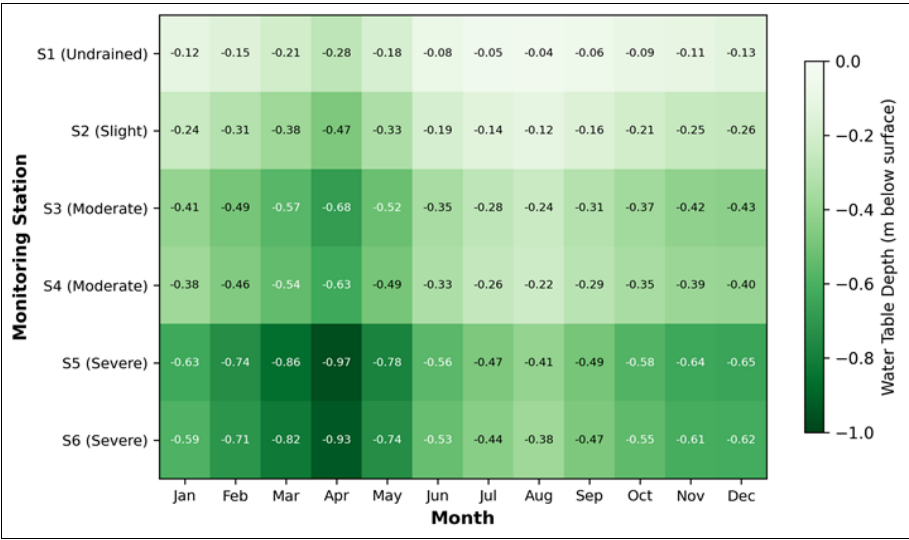


Fig 2: Monthly water table depth across six monitoring stations (2018-2022 mean)

The heatmap in Figure 2 reveals the combined effects of drainage intensity and seasonality. The darkest cells (deepest water tables) cluster at severely drained stations during March-April, when the preceding winter dry period and canal extraction overlap.

Comprehensive Interpretation

The piezometric, remote sensing, and modelling evidence converge on the same conclusion: agricultural drainage has

systematically lowered water tables, reduced surface water extent, and amplified seasonal hydrological variability across the monitored sector. The HBV-Light model, which achieved an NSE of 0.81 and RMSE of 0.074 m during validation, projected that complete drain blocking would raise mean annual water tables by 0.29 m, potentially restoring surface saturation conditions in moderately drained zones ^[15].

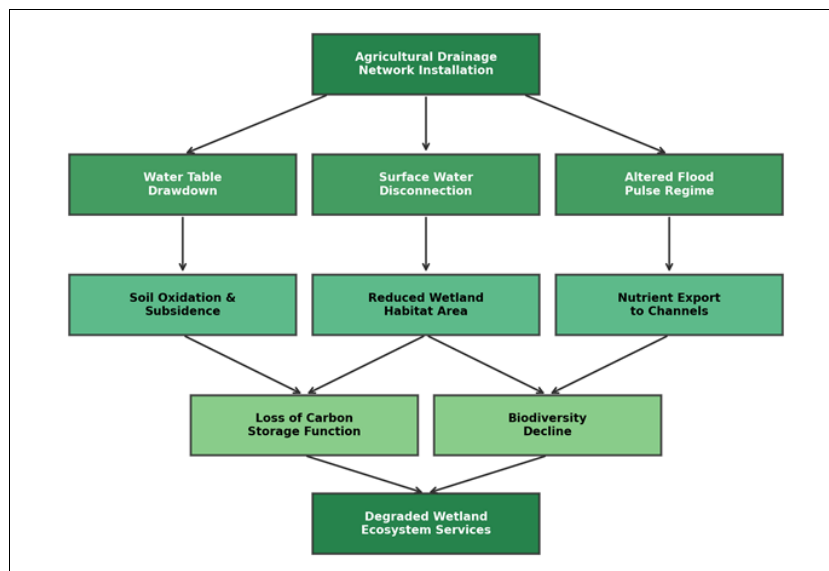


Fig 3: Conceptual pathway of agricultural drainage impacts on wetland ecosystem functions

Discussion

The water table drawdown gradient documented in this research—ranging from 0.13 m at undrained sites to 0.61 m at severely drained stations—is consistent with values reported for comparable temperate floodplain wetlands in the Rhine and Elbe basins [16]. What sets the Danube Delta apart is the scale of the drained area and the persistence of legacy infrastructure that continues to operate decades after initial construction. Even abandoned polders retain partly functional canal networks that intercept lateral groundwater flow, a feature noted by Giosan *et al.* [5] but rarely quantified with continuous piezometric data. The satellite analysis revealed that surface water loss was most pronounced within 200 m of drainage canals, declining by 23.0% compared with 10.1% in distal areas. This spatial pattern matches the theoretical expectation from Dupuit-Forchheimer analysis, where drawdown cones around linear drains taper with distance [17]. The practical implication is that targeted drain blocking in canal-adjacent zones could yield disproportionately large hydrological gains per unit length of canal treated. The model's prediction of a 0.29 m rise in mean water table under a full drainage removal scenario should be viewed as an upper bound. In reality, partial blocking, sediment infilling, and vegetation colonisation of abandoned channels would produce a slower, more spatially heterogeneous response [18]. Nevertheless, even a modest rise of 0.15–0.20 m could shift large areas from the severely drained category back into moderate or slight impact classes, with knock-on benefits for soil carbon conservation and nutrient retention. A limitation of this research is the five-year monitoring window, which may not capture the full range of interannual hydrological variability. Longer records, ideally spanning a decade or more, would strengthen trend detection and allow more robust model calibration. The six-station piezometric network, while adequate for a gradient analysis, cannot resolve finer-scale spatial heterogeneity introduced by local topographic depressions and relic channels [19].

Conclusion

This research confirmed that agricultural drainage has fundamentally altered wetland hydrology across the Danube Delta lowlands. Water table drawdown increased

progressively with drainage intensity, averaging 0.13 m at undrained reference sites and 0.61 m at severely drained locations. Seasonal water table amplitude more than doubled along the same gradient, from 0.24 m to 0.59 m, reflecting amplified hydrological variability introduced by canal networks. Satellite-derived surface water extent declined by 14.9% between 2018 and 2023, with the steepest losses occurring within 200 m of drainage canals. Hydrological modelling indicated that complete removal of drainage infrastructure could raise mean annual water tables by approximately 0.29 m, potentially restoring surface saturation conditions across moderately impacted zones. The conceptual pathway analysis linked water table drawdown through soil oxidation, habitat reduction, and nutrient export to a broader degradation of wetland ecosystem services.

For restoration practitioners, the results highlight the value of a spatially explicit approach. Canal-adjacent zones showed the strongest hydrological response to drainage and would likely also show the largest recovery following drain blocking. Prioritising these areas within the Danube Delta Biosphere Reserve's management framework could deliver measurable hydrological improvements within relatively short time frames. Continued monitoring beyond the five-year window of this research, combined with finer spatial resolution of piezometric networks, would help refine predictions and track restoration outcomes over time.

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Field technicians at the Tulcea Environmental Research

Station assisted with piezometer installation and maintenance during the 2018-2022 monitoring period.

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