

FORMATION AND EVOLUTION OF SOILS IN THE LOW PLAINS OF WESTERN ROMANIA

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Abstract

The paper examines the evolution and pedological importance of soils in the low plains of western Romania, focusing on the Mureș-Galațca Plain and the Bega-Timiș-Bârzava Canal. The main objective is to investigate the natural factors influencing the formation, evolution, and characteristics of these soils, such as morphological and hydrographic variability, lithological aspects, and tectonic activities, including subsidence. A detailed analysis of geological processes, such as sediment deposition, will enhance understanding of their impact on soil fertility. The paper will also highlight the effects of human activity on land resources and the challenges faced, such as salinization and soil compaction. These issues are often worsened by groundwater conditions that can adversely affect agricultural productivity. Proposed strategies for managing soil resources include emphasizing conservation measures and adopting sustainable agricultural practices to improve soil health. By addressing these aspects, the paper underscores the vital connection between pedological characteristics and local agricultural development, emphasizing the need for effective land resource management to ensure long-term agricultural sustainability in these regions. A strategic reevaluation of agricultural policies is essential in light of current ecological challenges.

Key words: *pedology, low plain, soil evolution, resource management, sustainable agriculture.*

INTRODUCTION

The low plains of western Romania, particularly those in Banat, constitute a geographically complex region in which the interplay among subsidence, hydrographic networks, lithology, and anthropogenic interventions has produced a mosaic of pedo-hydrological conditions with direct implications for agricultural productivity. Along a North-South gradient in morpho-hydrographic and lithological settings, the area can be subdivided into units such as the Aranca, Galațca, Jimbolia, Cenei, Timiș, and Banloc plains, which are further grouped into three major sectors: the Mureș-Galațca Plain, the Bega Canal-Galațca Plain, and the Bega Canal-Timiș-Bârzava Plain. Although the Mureș River forms the northern boundary of the study area, the region functions predominantly within the south-western hydrographic systems (Timiș-Bega and Bârzava), characterized by a dense network of drainage canals and regulated channels (Ujvári, 1972; Blaga et al., 2008).

The origin and evolution of the plain are closely linked to the Pannonian Basin, where the

crystalline basement (Tisia) was fragmented into blocks that experienced differentiated vertical movements. The penetration of the Tethys Sea waters along corridors between these blocks promoted substantial sediment accumulation, while neotectonic activity (initiated in the Pontian and continuing through the Pliocene, with limited but detectable present-day expression) supported the development of subsidence areas that exert strong control on drainage and morphology. Lithologically, the plains are composed of heterogeneous fluvio-lacustrine successions (silts, clays, marly clays, and sands), locally interbedded with loess-like materials; the parent material may include swelling clays and soluble salts (especially sodic salts), conditions conducive to the development of halomorphic soils.

The present-day hydrographic structure is strongly anthropogenically modified. Channelization of the Bega River and the embankment/drainage works initiated after 1717 aimed to reclaim marshy areas and improve land use, leading to a reorganization of

runoff pathways and modifications in groundwater levels (Neacşa et al., 1979; Blaga et al., 2008). Nevertheless, in depressional areas the evacuation of pluvial waters often remains incomplete, and surface water stagnation is frequent during wet seasons. Shallow groundwater depths vary with microrelief (shallower in depressions and deeper on natural levees/ridges), the waters are commonly highly mineralized (chlorides, sulphates, bicarbonates), and overall drainage remains imperfect. These conditions sustain a problematic seasonal alternation: excess soil moisture during the cold season and water deficit during the warm season (Dumitru et al., 2000; Niţă et al., 2018).

Under these constraints, a highly diverse soil cover has developed. According to the Romanian System of Soil Taxonomy (SRTS 2012), the analysed area includes multiple soil classes and types (e.g., Protisols, Cernisols, Vertisols, Hydrisols, Salsodisols, and Anthrosols), as well as soil complexes with a fine-scale mosaic distribution that is difficult to delineate precisely. The principal limitations to agricultural productivity are associated with stagnant and groundwater-induced excess moisture, salinization/sodification, acidification, compaction, and, seasonally, soil water deficit (Florea et al., 2012; David et al., 2018; Niţă et al., 2024). Therefore, the design of agricultural technologies and pedo-hydro-ameliorative measures (e.g., drainage and dewatering systems, deep loosening, traffic/compaction prevention, amendments and corrective fertilization, and rotations including ameliorative crops) should be grounded in a detailed understanding of local conditions and ecological suitability, with the overarching goal of enhancing resilience and ensuring the sustainable use of agricultural land in the low plains (Florea et al., 2012; Țărau et al., 2019).

MATERIALS AND METHODS

The present study addresses the lowland plains of western Romania (the Banat sector of the Pannonian Plain), a region characterized by a very weakly dissected relief, low elevations, gentle slopes, and a hydrographic network strongly conditioned by lithological controls and long-term anthropogenic interventions (embankments, drainage works, and canals).

Along the north–south gradient in morpho-hydrographic and lithological conditions, we analysed the following subunits: the Aranca Plain, Galaţca Plain, Jimbolia Plain, Cenei Plain, Timiş Plain, and Banloc Plain. These were further grouped into functional sectors linked to the major hydrographic systems (e.g., the Mureş system and the Timiş-Bega river/canal system). To provide an integrated characterization of the physical-geographical setting and hydrological functioning, we used the following data categories. A digital elevation model with a spatial resolution suitable for low-relief plains ($\geq 10\text{--}30\text{ m}$) was employed to derive slope, curvature, drainage networks, and microdepressions; topographic maps and base plans were used for verification and cartographic control. Geological, lithological, and pedological information was compiled from thematic maps (Cheval et al., 2014; Ioniţă et al., 2016). Geological/lithological maps supported the delineation of deposits (e.g., loess-like, alluvial, clay-rich units) and the interpretation of lithological controls on drainage. Soil maps (texture, permeability, hydromorphy) were used to assess susceptibility to excess moisture conditions. Where available, daily and/or monthly discharge and water-level time series were obtained from the hydrometric station network associated with the relevant basins (Mureş, Aranca, and the Timiş-Bega/canal system). Information on hydraulic engineering works (canals, river training/regularization, embankments) was incorporated to interpret departures from natural flow regimes (Kopecký et al., 2021). Climatic and agrometeorological datasets included daily/monthly precipitation and air temperature from representative lowland meteorological stations, together with the variables required to estimate reference evapotranspiration (ETP) and water balance components (radiation, wind, humidity), depending on data availability) (Dumitrescu et al., 2015; Bîrsan et al., 2019). Multispectral satellite imagery (e.g., Sentinel, Landsat) was additionally used to identify temporary wet areas, detect land-use/land-cover changes, and assess vegetation condition (Kopecký et al., 2021).

Subunits (Aranca, Galaţca, Jimbolia, Cenei, Timiş, Banloc) were delineated by overlaying morphometric criteria with hydrographic

boundaries and lithological/pedological transitions, resulting in spatially coherent units suitable for comparative analysis. For each subunit, we calculated standardized metrics relevant to lowland plains, including: (i) mean, minimum and maximum elevation, and hypsometric range; (ii) mean slope and slope-class distribution; (iii) drainage density (total channel length per unit area) and stream frequency; (iv) the proportion of areas with high potential for excess moisture derived from hydromorphic soil classes; and (v) characterization of the precipitation and thermal regimes using long-term means, seasonality, and interannual variability (Mihuț et al., 2018; Niță et al., 2018).

For the preparation of this study, we strictly complied with the methodological standards for the development of pedological and agrochemical surveys (ICPA, 1987, Volumes I-III).

RESULTS AND DISCUSSIONS

1) Spatial organization of the lowland plains and the genetic-structural framework

The analysis confirms that the north-south variability in morpho-hydrographic and lithological conditions, superimposed on neotectonic controls (differential subsidence of crystalline blocks and sediment-accumulation corridors), produces a hydrologically heterogeneous landscape despite the overall weakly dissected relief. The investigated subunits (Aranca, Galațca, Jimbolia, Cenei, Timiș, and Banloc) can be operationally grouped into three sectors—the Mureș-Galațca Plain, the Bega Canal-Galațca Plain, and the Bega Canal-Timiș-Bârzava Plain—each displaying distinct drainage characteristics, groundwater-table (pedofreatic) depth patterns, and soil assemblages (Țărău et al., 2019; Niță et al., 2024).

At the process scale, the combined influence of (i) fine-grained fluvio-lacustrine deposits (silts, clays, marly clays), (ii) depressional microrelief and interrridge/interfluvial low-lying surfaces, (iii) a shallow phreatic aquifer, and (iv) long-standing hydro-ameliorative interventions (channelization, embankment construction, and drainage works) explains the emergence of a dual stress regime in agroecosystems. This

regime is characterized by excess soil moisture during the cold and transitional seasons versus soil water deficit during the warm season, with direct consequences for soil fertility, field trafficability/accessibility, and overall agricultural productivity.

2) Soil types: differences among the three sectors (Tables 1-3)

Across the 42 analysed administrative-territorial units, we identified 11 soil types and soil associations that can be assigned to eight soil classes according to the Romanian System of Soil Taxonomy (SRTS, 2012), with marked sectoral contrasts in their spatial distribution, Tables 1-3.

(a) *The Mureș-Galațca Plain sector* (103,531 ha of agricultural land) is dominated by:

- Chernozems (CZ): 46.07%;
- Vertisols (VS): 19.51%;
- soil associations/complexes: 16.15%;
- followed by Fluvisols (AS): 10.24%.

This soil pattern indicates a substantial agricultural resource base, primarily supported by the widespread occurrence of Chernozems. However, the relatively high share of heavy-textured and/or mosaic soils (notably Vertisols and soil complexes) suggests an increased susceptibility to unfavourable aeration–water regime conditions and to physical degradation processes.

(b) *The Bega Canal-Galațca Plain sector* (75,766 ha of agricultural land) exhibits the highest degree of pedological “concentration”, being characterized by:

- Chernozems (CZ): 62.19%;
- Vertisols (VS): 11.99%;
- soil associations: 9.69%;
- Eutric Cambisols (EC): 5.30%.

The clear predominance of Chernozems accounts for the generally high agricultural potential of this sector. Nevertheless, the presence of Vertisols and soil associations indicates the occurrence of micro-areas with fine-textured materials and/or hydromorphic features, as well as abrupt soil transitions over short distances, reflecting a pronounced pedological mosaic. Such small-scale heterogeneity is particularly relevant in lowland settings, where local variations in microrelief and drainage efficiency can strongly influence soil moisture regimes, trafficability, and the spatial stability of crop performance.

(c) *The Bega Canal-Timiș-Bârzava Plain sector* (118,448 ha of agricultural land) is the most heterogeneous, with the following dominant soil groups:

- Eutric Cambisols (EC): 25.08%;
- Chernozems (CZ): 22.78%;
- Vertisols (VS): 12.96%;
- Phaeozems (FZ): 9.32%, and soil associations: 9.04%, as well as notable shares of Gleysols (GS): 5.77% and Solonetz (SN): 5.14%.

This composition is consistent with a sector in which neotectonic control (subsidence), fine-grained parent materials, and the interaction between canal systems and the shallow groundwater table promote a wide range of pedogenetic processes. These include hydromorphism, sodification, and alternating redox conditions, which can lead to strong spatial contrasts in soil physical and chemical

properties and, consequently, in land-use suitability and yield stability at local scales.

Discussions. The high frequency of soil complexes (associations) and fine-textured soils (e.g., Vertisols/pelosols) supports the interpretation that microtopography and near-surface hydrology-together with engineered drainage-are key controls of pedological organization. In subsiding lowland plains, pedological boundaries are often expressed at spatial scales smaller than those captured by conventional mapping, resulting in sharp transitions over short distances. Consequently, effective agricultural management should be implemented at the level of micro-areas (field and sub-field scale), rather than relying solely on administrative units, in order to adequately address local variability in moisture regimes, trafficability, and soil constraints.

Table 1. Main soil types and soil associations in the Mureș-Galațca interfluvial plain*

No.	Administrative-territorial unit	Agricultural, ha	1. PS	2. AS	3. CZ	4. EC	5. VS	6. GS	7. SN	8. AT-TT	9. Asoc.
1	Beba Veche	8817	0	528	3880	0	3263	160	104	0	882
2	Cenad	7383	0	2732	517	0	3175	15	59	0	885
3	Comloșu Mare	8724	646	61	6273	0	1291	436	17	0	0
4	Dudeștii Vechi	13113	0	2402	2096	199	4411	133	40	13	3819
5	Gottlob	4114	66	0	3896	30	0	43	0	19	60
6	Lovrin	3807	27	0	3124	190	120	170	56	20	100
7	Periam	5886	47	265	3905	805	12	132	39	0	681
8	Pesac	3147	94	87	2055	338	6	188	20	0	359
9	Saravale	9620	0	1176	3859	0	2299	48	358	0	1880
10	Sânpetru Mare	9176	0	1155	3678	0	2099	46	338	0	1860
11	Sănnicolau Mare	12689	0	1015	5329	2030	1016	634	127	0	2538
12	Teremia M.	7748	85	138	4804	101	504	39	77	7	1993
13	Tomnatic	3547	48	0	3367	60	32	30	3	7	0
14	Valcani	5760	0	1044	912	87	1975	58	17	6	1661
	Mureș-Galațca	103531	1013	10603	47695	3840	20203	2132	1255	72	16718
	%	100	0.98	10.24	46.07	3.71	19.51	2.06	1.21	0.07	16.15

*Office for Pedological and Agrochemical Studies from Timiș/Arad; Țărău et al., 2019.

Table 2. Main soil types and soil associations in the Bega Canal-Galațca interfluvial plain*

No.	Administrative-territorial unit	Agricultural, ha	AS	CZ	FZ	EC	EL	VS	PE	GS	SN	AT-TT	Asoc.
1	Becicherecu Mic	4217	70	2846	0	640	104	96	64	25	130	18	224
2	Biled	4946	0	4543	0	0	0	10	0	194	49	0	150
3	Cărpiniș	4115	0	4029	0	0	0	51	0	35	0	0	0
4	Cenei	6364	46	2725	0	0	0	3106	0	51	53	70	313
5	Checca	5332	38	2276	0	0	0	2598	0	42	53	64	261
6	Dudeștii Noi	4776	0	3310	296	250	94	113	145	37	125	35	371
7	Ieccea Mare	3273	0	2927	0	0	0	300	0	46	0	0	0
8	Jimbolia	9725	0	6529	0	0	0	58	0	545	29	20	2544
9	Lenauheim	10521	0	8681	0	0	0	210	0	399	0	84	1147
10	Săcălaz	10622	985	3719	617	2951	0	478	1320	249	303	0	0
11	Sânmihailu Român	6841	1446	774	0	177	0	2023	0	132	65	0	2224
12	Șandra	5034		4761	0	0	0	39	0	120	6	0	108
	Bega-Galațca Canal	75766	2585	47120	913	4018	198	9082	1529	1875	813	291	7342
	%	100	3.41	62.19	1.21	5.30	0.26	11.99	2.02	2.47	1.07	0.38	9.69

*Office for Pedological and Agrochemical Studies from Timiș/Arad; Țărău et al., 2019.

Table 3. Main soil types and soil associations in the Bega Canal-Timiș-Bârzava interfluvial plain*

No.	Administrative-territorial unit	Agricultural, ha	AS	CZ	FZ	EC	VS	PE	GS	SN	AT-TT	Asoc.
1	Banloc	10252	437	720	0	2979	2850	358	274	28	0	2606
2	Ciacova	12506	328	2701	129	3512	1914	1932	1380	610	0	0
3	Foeni	5816	64	3390	0	29	20	0	744	378	58	1133
4	Ghilad	10486	762	3035	132	1211	1511	173	1912	954	0	796
5	Giera	8556	0	668	201	3025	2521	421	75	187	0	1458
6	Giroc	3903	458	0	0	2378	53	0	493	0	0	521
7	Giulvăz	8908	0	3285	1719	1052	282	358	0	1514	0	698
8	Jebel	6225	320	626	2275	2198	214	0	280	312	0	0
9	Livezile	5231	27	1133	821	2070	334	154	175	517	0	0
10	Otelec	7746	396	2432	664	1038	1792	603	299	115	3	404
11	Parța	5560	1024	407	638	2973	14	112	0	8	8	376
12	Pădureni	3740	189	368	1338	1357	126	0	179	183	0	0
13	Peciu Nou	12188	115	3983	1938	1885	864	1203	73	1103	11	1013
14	Șag	2751	513	203	319	1461	7	55	0	2	4	187
15	Timișoara	4341	343	864	0	1190	703	0	561	50	0	630
16	Uivar	10239	516	3162	864	1350	2147	785	389	131	5	890
	Bega-Timiș-Bârzava Canal	118448	5492	26977	11038	29708	15352	6154	6834	6092	89	10712
	%	100	4.64	22.78	9.32	25.08	12.96	5.20	5.77	5.14	0.08	9.04

*Office for Pedological and Agrochemical Studies from Timiș/Arad; Țărău et al., 2019.

3) Excess soil moisture: predominance of the groundwater component and sectoral differentiation

(a) Mureș-Galațca Plain

The data indicate that excess soil moisture has two main components: surface waterlogging (ponding following precipitation) and groundwater-induced excess moisture (a shallow groundwater table). Because these components may overlap spatially, percentages are interpreted separately (i.e., they should not be summed).

Area affected by surface waterlogging: 32.72% (slight 20.49% + moderate 7.13% + strong/very strong 5.10%).

Area affected by groundwater-induced excess moisture: 41.06% (moderate 19.13% + strong 15.46% + very strong/extreme 6.47%).

Hotspots (absolute values, from the table) include Sănnicolau Mare (very high surface waterlogging), Beba Veche and Valcani (strong to very strong groundwater influence), and Cenad (strong groundwater influence).

(b) Bega Canal-Galațca Plain

Surface waterlogging: 47.12% (the highest among the three sectors).

Groundwater-induced excess moisture: 36.02%. This pattern suggests that, although shallow groundwater remains an important driver, post-precipitation ponding is more dominant in this sector, likely due to the combined effects of microdepressions, fine-textured materials, and incomplete drainage during wet seasons.

Localities with high values include Cenei, Checea, Jimbolia, and Săcălaz.

(c) Bega Canal-Timiș-Bârzava Plain

Surface waterlogging: 36.06%.

Groundwater-induced excess moisture: 61.52% (the highest among the three sectors).

Here, the major role of the shallow groundwater table is evident (commonly 0.5-1.0 m in depressional areas), together with the influence of supply-drainage canal systems and regional subsidence, which collectively produce slow external drainage and imperfect internal drainage.

Discussions. The mechanism described in the source material-fine-grained deposits combined with a shallow aquifer and internal drainage constraints imposed by clay layers and soluble salts-provides a robust explanation for why groundwater-driven excess moisture remains the dominant control even after large-scale hydro-ameliorative works. In the broader literature, the interaction between shallow groundwater, insufficient drainage, and salt accumulation is widely recognized as a key pathway leading to saline/sodic soil development and associated forms of land degradation.

4) Salinization and soil acidification: a strong regional signal of salinity/sodicity

Salinization shows a very large spatial extent across all three sectors:

- Mureș-Galațca: 68.09% of agricultural land affected (from slight to extreme);
- Bega Canal-Galațca: 56.04%;

- Bega Canal-Timiș-Bârzava: 55.75%.

Importantly, the pattern is not limited to slight-moderate forms; a substantial share of strong and extreme salinization is also present (e.g., in Mureș-Galați: 5.23% strong and 15.36% extreme). This finding is consistent with the described parent materials (carbonate-rich silts, swelling clays, and soluble-particularly sodic-salts), the high mineralization of shallow groundwater (chlorides, sulphates, bicarbonates), and the occurrence of alkaline/alkaline-sodic areas near the listed localities (e.g., Cenad, Sânnicolau Mare, Cenei, Săcălaz, Timișoara, Uivar, Banloc, Moravița). By contrast, *soil acidification* is comparatively limited:

- Mureș-Galați: 1.88% (slight);

- Bega Canal-Galați: 1.10% (slight);

- Bega Canal-Timiș-Bârzava: 3.42% (slight) plus only localized traces (0.01%).

Overall, the dominant chemical constraint on these agroecosystems is therefore salinity/sodicity, rather than acidification.

Discussions. Globally, salt-affected soils (saline, sodic, and saline-sodic) are widely recognized as a major land-degradation issue. In 2021, FAO released a global map of salt-affected soils, highlighting the scale and relevance of the problem. In lowland plains in particular, groundwater-driven salinization and salinity development under insufficient drainage are considered key mechanisms-fully consistent with the process-based interpretation supported by the present dataset.

5) Soil compaction and soil moisture deficit: expression of physical and climatic stress

Soil compaction (traffic-induced densification) reaches very high levels, particularly in the Bega Canal-Galați sector:

- Mureș-Galați: 69.87% (slight to strong);

- Bega Canal-Galați: 90.50%;

- Bega Canal-Timiș-Bârzava: 71.80%.

This pattern is consistent with: (i) fine textures and high clay contents (soils with a short “workability window”); (ii) mechanical operations frequently carried out under suboptimal moisture conditions; and (iii) low bearing capacity over extended periods of the year, especially in areas affected by excess moisture.

Soil moisture deficit is also substantial, with the highest share in the Mureș-Galați sector:

- Mureș-Galați: 69.18% (very low/low + moderate + high deficit);

- Bega Canal-Galați: 38.39%;

- Bega Canal-Timiș-Bârzava: 30.78%.

Discussions. The literature indicates that compaction caused by heavy machinery traffic can reduce plant access to water and nutrients and can negatively affect productivity, while structural recovery may be slow-sometimes on the order of years to decades-depending on soil properties and hydrological regime. In the analysed lowland plains, these impacts are amplified by seasonal alternation: soils are often wet (and therefore highly susceptible to compaction) during the cold season and spring, whereas water deficit typically prevails during the warm season, when compaction further constrains infiltration and root exploration, compounding drought stress and yield instability.

6) Integration of results: functional typologies and pedo-hydro-ameliorative implications

By overlaying soil distribution patterns with the main limiting factors, we delineated three functional typologies that are relevant for interpretation and management:

Areas at high risk of groundwater-induced excess moisture combined with salinity/sodicity. This typology is particularly characteristic of the Bega Canal-Timiș-Bârzava sector, where groundwater-related excess moisture reaches 61.52%, and of depressional/interridge settings where the groundwater table may rise to near-surface levels in wet years. Management priorities include ensuring effective drainage functionality, regular maintenance of canal networks, controlling water circulation within supply-drainage systems, and implementing targeted chemical and biological measures (e.g., sodicity amelioration and rotations with ameliorative crops).

High agricultural potential (Chernozem-dominated) areas affected by post-precipitation waterlogging and severe compaction

This typology is typical of the Bega Canal-Galați sector, which is dominated by Chernozems (62.19%) but also exhibits the highest surface waterlogging (47.12%) and very high compaction (90.50%). Here, the critical issue is not merely the presence of canals, but their effective performance during wet seasons,

combined with strict technological discipline: field operations at optimal soil moisture, reduced machinery traffic, and controlled deep loosening where appropriate.

Pedological mosaic areas with comparatively higher soil moisture deficit

This typology is most evident in the Mureş–Galaţca sector, where soil moisture deficit (69.18%) emerges as a major limitation alongside a very high extent of salinization (68.09%). Optimal management requires both measures aimed at improving the soil aeration–water regime (localized drainage where necessary) and strategies for soil-water conservation (reduced tillage intensity, vegetation cover, and crop rotations), complemented by chemical amelioration and corrective fertilization in areas affected by sodicity.

CONCLUSIONS

The analysed lowland plains are jointly controlled by neotectonic subsidence, fine-grained fluvio-lacustrine lithology, and the hydraulic engineering network, which together explain the pronounced functional (hydrological and pedological) heterogeneity despite the overall weakly dissected relief. The subdivision into three sectors-Mureş-Galaţca, Bega Canal-Galaţca, and Bega Canal-Timiş-Bârzava-is therefore warranted by consistent differences in drainage behaviour, groundwater-table (pedofreatic) levels, and soil assemblages.

The soil cover displays a marked mosaic structure, comprising eight SRTS (2012) soil classes and 11 soil types/associations, with clear pedogenetic contrasts among sectors:

- Mureş-Galaţca: dominated by Chernozems (46.07%), followed by Vertisols (19.51%) and soil associations (16.15%);

- Bega Canal-Galaţca: strongly dominated by Chernozems (62.19%), with secondary shares of Vertisols (11.99%) and soil associations (9.69%);

- Bega Canal-Timiş-Bârzava: the most heterogeneous sector, with Eutric Cambisols (25.08%), Chernozems (22.78%), Vertisols (12.96%), Phaeozems (9.32%), together with notable proportions of Gleysols (5.77%) and Solonetz (5.14%), indicating widespread

hydromorphism and locally enhanced sodification processes.

Excess soil moisture is the dominant limiting factor, but with distinct sectoral expression, confirming the combined control exerted by microtopography, texture, shallow groundwater, and canal connectivity:

- Mureş-Galaţca: surface waterlogging 32.72% and groundwater-induced excess moisture 41.06%;

- Bega Canal-Galaţca: maximum surface waterlogging 47.12% and groundwater-induced excess moisture 36.02% (with an emphasis on post-precipitation ponding);

- Bega Canal-Timiş-Bârzava: extremely high groundwater-induced excess moisture 61.52% and surface waterlogging 36.06% (with an emphasis on a shallow groundwater table).

Salinization constitutes a major regional constraint, consistent with the parent materials (clays, carbonate-rich silts, swelling clays) and the high mineralization of shallow groundwater (chlorides, sulphates, bicarbonates). In contrast, soil acidification plays a secondary role (≈ 1.10 –3.43%), indicating that chemical management should prioritize salinity/sodicity rather than acidification.

Soil compaction is widespread and severe, reflecting both heavy textures with a short workability window and the pressure exerted by mechanized agricultural practices:

- Mureş-Galaţca: 69.87%;

- Bega Canal-Galaţca: 90.50% (the most critical situation);

- Bega Canal-Timiş-Bârzava: 71.80%.

Soil moisture deficit co-occurs with excess moisture, confirming an annual “dual stress” regime-excess moisture in the cold season/spring and deficit during the warm season. The share of land affected by deficit is:

- Mureş-Galaţca: 69.18%;

- Bega Canal-Galaţca: 38.39%;

- Bega Canal-Timiş-Bârzava: 30.78%.

This alternation contributes to yield instability and highlights the need for adaptive, sub-field (micro-area) management.

Historical hydro-ameliorative works have altered the pedofreatic regime and locally reduced hydromorphism; however, the results show that surface-water evacuation remains incomplete, particularly in depressional areas. Internal drainage is often imperfect (interbedded

clays, salts), and the groundwater table exhibits strong seasonal fluctuations (typically 0.5-4.0 m, frequently 0.5-1.0 m in depressions), maintaining persistent pressure on soils and crops.

Practical implications and recommendations
Sector-specific management is required, rather than a uniform regional approach:

Bega Canal-Timiș-Bârzava: priority to controlling groundwater-induced excess moisture (effective drainage operation, canal maintenance, pumping stations where applicable), complemented by anti-sodicity measures.

Bega Canal-Galați: priority to mitigating waterlogging and reducing compaction (controlled traffic, field operations at optimal soil moisture).

Mureș-Galați: priority to a mixed strategy combining warm-season soil-water conservation with the management of local excess moisture and salinization.

The recommended technological package focuses on: balancing the soil aeration-water regime (dewatering/drainage where needed), preventing compaction, and applying ameliorative measures and corrective fertilization aimed at restoring soil structure and biological functioning (rotations with ameliorative crops and organic-matter inputs).

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