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Thermo-Hydro-Mechanical Modelling of Flood Embankments

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ABSTRACT: Flood embankments will remain a primary asset in flood protection systems, making their maintenance and integrity essential for every community. However, these embankments are highly vulnerable to fluctuations in atmospheric conditions and water dynamics. Such variations can severely impact the embankment's performance, potentially leading to serviceability issues or instability. Advanced numerical modelling represents a key, if not the only, pathway towards a robust and holistic assessment of such natural hazards and towards the development of appropriate engineering solutions for the long-term maintenance and adaptation of existing and construction of new flood defenses. This paper presents a framework for advanced transient thermo-hydro-mechanical (THM) coupled numerical analyses of flood embankments. The first part outlines the specific context of flood protection in Serbia, as well as characteristic site conditions and projected hydro-climate challenges. The second part introduces a numerical modelling methodology to simulate coupled thermal, hydraulic, and mechanical processes under changing climate conditions, incorporating also vegetation effects. This structured approach provides a robust framework for evaluating embankment performance and developing adaptive, climate-resilient flood protection.

KEYWORDS: Flood, embankments, numerical analysis

1 INTRODUCTION

Floods represent the most impactful natural hazard globally, affecting more than 1.8 billion people, 90% of whom live in low- and middle-income countries (Rentschler, Salhab & Jafino, 2022). Between 1980 and 2011, river floods in Europe alone affected over 5.5 million people, caused more than 2,500 fatalities, and generated economic losses exceeding 90 billion euros (EU Commission – FP7, 2018). Serbia is among the most vulnerable countries in this regard, with the catastrophic May 2014 flood affecting over 25% of the population and causing damages that exceeded 4% of the national GDP (UNDP Serbia, 2024).

Flood defense embankments are critical infrastructures designed to safeguard human lives, property, and ecosystems. Despite growing advocacy for nature-based solutions, these earthen structures will remain the backbone of flood protection systems in Europe and worldwide. However, their resilience is increasingly challenged by climate change, as intensified hydrometeorological extremes exert strong impacts on embankment stability and serviceability (Zhang et al. 2025; Tang et al. 2018). Embankments are particularly susceptible to fluctuations in atmospheric and hydrological conditions, such as extreme rainfall, prolonged floods, droughts, and heatwaves. These variations alter soil moisture regimes, pore water pressures, suction, and temperature distributions, ultimately governing their mechanical response (Tarantino & Di Donna 2019).

Understanding and predicting these processes is complicated by the fact that embankments operate at the intersection of multiple systems. Predicting long-term performance therefore requires approaches that move beyond conventional geotechnical assessments. Advanced thermo-hydro-mechanical (THM) modelling provides such a framework, enabling explicit consideration of climate forcing, hydrological dynamics, and soil–vegetation interactions. By coupling heat and water fluxes with mechanical behaviour, these models capture the transient processes that control embankment response under changing conditions.

Addressing the outlined challenges requires an integrated perspective that combines climatic, hydrological, and geotechnical aspects within a single framework. In this context, the paper first examines flood protection challenges in Serbia, focusing on the river Tamnava catchment. Climate and hydrological conditions, representative embankment geometry, and soil stratigraphy are outlined as essential components for assessing embankment behaviour. The second part introduces the framework for numerical analysis based on the finite element method, designed to capture thermo-hydro-mechanical interactions and to provide a basis for evaluating the long-term performance of flood embankments under changing climate conditions.

2 FLOOD PROTECTION CHALLENGES IN SERBIA

2.1 *Flood protection system in Serbia*

Flood protection systems in Serbia face particular challenges due to their scale, composition, and exposure to climate extremes. The country relies on more than 3,600 km of embankments along the Danube, Sava, Tisa, Morava, and Drina rivers, protecting approximately 1.6 million hectares of agricultural land and numerous urban settlements. However, recent history has revealed their vulnerability: the 2014 floods caused significant damage and displaced thousands of people, while subsequent events in 2019, 2020, and 2021 again highlighted weaknesses in the protection system. At the institutional level, maintenance is often constrained by limited financial and technical capacity, while current practice relies heavily on empirical safety factors rather than advanced coupled analyses.

2.2 *Data for advanced coupled analyses*

The coupled THM analyses of embankment behaviour under changing hydroclimatic conditions necessitate series of precipitation, temperature, potential evapotranspiration and water levels. In case of the embankment lifecycle analyses, the series in the historic period and in the future are needed. Historic series can be compiled from the available records, while the future series imply development of the climate and hydrologic projections. The climate projections of precipitation and temperatures are obtained by running GCM-RCM chains, i.e., combinations of the General Circulation Models (GCM), and Regional Climate Models (RCM), under an assumed climate change scenario, and bias-adjusting the simulated variables to match distributions of the corresponding observations in the reference (baseline) period (Hakala et al. 2019). GCMs provide simulations of the global climate system based on fundamental physical principles, while RCMs offer a finer spatial representation of climate processes over a limited domain. This two-step approach allows capturing both large-scale climate dynamics and finer regional variations that directly affect hydrological conditions and soil behaviour.

The projected precipitation and temperature serve as the input to a formulation of the boundary conditions of the numerical model and hydrological model to simulate future flow series at selected points on the stream network (e.g., locations of stream gauges). Water levels that correspond to simulated flows can be obtained either by using a rating curve (if available at the considered river section), or by developing a comprehensive hydrodynamic model, which is then forced with the simulated flows. As for the potential evapotranspiration series, they can be obtained from the temperature and radiation series (Oudin et al. 2005). Uncertainty associated with the future projections is taken into account by developing hydroclimatic projections with an ensemble of GCM-RCM modelling chains run under different climate change scenarios.

2.3 *Tamnava catchment*

The proposed framework is applied to a flood embankment section in the town of Ub in the Tamnava catchment in the west of Serbia (Figure 1). This 726 km^2 large catchment is notorious for frequent flooding and severe flood damages. While flash floods occur in the headwater parts of the catchment, the downstream parts are often hit by the fluvial flooding, which is caused by heavy convective rain events. The Tamnava catchment hosts intensive agriculture, and various commercial activities focused in the towns of Koceljeva and Ub (Figure 1). Furthermore, the open-pit coal mines that the country's power supply heavily relies on are located immediately downstream of the catchment (Figure 1). Flooding of these open pits (especially, the Tamnava Zapadno polje mine) during the great flood in May 2014 caused enormous damages from disrupted energy production and costly recovery.

The Tamnava catchment is presently unregulated, i.e., there are no reservoirs implemented; hence, flood protection relies solely on the embankment system. The system includes embankments in towns of Koceljeva and Ub designed to protect against 100-year floods, and embankments sized against 25-year floods, built to protect agricultural farms (Figure 1).

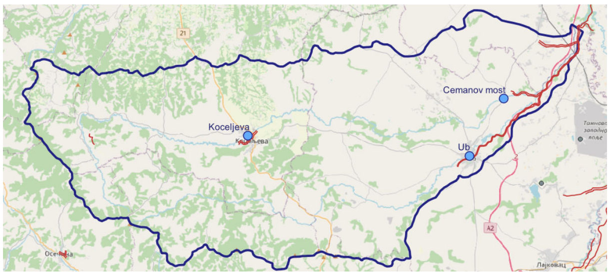

Figure 1. Flood embankments (indicated by red lines) in the Tamnava catchment. The gray area presents an open-pit coal mine, while blue circles indicate stream gauges in the catchment.

2.4 *Climate in Tamnava catchment*

As part of the hydroclimatic input data, climate projections of temperature and precipitation are derived from the Digital Climate Atlas of Serbia (Ministry for Environmental Protection of the Republic of Serbia, 2022). These projections are based on an ensemble of GCM–RCM chains under the high-emission RCP 8.5 (Representative Concentration Pathway) scenario and have been subsequently bias-adjusted to match observed distributions in the baseline period. The Representative Concentration Pathways define standardized greenhouse-gas emission scenarios, which specify the conditions under which these modeling chains generate projections of future climate. In addition to RCP 8.5, the Digital Climate Atlas also provides projections for the intermediate RCP 4.5 scenario.

Figure 2 and Figure 3 illustrate the evolution of these variables over the period 1961-2100, showing a consistent increase in average monthly temperatures across all months, with a progressive year-to-year warming that intensifies towards the end of the century. Precipitation patterns exhibit more pronounced seasonal variability: increases are projected in the first part of the year (January to April) and again in late autumn and winter (October to December), whereas significant reductions are expected during the summer months of July, August, and September when compared to the reference period 1961–1990.

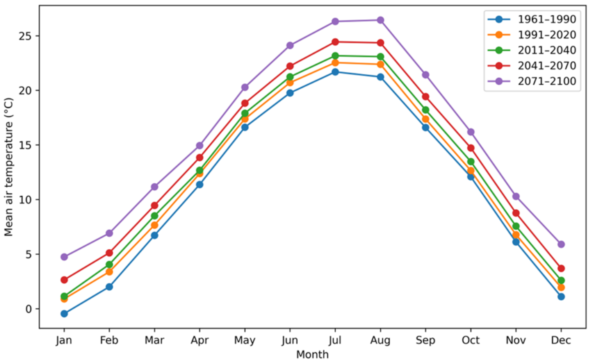

Figure 2. Mean air temperature data, RCP 8.5

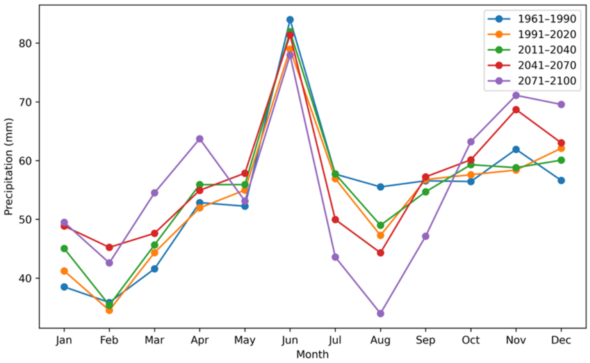

Figure 3. Precipitation data, RCP 8.5

2.5 *Hydrological modelling of the Tamnava catchment*

Water levels and stream flows are observed at the gauges in the Tamnava catchment: namely, Koceljeva, Ub and Čemanov most (Figure 1). Mean annual flow at Koceljeva and at Ub amounts to approximately 1 m^3/s. The greatest observed flows at these gauges amount to 178 m^3/s and 146 m^3/s, respectively, and were observed during the great flood in May 2014.

Future hydrological changes in the Tamnava catchment were assessed using projections of precipitation and temperature obtained from an ensemble of GCM–RCM modelling chains, bias-adjusted against observations at the nearest available climate station and applied for two future periods: the near future (2041–2070) and the distant future (2071–2100), under RCP 4.5 and RCP 8.5 scenarios, for comparison. These climate projections were used to force the calibrated HBV-Light hydrological model (Seibert and Vis, 2012), allowing estimation of changes in streamflow at the Ub gauge. The results suggest moderate increases in mean runoff – up to 14% in the near future and 9.7% in the distant future (ensemble medians) – though uncertainty remains high due to the spread among ensemble members. More importantly, a distinct seasonal redistribution of flows is projected, with RCP 8.5 indicating higher spring and early summer flows, particularly in June in the near future and April in the distant future as illustrated by the intra-annual flow distribution diagrams (Figure 4).

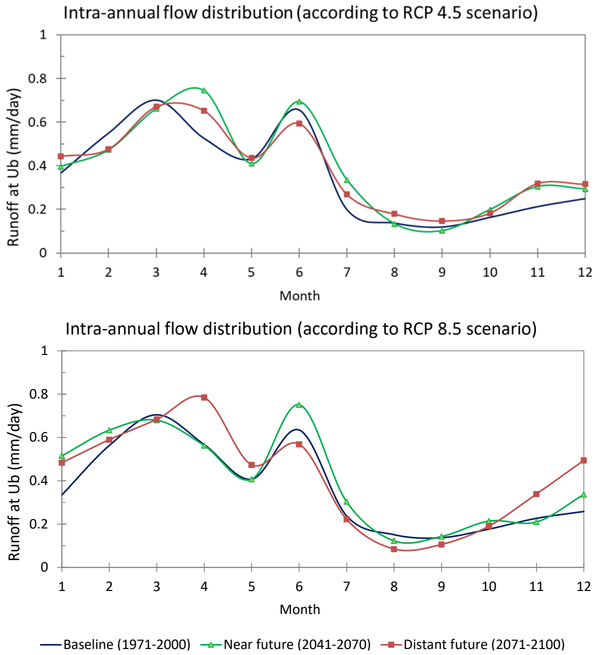

Figure 4. Change in the intra-annual flow distribution in the near- (2041-2070) and distant future (2071-2100) at the Ub stream gauge according to the RCP 4.5 (top) and RCP 8.5 climate change scenarios (bottom panel). The graphs show the ensemble median obtained by forcing the HBV-light hydrological model with the bias-adjusted outputs of the eight climate modelling chains.

2.6 *Configuration of the Tamnava embankments*

The embankments along the Tamnava River were originally built with an average height of about 3 m, a crest width of 4 m, and slopes of 1:2.5 on the unprotected side and 1:3 on the protected side. They were constructed mainly from silty-clayey soils, with some stretches of silty-sandy or clayey-sandy material. In its initial condition, an embankment did not provide sufficient protection against the 1-in-100-year flood (Q1%). In some sections the available freeboard was less than 1.0 m, in others reduced to about 0.5 m, while locally the crest even lay below the Q1% flood level.

Following major flood events, these deficiencies prompted reconstruction works aimed at raising and strengthening the embankment. The upgraded design included increasing the crest level to provide protection against the 1-in-1000-year design flood (Q0.1%), widening it to 6 m, and introducing a central clayey core to ensure impermeability, combined with sandy material for reinforcement on the downstream side. For certain locations, additional stability and erosion protection were provided by 30 cm thick Reno mattresses laid over a geotextile filter, with gabion units to ensure durability. The surface was topsoiled and grassed, while a 3 m wide service road was formed along the protected toe for inspection and maintenance access.

The adopted solution (type 1, Figure 5) retained the unprotected slope in its existing state, while the extension and raising were carried out on the protected side. In these sections, the embankment height was increased by 1.3 m to a maximum of 2.0 m, resulting in a reconstructed height ranging from 3.5 m to 5.5 m. Where reconstruction toward the protected side was not feasible due to the presence of existing structures (e.g., the highway), the works were carried out toward the unprotected slope (type 2, Figure 6). In this case, the average crest raising ranged from 0.3 m to 1.5 m, while the reconstructed embankment height varied between 2.3 m and 4.9 m.

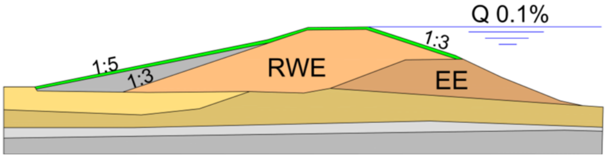

Figure 5. Type 1 embankment (EE – existing embankment, RWE – raised and widened part).

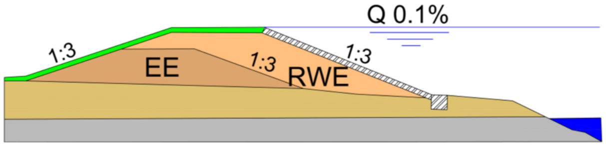

Figure 6. Type 2 embankment (EE – existing embankment, RWE – raised and widened part).

The upper few meters of foundation subsoil consist of silty-sandy clayey sediments, with irregular inclusions and lenses of clayey material. Beneath this stratum, the subsoil is composed of alluvial sandy and gravelly deposits, which form a more permeable foundation layer typical of the Tamnava floodplain.

3 NUMERICAL MODELLING OF FLOOD EMBANKMENT

From above data for Tamnava catchment, projected climatic trends indicate increased warm temperature extremes and reduced summer precipitation, resulting in lower soil water content and groundwater levels. At the same time, land surface temperature (LST), a key driver of soil–atmosphere interactions, is expected to rise more than the global average, further influencing vegetation growth, soil moisture, and ultimately, slope stability (ESA Climate Office, 2024). Although prolonged dry periods can reduce pore pressures and seemingly improve stability, they promote desiccation cracking and preferential seepage paths, which allow rapid pore pressure build-up during subsequent extreme rainfall. Additionally, repeated desiccation–wetting cycles are known to accelerate internal erosion and deformation, especially in vegetated slopes (Zhang et al. 2025).

The finite element method of analysis is the most widely used computational approach for assessing the stability and serviceability of geotechnical structures under various environmental perturbations. The study of flood embankments in Serbia employs the software platform ICFEP (Imperial College Finite Element Program; Potts and Zdravkovic 1999, 2001), which utilises a modified Newton-Raphson nonlinear solver with an error-controlled sub-stepping stress-point algorithm. This section outlines key modelling capabilities necessary for the assessment of flood embankments exposed to soil-vegetation-atmosphere interaction. The framework has been applied successfully in the assessment of natural (Pedone et al., 2022) and infrastructure slopes (Tsiampousi et al. 2017), as well as earth dams (Miltiadis et al. 2025) and embankments (Guo, 2021; Pujevic and Zdravkovic 2024).

The finite element (FE) formulation in ICFEP is fully thermo-hydro-mechanically (THM) coupled for unsaturated soils and derivation of the governing equations is detailed in Potts et al. (2021). It adopts two independent stress variables, matric suction ($s = u_a - u_w$) and net stress ($\bar{\sigma} = \sigma_{tot} - u_a$), where u_a and u_w are the air and water pressure in the pores, respectively. To enable realistic values of the air entry suction, s_{air}, (i.e. > 0 kPa) to be used in unsaturated mechanical models, the formulation further introduces the equivalent suction, $s_{eq} = s - s_{air}$, and equivalent stress, $\sigma = \bar{\sigma} + s_{air}$. Compared to formulations found in the literature, this formulation considers independently the effect of matric suction on direct strains and the effect of net stress on volumetric water content, extending the work of Darkshanamurthy et al. (1984) and Wong et al. (1998).

3.1 *Material modelling*

Mechanical behaviour. Constitutive models available in ICFEP to simulate the mechanical response of unsaturated soils range from simpler Mohr-Coulomb type models (Fredlund et al., 1978) to advanced models based on critical state soil mechanics. The constitutive model of Georgiadis et al. (2005) and Tsiampousi et al. (2013a) is developed for simulating the behavior of moderately expansive unsaturated soils and is adopted here for the simulation of the Tamnava flood embankments. The model, IC SSM (Imperial College Single Structure Model), adopts a standard concept of a single-porosity structure valid for most geomaterials and represents a modified and generalised version of the Barcelona Basic Model (BBM) of Alonso et al. (1990).

The IC SSM is formulated in the $J - p - \theta - s_{eq}$ space, where J is the deviatoric stress invariant, p is the mean net stress, θ is the Lode's angle in the deviatoric plane. It introduces versatile shapes for yield and plastic potential surfaces that particularly improve the modelling of overconsolidated clays; a nonlinear isotropic compression curve which reduces the unrealistically large amount of potential collapse at high stresses; a nonlinear increase of apparent cohesion with suction by linking it to the degree of saturation, S_r; and the Matsuoka-Nakai (1974) shape of the yield and plastic potential surfaces in the deviatoric plane, which improves the modelling of soil strength under non-triaxial compression loading.

Hydraulic behavior – water retention. The FE model of the Tamnava embankments adopts in the first instance a non-hysteretic van Genuchten (1980) type soil water retention (SWR) model which can also include the effect of the specific volume, v, as depicted in Figure 7 and in the expression below:

$$S_r = \left[\frac{1}{1 + \left[\alpha \cdot (v-1)^{\psi} \cdot s_{eq}\right]^{n}}\right]^{m} \cdot (1 - S_{r0}) + S_{r0} \qquad (1)$$

where α, m and n are the fitting parameters; ψ controls the effect of the specific volume; and S_{r0} is the degree of saturation in the long term.

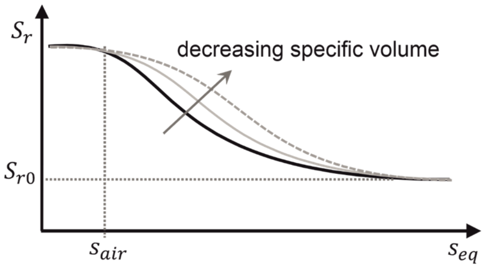

Figure 7. Non-hysteretic SWR model with or without the specific volume effect.

The effect of the more realistic SWR hysteresis will be also examined with the available 3D SWR model (Tsiampousi et al. 2013b) which is capable of tracking both the void ratio changes and the wetting/drying history of the soil.

Hydraulic behaviour – permeability. Realistic modelling of soil permeability (hydraulic conductivity) is particularly pertinent in problems involving atmospheric effects of rainfall infiltration and evapotranspiration. This is a key parameter that controls the amount of water able to enter or leave the soil.

The increase in soil suction during dry periods, associated with desaturation in the soil, is likely to cause a reduction of permeability in the intact material. However, tension or desiccation cracks in shallow ground are often observed during such periods, which contribute to the increase of global soil permeability. This duality of soil permeability is captured in ICFEP with a permeability model depicted in Figure 8 (Potts and Zdravkovic 1999). The reduction of permeability from the saturated state, k_{sat}, to a minimum value, k_{min}, is linked to the magnitude of suction, s_{eq}, through a logarithmic expression:

$$\log k = \log k_{sat} - \frac{s_{eq} - s_{eq,1}}{s_{eq,2} - s_{eq,1}} \log \frac{k_{sat}}{k_{min}} \qquad (2)$$

while the permeability increase due to desiccation cracking is linked to the occurrence of tensile principal total stress:

$$\log k = \log k_{sat} - \frac{\sigma_t - \sigma_{t1}}{\sigma_{t2} - \sigma_{t1}} \log \frac{k_{max}}{k_{sat}} \qquad (3)$$

An alternative variable for the horizontal axis of the desaturation model is the degree of saturation, S_r, using the following relationship:

$$k = k_{sat} \cdot \Theta^{\frac{1}{2}} \cdot \left[1 - \left(1 - \Theta^{\frac{1}{a}}\right)^{a}\right]^{2} \qquad (4)$$

where $\Theta = (S_r - S_{r,LT})/(1 - S_{r,LT})$, $S_{r,LT}$ is a long-term degree of saturation and a is a fitting parameter.

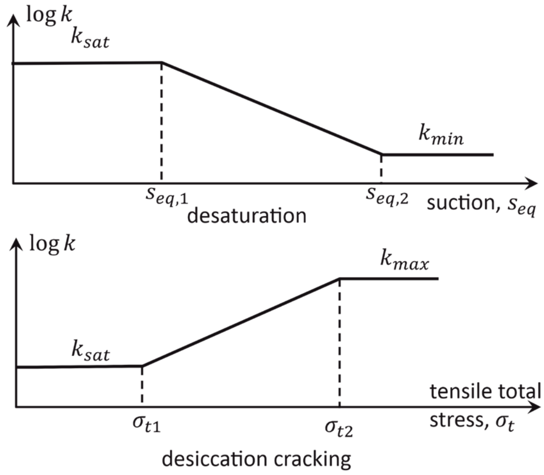

Figure 8. Permeability model for desaturation and desiccation.

3.2 *Hydraulic boundary conditions*

Finite element analyses of geotechnical problems involving soil-vegetation-atmosphere interaction require application of boundary conditions that can simulate rainfall infiltration (precipitation), evaporation from the ground surface and transpiration through plants. This section provides a brief overview of the relevant hydraulic boundary conditions employed in the numerical model of the Tamnava embankments.

Precipitation. This is a dual boundary condition that prescribes either the magnitude of flow rate or the magnitude of pore water pressure along a relevant boundary in a FE mesh (Potts and Zdravkovic, 1999). In the case of modelling a rainfall, if the soil has sufficient permeability and/or the rainfall intensity is small, the soil may be able to absorb the water and therefore a flow boundary condition is activated, prescribing the flow rate, q_{nb}, over the boundary. Otherwise, if the soil is less permeable and/or rainfall intensity is high, the soil may not be able to absorb the water, which will pond on the surface or run off. In this case a pore pressure boundary condition is activated, prescribing the appropriate magnitude of the pore fluid pressure, p_{fb}, on the boundary.

Clearly, conditions may change during an increment of the analysis, hence needing a switch from the boundary condition detected at the beginning of that increment. This requires an automatic incrementation algorithm and that developed in ICFEP is based on the work of Abbo and Sloan (1996) and Sheng and Sloan (2001), for stress-strain behavior in non-linear FE analysis. Its further development, to operate in conjunction with the precipitation boundary condition, is detailed in Smith (2003) and Smith et al. (2008). The purpose of this algorithm is to break down the size of the initial increment to smaller sub-increments in order to apply an appropriate precipitation boundary condition (i.e. flow rate or pore fluid pressure) as it changes over the increment.

The geotechnical numerical model for the Tamnava flood embankments incorporates rainfall projections for the Tamnava catchment, discussed above, as precipitation boundary condition.

Evapotranspiration. The amount of water uptake from a depth below the ground surface is governed by the root depth and density, permeability of the soil-root system and the availability of water. The modelling of this process in the Tamnava embankments adopts the root water uptake model (RWUM) developed in ICFEP by Nyambayo and Potts (2010).

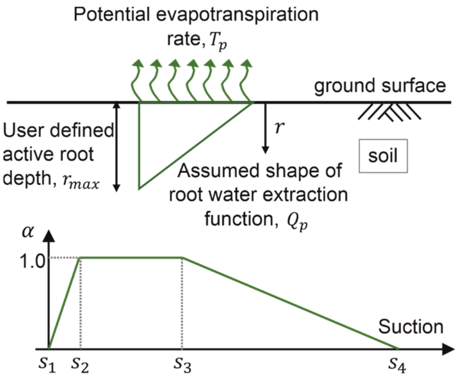

Figure 9. The root water uptake model: (a) water extraction function when $\alpha = 1$; (b) variation of α with suction.

With reference to Figure 9, the RWUM defines the amount of water, Q_p, that could potentially be extracted from the ground if the supply of water was unlimited:

$$Q_p = \frac{2T_p}{r_{max}}\left(1 - \frac{r}{r_{max}}\right) \qquad (5)$$

where r_{max} is the maximum root depth, defined as the analysis input and reflecting the limit depth below which the root water uptake is zero; r is the current root depth and T_p, is the potential evapotranspiration rate assumed to vary linearly with root depth. However, the supply of soil moisture is normally not unlimited, thus the actual evapotranspiration, Q_{ac}, is smaller than Q_p and is calculated using a suction-dependent parameter, α, according to Feddes et al. (1978) and depicted in Figure 9, as $Q_{ac} = \alpha \cdot Q_p$. Values of equivalent suction s_{eq1} to s_{eq4} are input parameters for the model and for suctions outside the two limits, s_{eq1} and s_{eq4}, the root water uptake is assumed to be zero. The former limit relates to water-logged conditions in the soil when roots are unable to function, while the latter limit relates to a permanent wilting point.

4 CONCLUSIONS

Flood defense embankments are subject to complex interactions between climate forcing, hydrological regimes, and geotechnical processes, which cannot be reliably addressed through conventional empirical approaches. This paper presents an advanced thermo-hydro-mechanical (THM) numerical framework tailored for the assessment of embankment behaviour under changing environmental conditions.

The framework integrates climate projections, hydrological modelling, and advanced finite element formulations for unsaturated soils, enabling explicit representation of coupled processes such as pore pressure distribution, desiccation–wetting cycles, and vegetation-induced suction changes. Its structured methodology provides a systematic basis for incorporating site-specific climatic, hydraulic, and geotechnical data into performance assessment.

While numerical results are not provided at this stage, the proposed framework establishes the foundation for detailed numerical analysis, offering a robust methodological tool to evaluate and adapt flood protection systems in Serbia and comparable environments.

5 ACKNOWLEDGEMENTS

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