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Preliminary assessment of vegetated store-and-release cover using phosphate mine waste in a semi-arid climate

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Abstract

Store-and-release (SR) cover systems, composed of fine- and coarse-grained materials, are commonly employed for mine tailings reclamation and are expected to maintain long-term performance for reclamation projects. This performance is primarily assessed through water balance components, particularly percolation control. Establishing native plant communities on these covers is crucial for sustaining their functionality over time. Vegetation influences SR cover performance by affecting water balance dynamics and modifying hydrogeological properties. However, its role is often overlooked in cover design and evaluation.

This study aims to assess the influence of vegetation on water dynamics within an SR cover system through a column experiment. Three instrumented SR cover columns were monitored using sensors measuring volumetric water content. Cover performance was monitored to evaluate variations associated with the presence (or not) of vegetation over the cover. The SR system relies on rainfall storage during the wet season and water release via evapotranspiration during the dry season. It consists of a 100 cm compacted fine-grained layer of phosphate mine waste (clay) designed to, for the first time in North Africa, mitigate acid mine drainage from sulphidic tailings at the abandoned Kettara mine site in Morocco's semi-arid climate.

Vegetation is hypothesised to impact cover hydrology by enhancing water infiltration and modifying water balance in the cover. These factors should be considered in hydrological modelling to design a sustainable SR cover that aligns with the long-term objectives of the mine closure plan for Kettara. Therefore, a multidisciplinary approach integrating both engineering and ecological principles is essential to ensure the effectiveness and longevity of SR cover systems in mine rehabilitation.

Keywords: *mine reclamation, column test, store-and-release cover, tailings, Kettara mine*

1 Introduction and background

Mine waste cover systems are critical components of mine closure strategies, aiming to restore waste deposits to stable, natural conditions and to minimise long-term environmental degradation. Cover systems fulfill multiple roles, including isolating acid drainage waste material, limiting the infiltration of atmospheric oxygen and water, controlling erosion, reducing contaminant migration and providing a medium for the establishment of vegetation communities (Mine Environment Neutral Drainage Program [MEND] 2012; O'Kane & Wels 2003). Among these functions, reducing net percolation into reactive waste materials is often a primary goal as it helps to minimise the release of contaminated drainage into surrounding ecosystems.

Cover systems can vary widely in design complexity, from simple monolayers to multilayered systems incorporating fine-grained materials, coarse layers, geosynthetic components and oxygen-consuming materials (MEND 2004). Classification of these systems is often based on their intended hydrological behaviour: for example, store-and-release (SR) covers, water-shedding covers and capillary break covers.

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However, distinctions among these types are not always clear-cut. For instance, a growth medium layer within a water-shedding cover still functions similarly to a SR layer by temporarily storing infiltrated water and facilitating its removal via evapotranspiration. In arid and semi-arid regions, SR covers are widely adopted due to their capacity to exploit the principles of variably saturated flow and root water uptake for effective waste isolation (Khire et al. 2000; Albright et al. 2004, 2010; Bareither & Benson 2012). These systems are designed to balance water input from precipitation with water output through evaporation and transpiraiton, preventing excess percolation that could compromise water quality.

Previous studies have explored the application of local materials in SR covers to promote sustainable closure solutions. At the site of the abandoned mine of Kettara (AMK) in Morocco, Bossé et al. (2013) evaluated the use of fine-grained phosphate limestone waste as a capillary break layer. Their column experiments demonstrated that under natural climatic conditions, the fine-grained layers effectively stored meteoric water and returned to near-residual moisture contents during dry seasons.

Building on this foundational work, the current study introduces the dimension of integrating local vegetation into the SR cover system. Vegetation can significantly influence cover hydrology by altering infiltration patterns, enhancing ET and modifying soil physical properties over time. These biological processes are essential for the long-term functionality and resilience of cover systems, particularly in semi-arid climates where water balance is delicate.

This research aims to assess the impact of local vegetation on the hydrological performance of an SR cover constructed from phosphate mine waste placed over acid generating tailings from the AMK. Instrumented column experiments were conducted to monitor variations in volumetric water content (VWC) under semi-arid climatic conditions. The experimental design includes vegetated and non-vegetated columns, allowing direct comparison of vegetation effects.

2 Material and methods

2.1 Study site

The AMK is located approximately 35 km northwest of Marrakech, Morocco (31°52’15” N, 8°10’31” W). The site operated between 1964 and 1981, producing over 13 million tonnes of sulphidic tailings, and now covers an area of approximately 16 hectares (Hakkou et al. 2008a, 2008b). The region has an arid to semi-arid climate, with mean annual rainfall ranging from 150 to 300 mm, predominantly during the winter months. Summers are characterised by low rainfall intensity, with average maximum temperatures reaching 42°C. The annual potential evapotranspiration (PET) is estimated at 1,980 mm (United Nations Environment Programme 1997).

The Kettara tailings pond contains approximately 1.78 million tonnes of highly acid-generating mine waste with net neutralisation potential values ranging from −453 to −22.5 kg $CaCO_3$/t. The tailings are characterised by low pH (2.7–4), high sulphate (47–4,500 mg/L) and elevated metal concentrations (Fe, Zn, Cu, Co) (Hakkou et al. 2008a, 2008b; El Khalil et al. 2008).

2.2 Climate and store-and-release cover concept

Selecting an appropriate mine cover system requires careful consideration of climate conditions, particularly the balance between precipitation and ET. The triangular diagram (Figure 1) illustrates how climate, rainfall and temperature guide the choice of cover technologies. In climates where the PET exceeds precipitation, maintaining soil saturation to inhibit oxygen ingress becomes extremely challenging. In such environments – typically arid to semi-arid regions – SR covers are preferred as they manage infiltration by temporarily storing rainwater in the cover material and release it gradually to the atmosphere through evapotranspiration.

In arid and semi-arid regions, where annual potential evaporation may surpass rainfall by factors of 3:1 or 4:1, SR covers must be carefully engineered to withstand short-term infiltration peaks during wet seasons.

Therefore, designing SR covers requires not only a good understanding of long-term climate trends but also the capacity to accommodate extreme weather variability to ensure their long-term effectiveness.

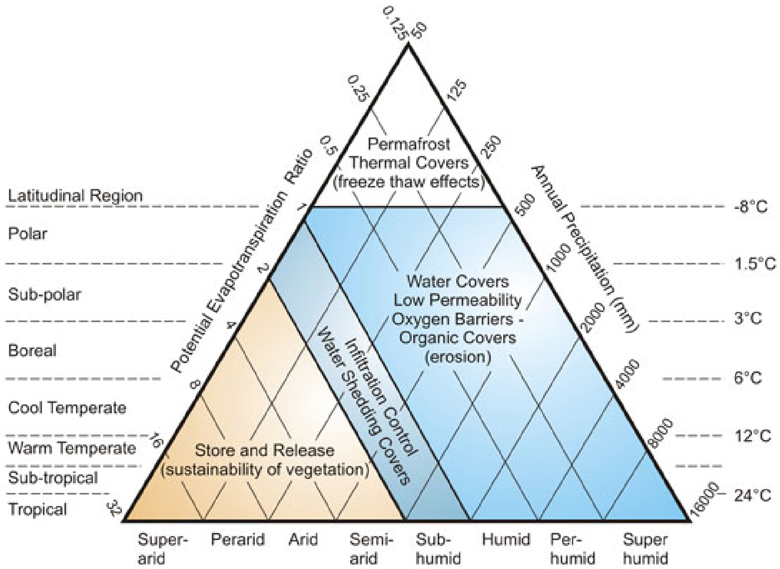

Figure 1 Cover systems and climate types (International Network for Acid Prevention 2009)

2.3 Materials used

The SR cover was constructed on the coarse-grained tailings at the AMK using phosphate limestone waste material sourced from the Ganntour Basin. Previous work by Hakkou et al. (2009) demonstrated the suitability of this material for SR cover applications, particularly in semi-arid and arid environments. The phosphate limestone waste material was classified as sandy silt according to the USCS. It is characterised by a specific gravity of 2.85. According to Bossé et al. (2013), the material exhibited a saturated hydraulic conductivity of 5.7×10^{-6} cm/s at a porosity of 0.43, which is suitable for supporting water storage and gradual release in an SR system.

From a geochemical and mineralogical perspective, chemical analyses conducted by Hakkou et al. (2009) showed high contents of CaO at 43 wt%, P_2O_5 at 16.9 wt% and SiO at 11.6 wt%. Minor concentrations of potential contaminants such as fluoride (F) at 1.73 wt%, chromium (Cr) at 137 ppm and Zn at 195 ppm were also detected. Mineralogical characterisation through X-ray diffraction confirmed a composition dominated by calcite and fluorapatite, each ranging between 25 and 45%, along with dolomite between 20 and 30% and quartz between 3 and 10%. According to Bossé et al. (2013), despite the presence of trace elements, kinetic leaching tests demonstrated that the phosphate limestone waste posed a negligible risk of contaminant release, confirming its environmental suitability for use in SR cover construction.

2.4 Experimental column design

Three cylindrical columns with a 100 cm height and 60 cm diameter were constructed using metal barrels. These barrels were coated with anti-corrosion paint and insulated with fibreglass to ensure thermal insulation. Each column was filled with phosphate limestone waste material, prepared through air-drying, screening to particles size <1 mm and compacting in successive layers (Figure 2).

The experimental columns were instrumented with VWC sensors to monitor moisture dynamics. ECH2O (EC-TM) water content probes were installed horizontally at depths of 25 and 75 cm. The columns were placed outdoors and exposed to natural climatic conditions to realistically simulate field performance. Over the experiment period, continuous monitoring was conducted to VWC. Two of the experimental columns were planted with native vegetation to investigate the effects of plant cover on water infiltration dynamics, while the third column was left unvegetated to serve as a control. However, due to technical issues encountered during the monitoring period, no data could be recorded for the unvegetated control column. To address this limitation, the results obtained by Bossé et al. (2013), who conducted a similar experiment under comparable conditions without vegetation, were used as a reference for comparison. The vegetation was mainly composed of *Atriplex sembaccata*, and the root depth was 21 ± 2 cm At the end of the experiment, the plants reached the fructification stage.

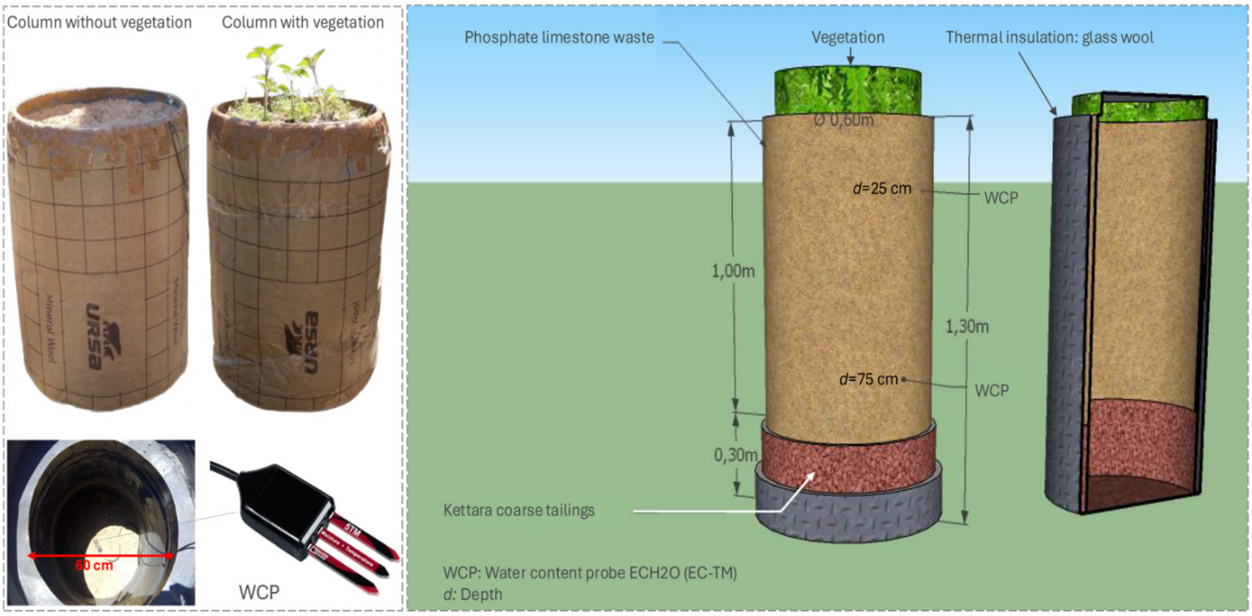

Figure 2 Experimental column configuration and sensor deployment

3 Results and discussions

3.1 Water content variation: natural events

The evolution of VWC and temperature at 25 and 75 cm depths within the experimental columns was monitored over one year, and the results of a five-month period are represented in Figure 3. The results obtained by Bossé et al. (2013) are represented in Figure 4. VWC at 25 cm exhibited substantial seasonal variation, with a gradual increase during the cooler months of January to mid-April followed by a sharp decline beginning in May. In contrast, VWC at 75 cm remained relatively stable at around 0.20 m^3/m^3 throughout the monitoring period, indicating limited deep percolation. This behaviour suggests that the upper layer of the SR cover effectively stores infiltrated precipitation during the wet season, subsequently releasing moisture back to the atmosphere through evaporation and plant transpiration as temperatures rise. The increase in VWC at shallow depth coincided with the rainy season while the later sharp decrease corresponded to rising temperatures and enhanced ET demand, which reached values exceeding 30°C. Temperature profiles at both depths showed similar trends though fluctuations were dampened at 75 cm, confirming the insulating effect of the thicker cover material.

The observed water retention dynamics are consistent with previous studies highlighting the importance of surface storage for SR cover performance in semi-arid climates (Khire et al. 2000; Albright et al. 2004; Benson & Bareither 2012). As noted by Scanlon et al. (2005), effective SR covers are designed to accommodate seasonal infiltration without allowing significant downward migration of water, relying heavily on evaporation and transpiration to maintain low percolation rates.

The influence of vegetation was particularly evident in vegetated columns, where the decline in VWC during the dry season was more pronounced compared to the bare control column. This observation supports the fact that plant transpiration significantly enhances moisture removal, thereby improving the overall effectiveness of SR covers (Wilsnack et al. 2001; Morris & Stormont 1997). The role of vegetation in maintaining the water balance by increasing water extraction from the cover system suggests that incorporating local plants can provide a long-term advantage for minimising net percolation and sustaining cover integrity in arid and semi-arid environments.

These observations are in agreement with previous work by Bossé et al. (2013), who reported similar findings in their instrumented column experiments. Their results showed that an SR cover consisting of a 100 cm layer of phosphate limestone waste material (<1 mm) effectively controlled the generation of contaminated mine drainage under semi-arid to arid climate conditions. Under natural climatic conditions, more than 94% of the annual net infiltration was released back into the atmosphere through evaporation. Their study also demonstrated that phosphate limestone waste could significantly limit deep percolation even after the application of the probable maximum precipitation (155 mm/day). These findings reinforce the potential of phosphate waste materials as viable candidates for sustainable SR cover construction in challenging climatic environments.

3.2 Water content variation: a simulated exceptional event

Figure 5 presents the evolution of VWC in the vegetated column before, during and after a simulated exceptional precipitation event. The experimental period is visually divided into three phases: pre-event, event and post-event. The results obtained by Bossé et al. (2013) are represented in Figure 6.

Prior to the simulated precipitation, the VWC at both depths remained relatively stable. At 25 cm, VWC maintained a moderate value with minor variations, while at 75 cm, VWC was slightly lower but steady, indicating limited infiltration under baseline conditions. During the exceptional rainfall event (highlighted in red), a sharp increase in VWC was recorded at 25 cm. This immediate response indicates rapid infiltration and water storage in the upper part of the SR cover. However, the VWC at 75 cm shows minimal immediate response, suggesting that the initial rainfall infiltration was largely absorbed and buffered by the upper soil layers, thus delaying deep percolation. In the post-event period (highlighted in green), VWC at 25 cm gradually declined as water was released back to the atmosphere, primarily through evaporation and plant transpiration. Meanwhile, a delayed and progressive increase in VWC was observed at 75 cm, indicating that a portion of the water eventually percolated downward, although at a much slower rate compared to the upper layer dynamics.

The rapid VWC rise at 25 cm demonstrates the strong storage capacity of the vegetated SR cover during heavy rainfall, preventing immediate percolation into deeper layers. The delayed response at 75 cm suggests that the system effectively attenuated infiltration, allowing time for significant moisture extraction by plants and evaporation before reaching deeper horizons. This behaviour aligns with the conceptual design of SR covers, where surface layers act as temporary reservoirs during high-intensity precipitation events (Albright et al. 2010; Benson & Bareither 2012).

Vegetation plays a critical role in this process by enhancing ET, which is especially important in post-event periods to restore the storage capacity of the cover and limit prolonged saturation that could lead to deep percolation. These results confirm the importance of integrating native vegetation into SR cover designs, particularly in semi-arid climates where exceptional rainfall events, though infrequent, can heavily stress the water retention system.

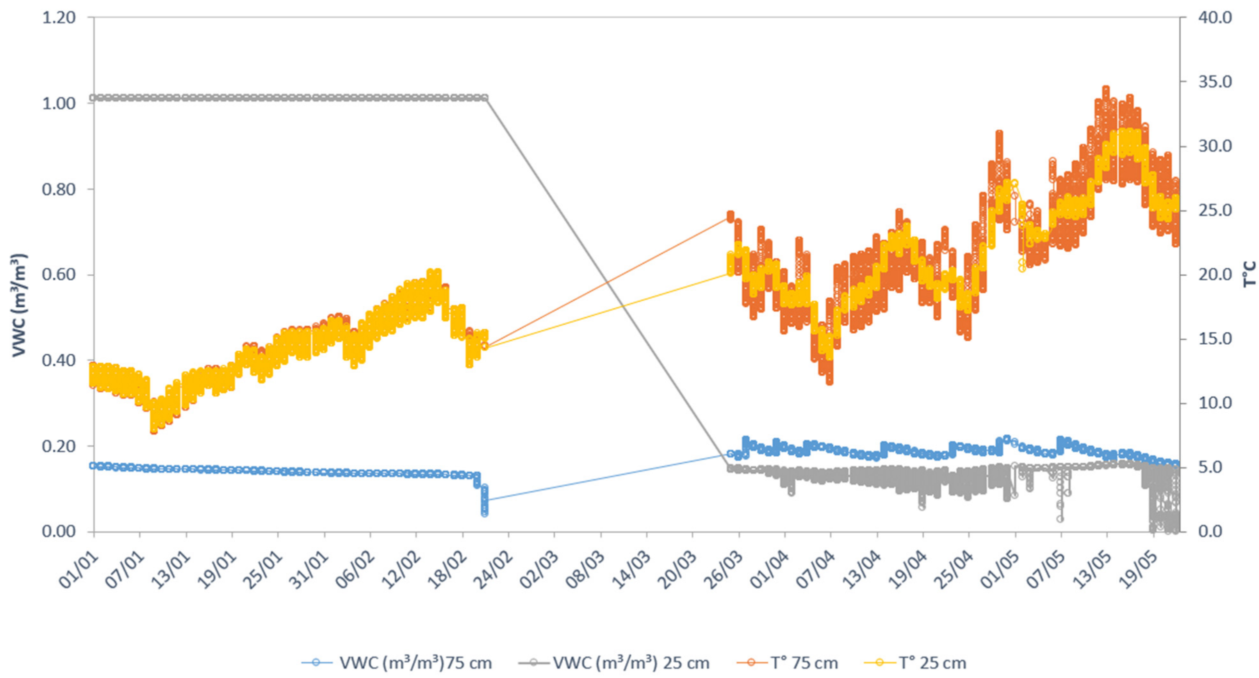

Figure 3 **Evolution of volumetric water content (VWC, in m^3/m^3) and temperature (°C) at two depths, 25 and 75 cm, within the experimental vegetated column**

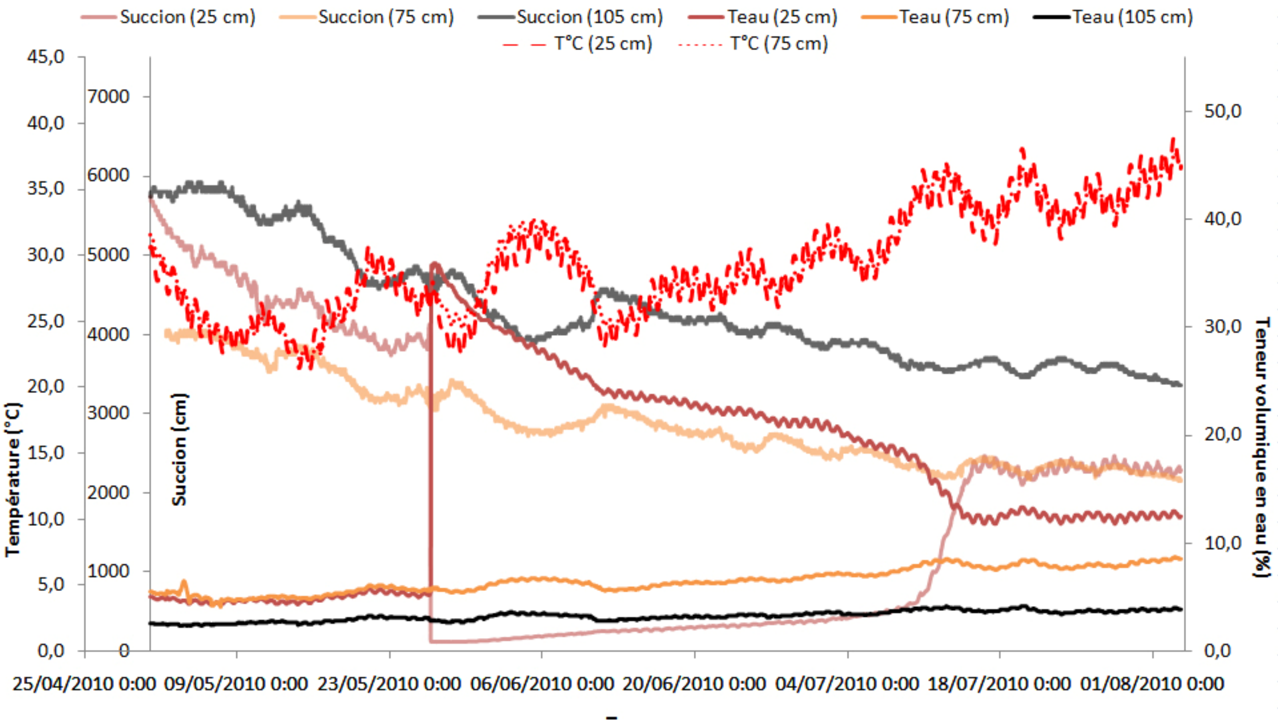

Figure 4 **Results of the in situ test for the unvegetated column composed of 100 cm of phosphate limestone waste (<1 mm) (Bruno 2013)**

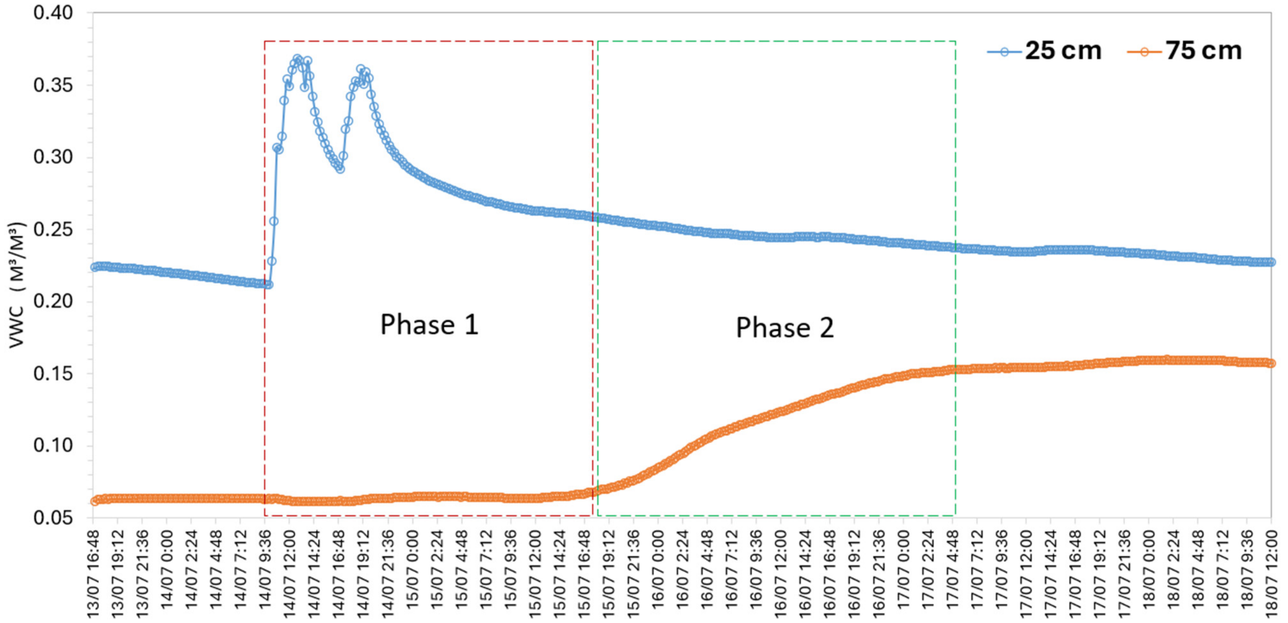

Figure 5 **Evolution of volumetric water content (VWC) in the vegetated column before, during and after a simulated exceptional precipitation event**

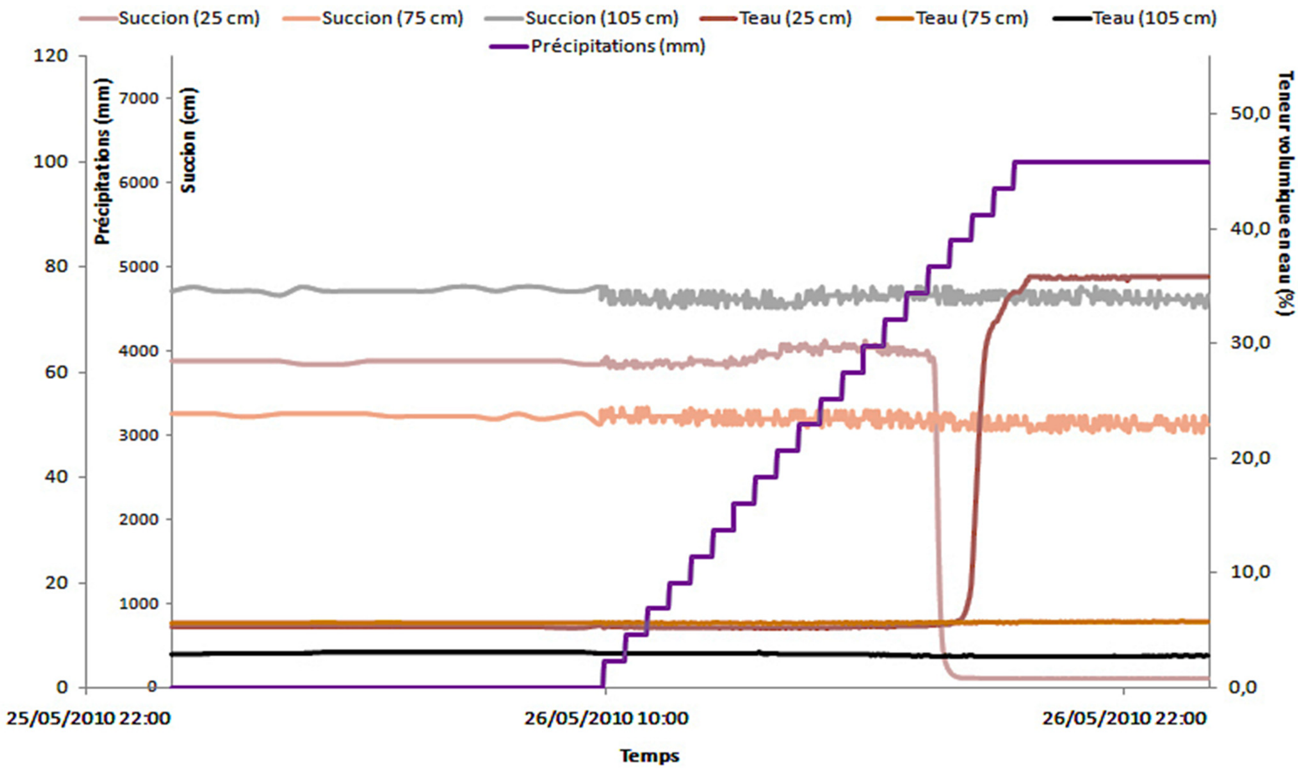

Figure 6 **Simulation of 100 mm of precipitation on the unvegetated column (Bruno 2013)**

3.3 Role of vegetation in store-and-release covers

An essential factor for the long-term success of SR cover systems is the establishment and sustainability of a suitable vegetation cover. Vegetation plays a critical role not only in enhancing ET and thus limiting water infiltration, but also in protecting the cover surface against erosion and sediment transport, particularly in sensitive receiving environments. Rapid revegetation following cover placement is often necessary, especially in cases where cover materials are prone to desiccation, crust formation or cementation upon exposure, which could compromise infiltration control and increase surface run-off.

In designing SR cover systems it is important to develop integrated objectives for both the cover structure and the vegetation community. Ideally, the planted vegetation should mimic the natural, diverse plant communities native to the surrounding region as these communities are more likely to provide resilient and self-sustaining performance over decades or even centuries (MEND 2012). Effective selection of plant species requires an understanding of how different functional groups respond to site-specific biotic and abiotic factors, including soil conditions, climatic variability and hydrological processes. Furthermore, design models should incorporate plant-specific parameters such as rooting depth, rooting patterns, leaf area index and dynamic ET rates, recognising that these attributes are not static but evolve with environmental conditions (Lamoureux et al. 2012).

The importance of vegetation is further emphasised when considering the physical properties of the cover materials. Long-term success of these covers relies on their ability to mimic natural hydrological cycles while maintaining minimal maintenance requirements. In regions with semi-arid climates, where the balance between rainfall and PET can vary seasonally, vegetation becomes a key factor in stabilising the system (Figure 7). Observations from other SR cover trials, such as those at the Cadia Hill gold mine, demonstrated that even initially unseeded covers which later developed volunteer vegetation experienced improved performance over time (Rohde et al. 2016). Introducing native species adapted to local climatic conditions could further enhance ET rates and reduce residual percolation. Overall, integrating ecological considerations, particularly the role of vegetation, into the engineering design of SR covers is fundamental to achieving long-term effectiveness in limiting rainfall infiltration, promoting environmental stability and ensuring sustainable mine site rehabilitation.

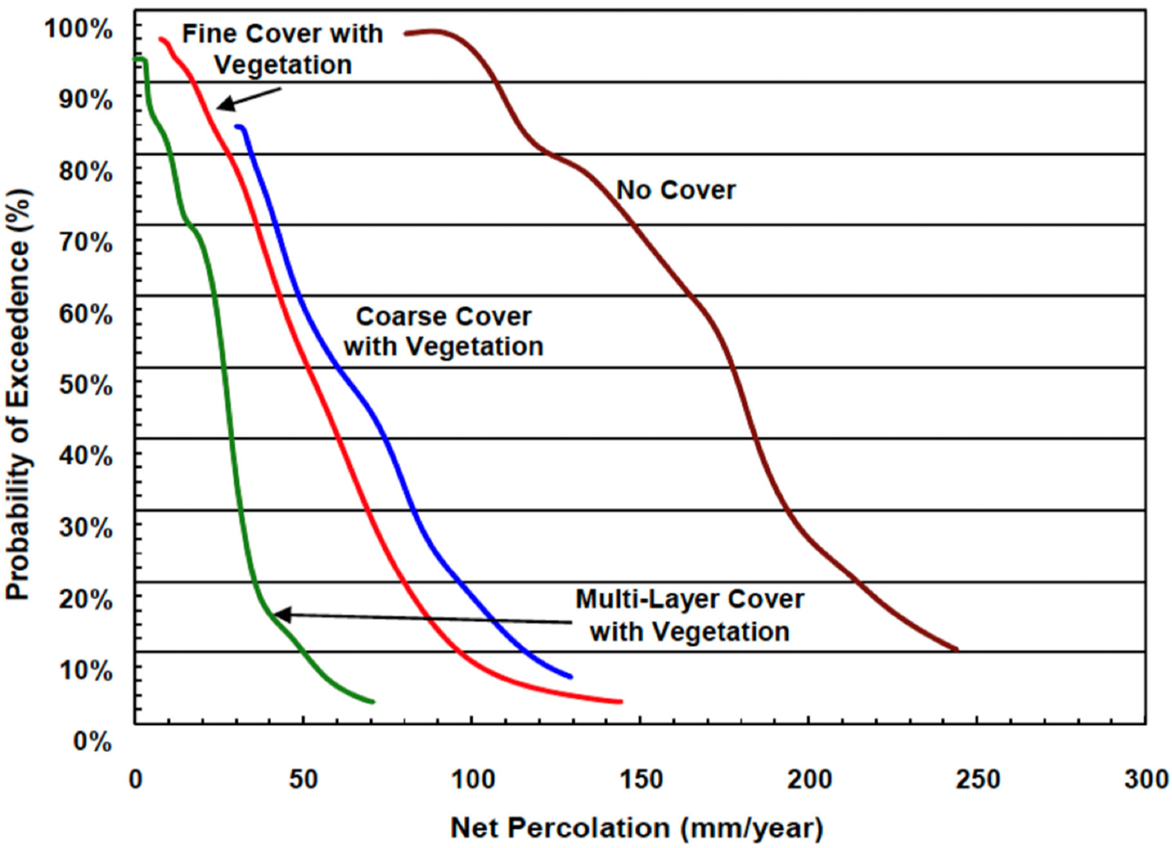

Figure 7 Illustration of the net percolation probability of exceedance curves generated from the results of continuous 100-year climate simulations for a "no cover" scenario and three different cover system scenarios (O'Kane & Ayres 2012)

4 Conclusion

This study demonstrated the effectiveness of a store-and-release (SR) cover system constructed with phosphate limestone waste material in controlling water infiltration under semi-arid climatic conditions. Through in situ monitoring using experimental columns, the SR cover successfully limited deep percolation by promoting water storage and subsequent release through evaporation and transpiration. Vegetated columns showed a tendency for enhanced moisture extraction compared to non-vegetated ones from previous study, highlighting the potential role of vegetation in improving SR cover performance and sustainability.

The results are consistent with previous findings in similar settings and reinforce the importance of integrating ecological and engineering principles into mine closure strategies. Establishing a resilient vegetation cover not only enhances hydrological control but also contributes to long-term system stability with minimal maintenance.

As a next step, the experimental results obtained will be used to calibrate and validate a numerical model using HYDRUS-1D. This modelling will allow for a better understanding of the coupled water flow and root water uptake processes within the SR cover system, and will support the design of optimised, site-specific rehabilitation strategies for the Kettara mine site and similar contexts.

Acknowledgement

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