Influence of vegetation and additional surface layers on the water balance of a reclamation cover with elevated water table

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Abstract

Water balance was measured for five field experimental cells with an oxygen-barrier type of reclamation cover combined with elevated water table including a control cell with functional layer of desulfurized tailings over a reactive tailings layer, and 4 other cells with additional layers and different vegetation. Hydrogeological (moisture content and suction in layers, water table positions in cells), and precipitation data collected throughout three successive growing seasons after revegetation were compared to investigate the effects of different material layering and vegetation scenarios on the water balance. Above- and below-ground vegetation developments were also monitored. Results showed that for all tested scenarios the main water balance component remained the evapotranspiration (79-98% of the total precipitated water). Herbaceous vegetation was found to provide much safer support for the cover performance than woody vegetation, keeping the reactive tailings more saturated during the whole study period (mean S_r>90.77%). In presence of woody plants, however, the S_r in the reactive tailings could reach a value as low as ~32%. Increasing the thickness of the additional layer over 30 cm above the functional layer with fine-grained HDS sludge could also pose a threat against its functionality by stimulating willow growth, lowering the water table position as well as the S_r in the reactive tailings. Finally, adding a coarse-grained capillary break layer impeded the willow root colonization of the functional layer in the short term but increased percolation and should be coupled to water conservation strategies in the overall system to maintain the elevated water table.

Keywords: oxygen-barrier cover systems, water balance, percolation, evapotranspiration, revegetation layers, reclamation of acid generating mine wastes, desulfurized tailings, willow

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1. Introduction

Mining operations and processing of minerals usually ends in disposal of large amounts of acid-generating waste materials in storage facilities that need be reclaimed at closure according to most environmental regulations. For this purpose, cover systems are frequently implemented over such facilities with a core mission of preventing or mitigating the movement of water and gaseous oxygen into the wastes, and thereby restricting the generation of acid (Bussière and Guittonny 2020). The ability of such an engineered cover system to perform successfully over its service life depends on maintaining its integrity in different aspects including its water balance (Vanapalli et al. 1997). This necessitates that the cover system provides proper support for all potentially interfering components including vegetation while functioning over an indefinite time without being disrupted (Pabst et al. 2018). On the other hand, revegetation is an obligatory practice during the post-mining stage in many countries and is also considered an indicator of restoration success (Vallauri et al. 2005). However, its establishment over the reclamation covers, including the oxygen-barriers, is alleged to be interfering with the cover's performance due to the potential effects on water balance (Lamoureux et al. 2012; Ng et al. 2019b).

In a humid climate, oxygen barriers are considered the most relevant types of reclamation covers to prevent the generation of acid mine drainage (AMD) due to sulfide minerals oxidation in tailings (Bussière and Guittonny 2020). Such covers can be created either by submerging the sulfide tailings under water (water cover) or by applying engineered soil covers over them to inhibit oxygen ingress into the tailings. Different types of engineered soil covers range from relatively simple monolayers to complex multi-layered structures (Bussière and Guittonny 2020).

Covers with elevated water table (EWT) are among the engineered oxygen-barrier systems which consists of elevating water table position and maintaining the reactive tailings at a high degree of saturation (or in a near-saturated state, S_r>85%), thereby restricting the oxygen diffusion as the oxygen is far less diffused in water or in such nearly-saturated medium, than it is in the air (~2.5×10^{-9} $m^2.s^{-1}$ vs. 1.8×10^{-5} $m^2.s^{-1}$ at 22° C, respectively). As shown in Fig. 1, in such configuration, deposition of a material layer above the reactive wastes is essential to reduce their interaction with atmosphere (Ethier et al. 2017; Pabst et al. 2017). This monolayer can either be composed of a coarse-grained material in order to prevent evapotranspiration and improve infiltration (Ouangrawa et al. 2009), or of a fine-grained material to enhance the capillary rise capacity and maintain the saturation state (Demers et al. 2008). For an efficient cover of this type, the capillary rise in the tailings, which is a function of the water table position and the material characteristics, must be sufficiently high to ensure that the reactive tailings located above the water table are kept close to saturation (Ouangrawa et al. 2010; Rey et al. 2016; Bussière and Guittonny 2020).

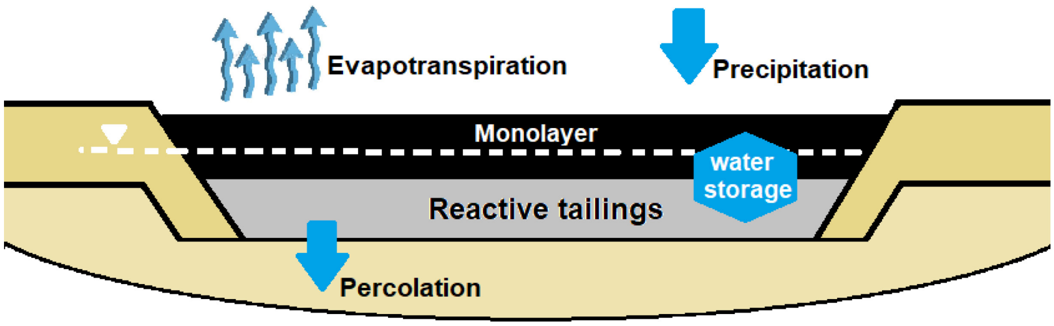

Fig.1: Schematic cross-section of a simple monolayer cover combined with elevated water table showing its water balance components

The simplified water balance (Wilcox et al. 2003; Melchior et al. 2010) in a cover system states that for a given volume of soil, over a given period of time, the amount of input water equals the amount of water withdrawn from the system:

$$P = ET + R + G + \Delta S \quad (1)$$

where P is precipitation, ET is evapotranspiration, G is percolation, and ΔS represents water storage variations. Like all other types of covers, once constructed, an oxygen-barrier cover may either host a pre-designed vegetation component or be subjected to natural plant succession (Swab et al. 2017). Vegetation and materials colonized by roots could have effects on the water balance of the reclamation cover and thereby influence its performance, especially because the functionality of an engineered oxygen-barrier cover depends on the ability of the system to maintain conditions close to water saturation. The vegetation impacts over such balance could be due to several processes: the first is the direct withdrawal of water through plant roots towards the leaves (transpiration) which can change the water storage of the cover materials (Proteau et al. 2020). This impact constitute a significant share of the water loss from the cover in humid climates (Waugh 2001). The second is the formation of bio-pores by root penetration (Guittonny-Larchevêque et al. 2016c; Beck-Broichsitter et al. 2018b; Zhang et al. 2021) and introducing organic matter (OM) into the cover materials which can alter their porosity infiltration capacity, and moisture retaining properties (Guittonny-Larchevêque et al. 2013, 2016a; Beck-Broichsitter et al. 2018a; Villagra-Mendoza et al. 2020; Iskandar et al. 2022). In an oxygen-barrier cover, formation of such porosity can change water flow in cover materials (Angers and Caron 1998; Nespoulous et al. 2019; Proteau et al. 2021), and affect infiltration, water storage and percolation.

Several studies have been performed to assess the role of vegetation on water balance in reclamation covers, mostly in case of landfill final covers or other cover types that act as water barriers by taking into account evaporation or potential evapotranspiration estimated by meteorological models in calculation of water balance (Woyshner and Yanful 1995; Wilson et al. 1997; Yanful et al. 2003; Albright et al. 2004; Apiwantragoon et al. 2015; Widomski et al. 2015). However, so far, limited studies have addressed the effects of vegetation layer on actual evapotranspiration and measured percolation components in context of an oxygen-barrier reclamation cover and in a humid climate.

Based on previous studies, vegetation is effective for both increasing and decreasing infiltration in mining soils depending on the type of vegetation and on the texture of the host soil (Bochet et al. 1999; Spain et al. 2006; Adu-wusu et al. 2007; Zuazo and Pleguezuelo 2008; Moreno-de las Heras et al. 2009; Fraser 2014; Zhang et al. 2015). It was also shown that vegetation has a major effect on increasing evapotranspirative rates and increasing/decreasing water storage (Shurniak and Barbour 2002; Williams et al. 2006; Fraser 2014; Arnold et al. 2015). These effects, however, could be different between herbaceous and woody types of vegetation since woody plants generally transpire more water and thus pump more water than herbaceous plants (Wang et al. 2011; Alaghmand et al. 2014). They also have deeper root systems than herbaceous plants (Alaghmand et al. 2014) which enables them to access water in the deeper soil horizons. Therefore, woody vegetation may maintain a deeper water table. On the contrary, herbaceous root systems usually have shallow distribution and can not easily access the deep waters in soils (Scanlan 2009). The root development pattern in each plant category is also quite different (Devitt and Smith 2002; Wu et al. 2017). In landfill or mining capping systems, deep-rooting vegetation could raise the risk of water loss from deeper layers and development of shrinkage cracks (Beck-Broichsitter et al. 2018a, b).Most recently in 2018, a field study was performed at Canadian Malartic mine site, Québec, Canada, assessing the effect of a model woody plant (clonal fast growing willows) on the water balance of a number of cells constructed over waste rock dikes

(Chevé et al. 2018). Results of this study showed that in a period of 3 months, evapotranspiration was the component with the highest contribution, with 58-87% of the total cumulative precipitation the first year. A follow-up study in the second year also showed that although there were no detectable effect of willow plants on percolation in the first year, they finally reduced the amount of deep infiltrated water in non-compacted soils by 28% (Guittonny et al. 2019). Based on literature, in humid climate, the mean normal transpiration rates for willow plantations during the growing season is 2.5-2.7 mm/day (Mirck and Volk 2010a, b; Frédette et al. 2019).

In current study, field measurements were performed over three years in five experimental cells simulating reclamation of AMD generating tailings using a desulfurized tailings cover (functional layer) with the elevated water table technique to quantify the influence of revegetation layer on the water balance components (i.e. percolation, water storage, and evapotranspiration). To achieve this objective, two model vegetation types for herbaceous and woody plants were selected and applied on the cells with different layering scenarios, including a control cell without vegetation. At the beginning of current study, the following hypotheses were stated:

(1) A significant increase in the share of evapotranspiration and a subsequent decrease in water storage in vegetated cells was expected compared to the control cell;

(2) Variations in the water balance components are potentially greater in cells with plants having larger green aerial parts and deeper rooting. We expected that the decrease in water storage and deeper water table will be threatening to the functionality of the cover in willow vegetated cells due to root colonization and desaturation of the cover's functional layer;

(3) A higher degree of saturation in the reactive tailings and functional layer were expected with the addition of a coarse-grained layer that provides a capillary barrier effect restricting upward water flow. Addition of a fine-grained layer with high moisture retaining capacity over the functional layer would also result in a high degree of saturation in the reactive tailings.

This research contributes to improve knowledge on the effects of revegetation layers (vegetation and materials colonized by roots) on the performance of oxygen-barrier covers used to reclaim acid generating mine wastes, through their influence on the water balance. This new and interdisciplinary knowledge will help to better integrate revegetation into the engineering and hydrogeological designs of oxygen barrier covers to ensure their long-term performance.

2. Materials and methods

2.1. Site description

The study was performed at the Doyon-Westwood mine site, located in the Bousquet Township, Abitibi-Temiscamingue region, Québec, approximately 40 kilometers east of Rouyn-Noranda city center. The deposit at this site consists of gold-bearing sulfide-rich minerals (IAMGOLD 2009) with both waste rock and tailings being considered acid generating due to their low net neutralization potential (NNP) (Demers et al. 2015a). A huge amount of high-density sludge (HDS) have been stored on site for over 15 years in dedicated ponds (Demers et al. 2015b) and more recently in the tailings ponds. Ever since the sludge deposition in dedicated ponds stopped, vegetation has been observed to naturally colonize the deposition ponds in remarkable diversity (Smirnova et al. 2013) which has further motivated the mine operators to valorize this material in the reclamation activities. This waste material was previously shown to have interesting geotechnical and geochemical properties as a construction material for oxygen barriers (Demers et al. 2015b). Feasibility of using mixtures of this material has been previously tested in construction of reclamation covers (Demers et al. 2015b; Mbonimpa et al. 2016).

The overall site is located in a boreal region with characteristic forest species including *Pinus banksiana* Lamb., *Picea mariana* (Mill.) Britton, *Populus tremuloides* Michx., *Betula papyrifera* Marsh., *Larix laricina* (Du Roi) K. Koch, and *Abies balsamea* (L.) Mill (Guittonny-Larchevêque and Lortie 2017). The growing season normally begins in mid-May and ends in late October, with a mean temperature during the three warmest months (June, July, and August) of around 15-17°C, a mean annual temperature of 1.5°C, and 97 frost-free days, on average. Mean annual precipitation is 929 mm (Guittonny-Larchevêque and Lortie 2017; Government of Canada 2020). Previous vegetation studies on this site have been performed on acid-generating waste rocks using fast-growing willows (Guittonny-Larchevêque et al. 2016b; Guittonny-Larchevêque and Lortie 2017). Several reclamation studies have been performed on the Doyon-Westwood's tailings storage facilities at the intermediate scale but did not include vegetation (Demers et al. 2015b; Rey et al. 2016). Based on these reclamation studies, the mine has considered reclaiming two of its tailings ponds with a monolayer cover (0.5 m of desulfurized tailings) combined with elevated water table. This type of reclamation cover fits well with the shallow water table position with respect to the tailings surface at these two ponds but would imply on-site production of desulfurized tailings.

2.2. Cells configuration and materials used

For the purpose of current study, five in-situ experimental cells were constructed in 2018-2019 on the waste rock piles of the Doyon-Westwood mine. Inspired from an earlier study (Bussière et al. 2007), these cells were excavated as inverse truncated pyramidal lysimeters with a drain at the bottom and fully lined with PVC geomembrane to collect percolation water (TEXEL TM240). All cells were filled with a 0.3 m thick overburden on top of a 0.5 m layer of desulfurized tailings (principal functional layer, identified as Goldex monolayer in Fig. 2) over 1 m of Doyon acid-generating tailings (Fig.2). The first three cells were built with the basic configuration: control cell 1 without vegetation, and cells 2 and 3 with two different vegetation types (herbaceous vs willow, respectively). Cells 4 and 5 had a 0.3 m-thick additional layer, a capillary break layer (CBL) or a high-density sludge (HDS) layer between the overburden and the cover's functional layer, respectively. Cells 3-5 had similar vegetation type (Table 1). The four vegetated cells were constructed and vegetated in June 2018 while the construction of the control cell without vegetation was completed in Spring 2019.

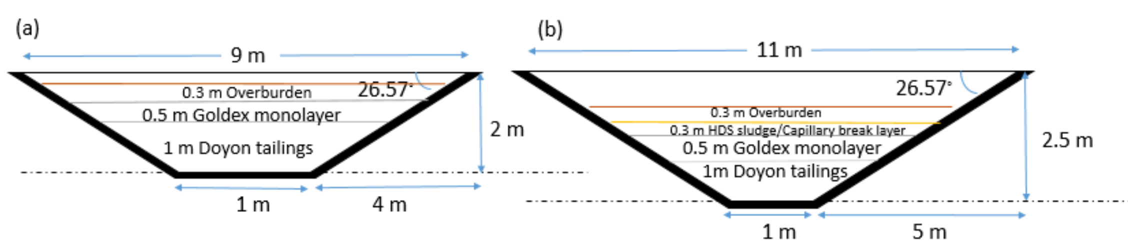

Fig. 2 Geometrical representation of the cells' cross-section: a) lysimeters 1-3 and b) lysimeters 4 and 5

Table 1: Design of the experimental cells

Cell name	Design of the revegetated layer
Lys-1	Control cell with no vegetation
Lys-2	Seeded herbaceous vegetation
Lys-3	Planted willows
Lys-4	Planted willows – 0.3 m capillary break layer (CBL)

Lys-5	Planted willows – 0.3 m water treatment sludge (HDS)

All materials used for the cell construction were obtained from the mine site, except for the desulfurized tailings, which were supplied from the Goldex mine (located within 71 km from the study site). Table 2 lists the range of properties for each material layer. Particle size analyses were performed using a Malvern mastersizer 3000 (Malvern Instrument, UK) and the average specific gravity (G_s) was measured via a helium pycnometer (AccuPyc 1330, Micromeritics, USA). Upon dismantling of the cells in 2021, porosity measurement were carried out via sand cone method (ASTM D1556-07) and soil ring samples (mean diameter and height of 64 mm and 31 mm, respectively, 2 samples from each layer) in the overburden and the fine-textured materials, respectively. For porosity measurement in the coarse CBL, a bucket with known volume, full of non-compacted material, was filled with water and weighed; the porosity was then estimated by dividing the mass of water by the total volume of the bucket. The saturated hydraulic conductivity of the tailings were predicted using the modified Kozeny–Carman equation (Mbonimpa et al. 2002) as 4×10^{-6}-2×10^{-5} cm/s for Goldex desulfurized and 2×10^{-5}-8×10^{-5} cm/s for the Doyon reactive tailings.

Table 2: Material properties: specific gravity (Gs, n=1 to 4), particle size distribution parameters and porosity (n=5 for overburden and tailings, and n=2 for capillary break and high density sludge).

Material	G_s (-)	Particle size distribution						Porosity (%)	
		D_{10} (µm)		D_{60} (µm)		C_U (-)			
		Min	Max	Min	Max	Min	Max	Min	Max
Overburden	2.7	5.17	6.50	71.20	81.70	11.99	14.24	36	42
Goldex tailings	2.7	3.24	4.93	39.25	74.22	12.11	15.34	36	44
Doyon tailings	2.7	3.65	5.74	26.66	52.42	7.31	9.88	42	50
Capillary break	2.7	22.98		624.54		27.17		25	
High density sludge	2.3	1.87		7.12		3.82		50	

2.3. Vegetation design

Vegetation in cells 3-5 included planting 1.2 m-long cuttings of *Salix miyabeana* (clone Sx64) at 1 m spacing and 0.3 m deep. With such a design, there were 64 willows in cell 3 and 100 willows in each of cells 4 and 5. This type of fast-growing willows was selected to enable timely maximized plant effects on the water balance (Guittonny-Larchevêque et al. 2016b; Chevé et al. 2018). Each cutting was locally fertilized at planting with 30 g of mineral fertilizer (NPK 21-2-4).

Herbaceous seeding in cell 2 was performed using a commercial lawn seeding mix combining grasses and legume (Ecoturf Herbionik grass seeds (Gloco, Botanix), 200 kg/ha) with 500 kg/ha of mineral fertilizer (NPK 21-2-4) (Burger and Zipper 2011). The exact herbaceous species were 23% *Festuca trachyphylla* (Hard Fescue, Rhino / Aurora), 20% *Festuca arundinacea* Grass fescue (Culumbra II / Chancellor), 20% *Festuca rubra* Creeping red fescue (Aberdeen) *E, 20% *Lolium perenne* Perennial ryegrass (Medaillon / Ragnar II), 14% *Poa pratensis* Kentucky blue grass (Appalachian / Midnight II), and 3% *Trifolium repens* White clover, by seed mass.

2.4. Cell instrumentation and water balance measurements

Each cell was instrumented with frequency-domain-reflectometry θ (volumetric water content) sensors (FDR probes, ECH$_2$O EC-5 type, METER Group, Inc. USA) and suction probes (Watermark, Irrometer Inc., USA), all positioned near the central axis of the cells: at a 0.1 m depth from the interface of the Goldex layer in the Doyon tailings, and in the middle of the two 0.25 m-sublayers of the 0.5 m Goldex layer (i.e. at 0.15 m and 0.45 m depths from Goldex surface). Additional probes were placed in the middle of each layer covering the Goldex layer (HDS, CBL, and overburden). Data from water content sensors were continuously collected each hour by Em50 Data Loggers (METER Group, Inc. USA) and calibrated for each material. Instantaneous suction data were also collected bi-monthly via a Watermark soil moisture meter (Irrometer Inc., USA). To determine the water table position, slotted casing PVC pipes (7.6 cm diameter) with known depths were installed 0.2 m above the bottom of the cells through which the instantaneous water table depths were measured bi-monthly via a dipper-T water level meter (HERON instruments Inc., Ontario, Canada). Fig. 3 depicts the instrumentation setup of the study cells.

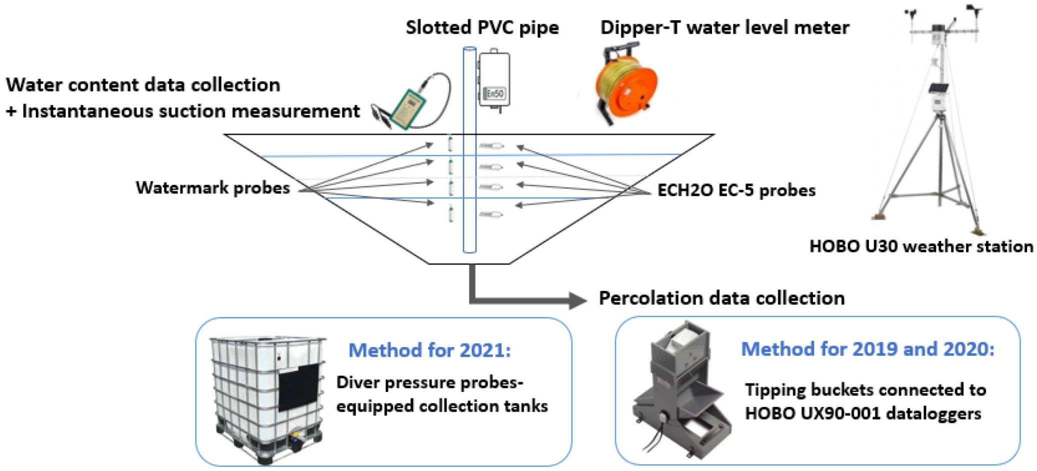

Fig. 3 Instrumentation plan for each experimental cell

Calibrated volumetric water contents (θ_i) were then converted into soil water storage in equivalent millimeters of rainfall (S_i) from the area of each cell (A_i) and the corresponding thickness of the materials (t_i). In fact, the θ_i values obtained were assumed to be the mean soil moisture content for the depth interval equal to the thickness. Considering the truncated pyramidal geometry of each layer, we have:

$$S_i\ (mm) = (\theta_i \times V_i)/A_i = \theta_i \times t_i \times (a_i^2 + a_i b_i + b_i^2)/3A_i \tag{2}$$

where:

V_i : volume of each layer

a_i: top side of the corresponding inverse truncated pyramid

b_i: bottom side of the corresponding inverse truncated pyramid

A_i: surface area of each cell

The total amount of water stored in the profile was therefore calculated as:

$$S = \sum_{i=1}^{n} S_i \tag{3}$$

Variations in water storage were calculated by integrating the increase or decrease in θ compared to an initial value (at the beginning of the period of interest).

$$\Delta S = S_f - S_i \tag{4}$$

Values of degree of saturation (S_r) could also be calculated for each layer using the volumetric water content and the mean porosity values measured for each cell.

$$S_{r_i} = \theta_i / n_i \quad (5)$$

Percolation (G) of the cells were drained out from the cells via PVC tubes of 5 cm diameter. In 2019 and 2020, these drain pipes were guided into tipping bucket arrangements (TBL/0.5L tipping bucket flow gauges, HyQuest Solutions, NSW, Australia) connected to HOBO UX90-001 data loggers. Flowrates were then measured with each pulse equal to 0.5L of percolation and water volumes were converted into equivalent mm of percolation as follows:

$$G_{cummulative}\ [\text{mm}] = \text{Number of pulses } \times 0.5 \times 10^{-3}\ [\text{m}^3]/A_i\ [\text{m}^2] \times 10^3 \quad (6)$$

In 2021, in order to verify the accuracy of the percolation data form the previous two years due to the reported inherent error of the tipping buckets (Schwamback et al. 2022), the drain pipes were connected into collecting tanks equipped with diver pressure probes and data loggers (van Essen, the Netherlands). A baro-diver was also installed beside the tanks so that at each time step, the difference between the baro and tank divers values was measured, converted into volumes using the dimensions of each tank, and then divided by the surface area of each lysimeter to obtain the equivalent mm of percolation. Table 3 lists the accuracies of all instruments used in the field setup.

Runoff and lateral drainage were considered minimal due to the flat topography of the area where lysimeters are installed and the flat soil layers. The amount of precipitation (*P*) was recorded using an onsite automated HOBO U30 weather station (Onset Computer Corporation, USA). Actual evapotranspiration (*ET*) was obtained by applying eq. 1 to each lysimeter:

$$ET = P - (G + \Delta S) \quad (7)$$

The exact periods of doing these measurements were 13 June-31 October 2019, 15 July-21 October 2020, and 23 June-27 September 2021. These were selected considering the freeze-free period in the cell materials and growing season to study the effect of active vegetation.

Table 3: Accuracy of the instruments installed in the lysimeter setup

Instrument	Accuracy
ECH2O EC-5	3%
Watermark suction probes	3%
TB/0.5L Tipping Bucket Flow Gauge	2-22% (depending on the flowrate)
Van Essen pressure diver probes	±0.5 cm H_2O

2.5. Regular field monitoring

All experimental cells were monitored for 2-4 years after revegetation (2019-2021). Aboveground development of the planted willows in lysimeters 3-5 were followed each year (on 2019-10-02, 2020-09-09, and 2021-09-16) by monitoring their survival, foliar surface, maximum height, and basal diameter. In lysimeter 2, plant cover was carefully observed in 2019 and 2020, and finally, on 5 October 2021, the total plant cover was analysed by the non-destructive point intercept method (Jonasson 1983). A measuring tape was diagonally fastened across the cell surface, then a rod was used to touch the surface every 10 cm along the measuring tape while noting the occurrence of each vegetation species at the contact point (Jonasson 1983).

The foliar surface in willow-planted cells was obtained by harvesting the entire leaves from three randomly selected plants on each cell, measuring the total surface of leaves for each plant via a LI-3100C leaf area meter (LI-COR Biosciences, Lincoln, NE, USA), and then calculating the mean value for each cell.

At the end of the study in Fall 2021, to analyze the depth of roots development at each vegetated cell, a number of observation trenches (4 per cell) were dug by means of a mechanical shovel. For this purpose, in lysimeter 2, trenches were cut parallel to the four sides, whereas in cells with willows, 4 individual trees were randomly selected to locate the toes of the trenches. After cutting the trenches, a metal grid of 5 cm×5 cm mesh (with total of 18×12 squares) was placed against the trenches and the root occurrence in each material layer was measured by dividing the number of root-containing squares by the total number of squares in the grid in that layer (108 squares in each the overburden and the Goldex layers) (Guittonny-Larchevêque and Lortie 2017). Also, the maximum rooting depth was deduced based on the root development in the four trenches of each cell.

3. Results

3.1. Hydrogeological behavior

Water balance was calculated using Eq. 1 for the three growing seasons. Fig. 4 shows the relative contribution of the water balance components during the growing seasons in the three measurement years. The main water budget component during all measurement years for all cell configurations was evapotranspiration, representing more than 80% of the cumulative rainfall. It can be observed from the pie charts that the water budget trends in each of the cells were roughly similar in all the three years, despite some small variations, meaning that the 2-4-year-old vegetation within our 3-year study timeframe had limited effect on the overall water balance of the cover system. There were variations for percolation and water storage components between cells, however. The relative storage was higher in cells 2 and 3 with basic designs (Goldex layer + overburden) and in presence of vegetation; whereas it decreased when an additional layer was implemented over the functional layer, while instead, the percolation tended to increase.

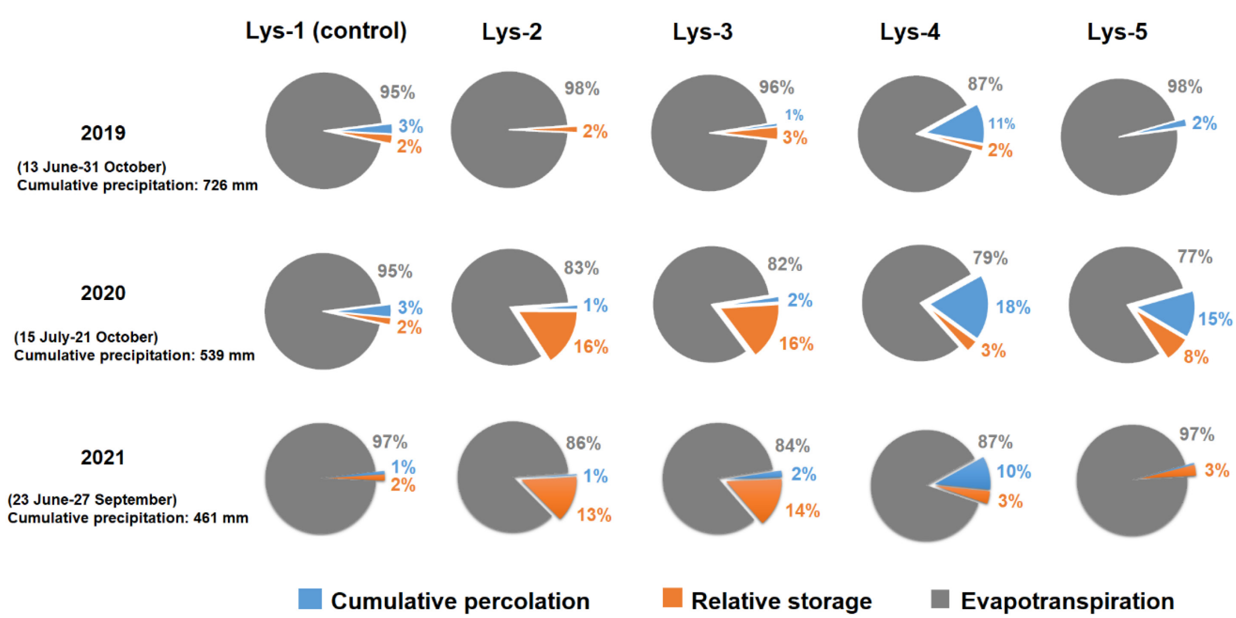

Fig. 4 Representation of the relative contribution of water balance components for the three measurement years

The variations of the degree of saturation in the cover layers with respect to daily precipitation for the different designs and the 2021 measurement year are illustrated in Figs. 5 and 6 (data for other years, 2019 and 2020, are shown in Fig. S1 of Online Resource 1). As seen for the control cell, generally, reactive Doyon tailings remained sufficiently water saturated ($S_r > 85\%$) during the three growing seasons to reduce oxygen diffusion, despite some fluctuations in 2020 summer (Fig. S1 of Online Resource 1). Adding the herbaceous vegetation in cell 2 caused significant desaturation in overburden and the functional layer of the cover (Goldex tailings), but the Doyon tailings remained highly saturated. As seen in cell 3, in presence of willow vegetation, the desaturation occurred also in the reactive tailings down to S_r of around 0.4, which corresponds to a lower water table level than what is needed to maintain the EWT efficiency and could have allowed oxygen ingress in the reactive tailings. Desaturation of the functional layer was also observed for cell 5 in which an additional HDS sludge layer covered the Goldex layer, while in cell 4 with additional capillary break layer, the reactive tailings generally remained around 80% water saturated.

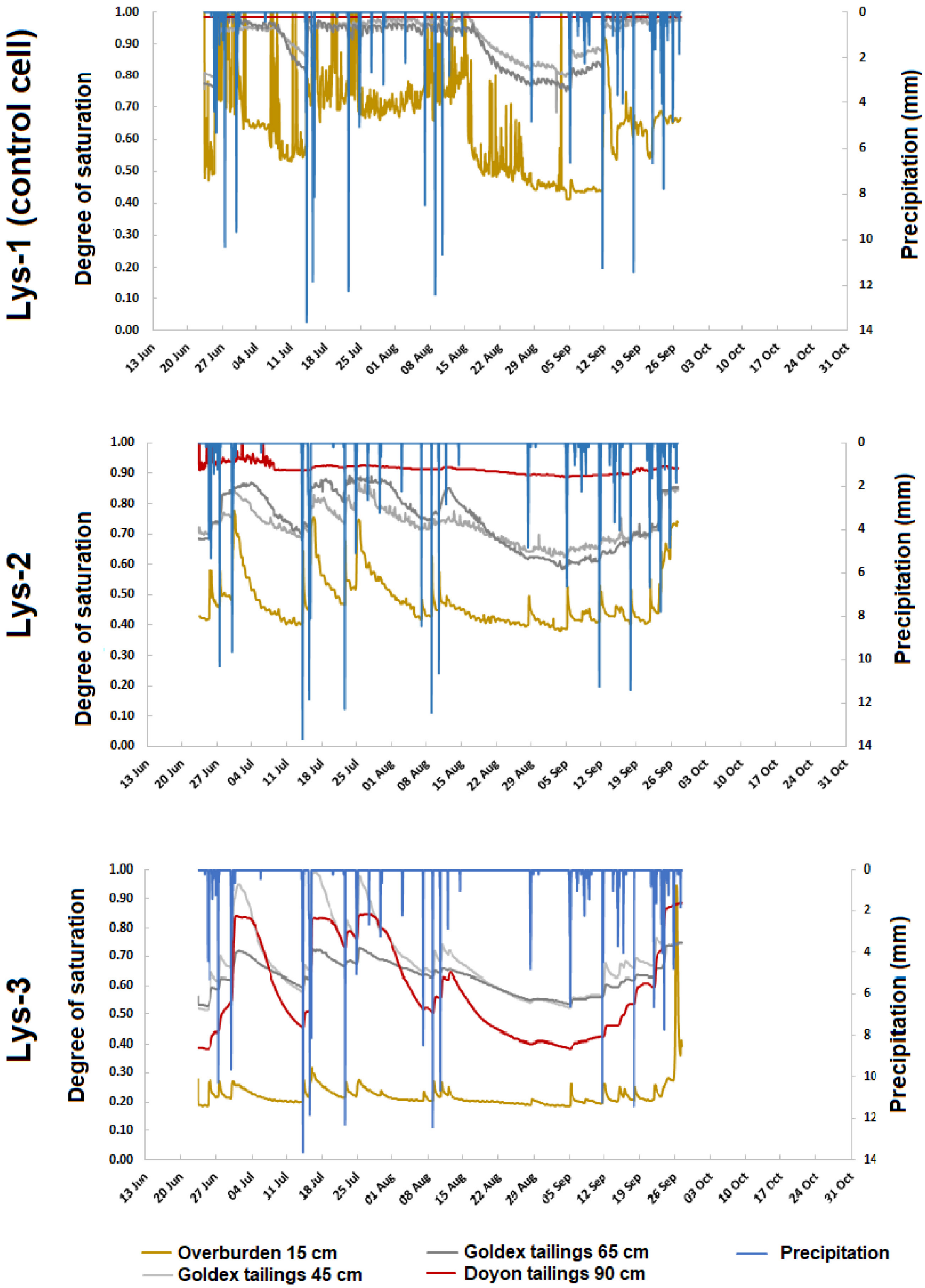

Fig. 5 Variations of the degree of saturation in each material layer for cells 1-3 in 2021

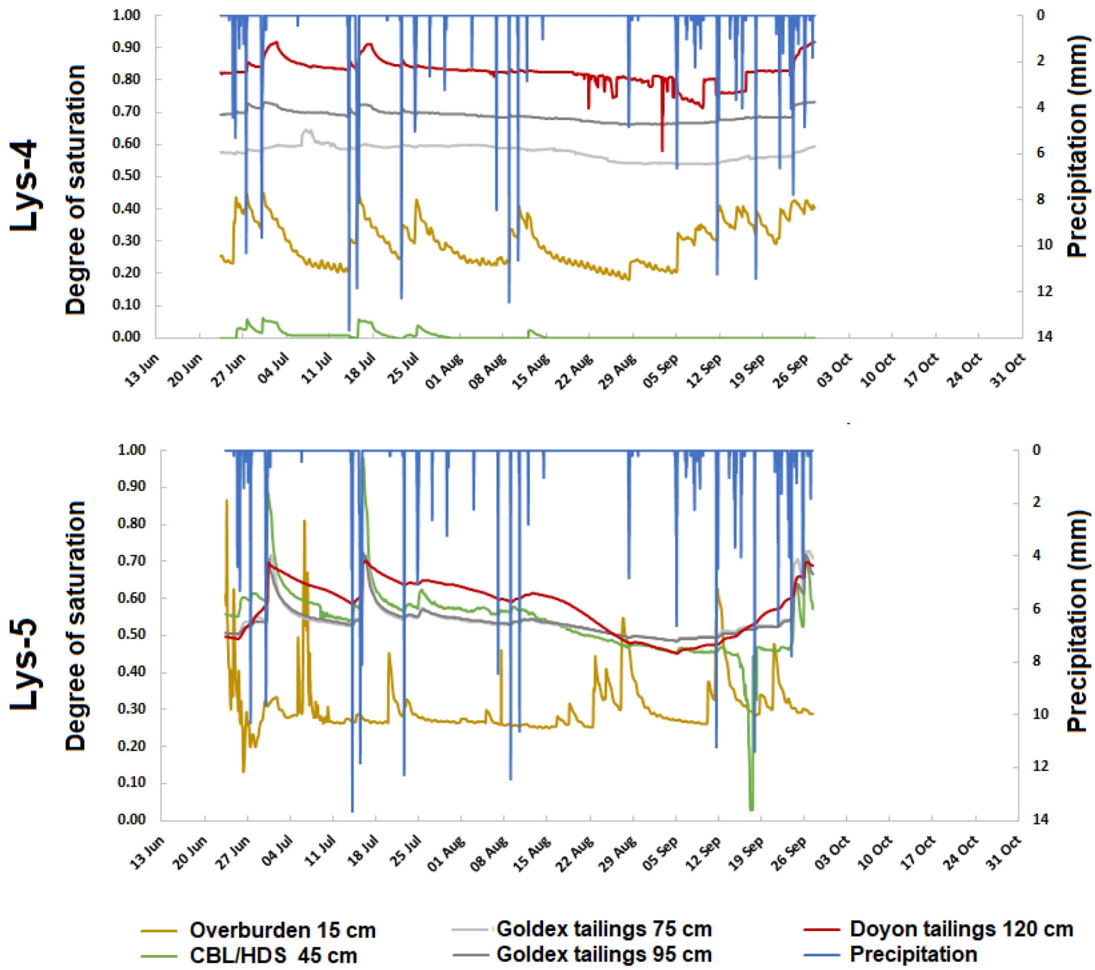

Fig. 6 Variations of the degree of saturation in each material layer for cells 4 and 5 in 2021

Fig. 7 shows the variations of water table position in the cells 1-3. Based on the data, a successful cover with elevated water table was achieved most of the time in the control cell (Lys-1) with respect to the degree of saturation in the reactive Doyon tailings (mean S_r >95%). In 2020, the water table remained in the Goldex layer; in 2019 and 2021 summers, however, it was lower (in the Doyon tailings) even though the reactive tailings remained sufficiently saturated for the whole period (Fig. 5). A similar trend as in the control cell in the summer season could be seen for Lys-2 and Lys-3 for all three years, despite the presence of vegetation. For cells 4 and 5 with the additional layers over the Goldex layer, the water level was generally at the base of the cell (data not shown) with the exceptions of Lys-4 in the late September 2020 (possibly due to a delayed recharge followed by the extreme rain event on 16 September 2020). Despite similar water table level for these two cells, their variations for the degree of saturation were different (Fig. 6); This could be due to the level being close to the AEV (2 m vs 1.8 m) and in the steep portion of the water retention curve where a small change in suction induces a large variation in water content.

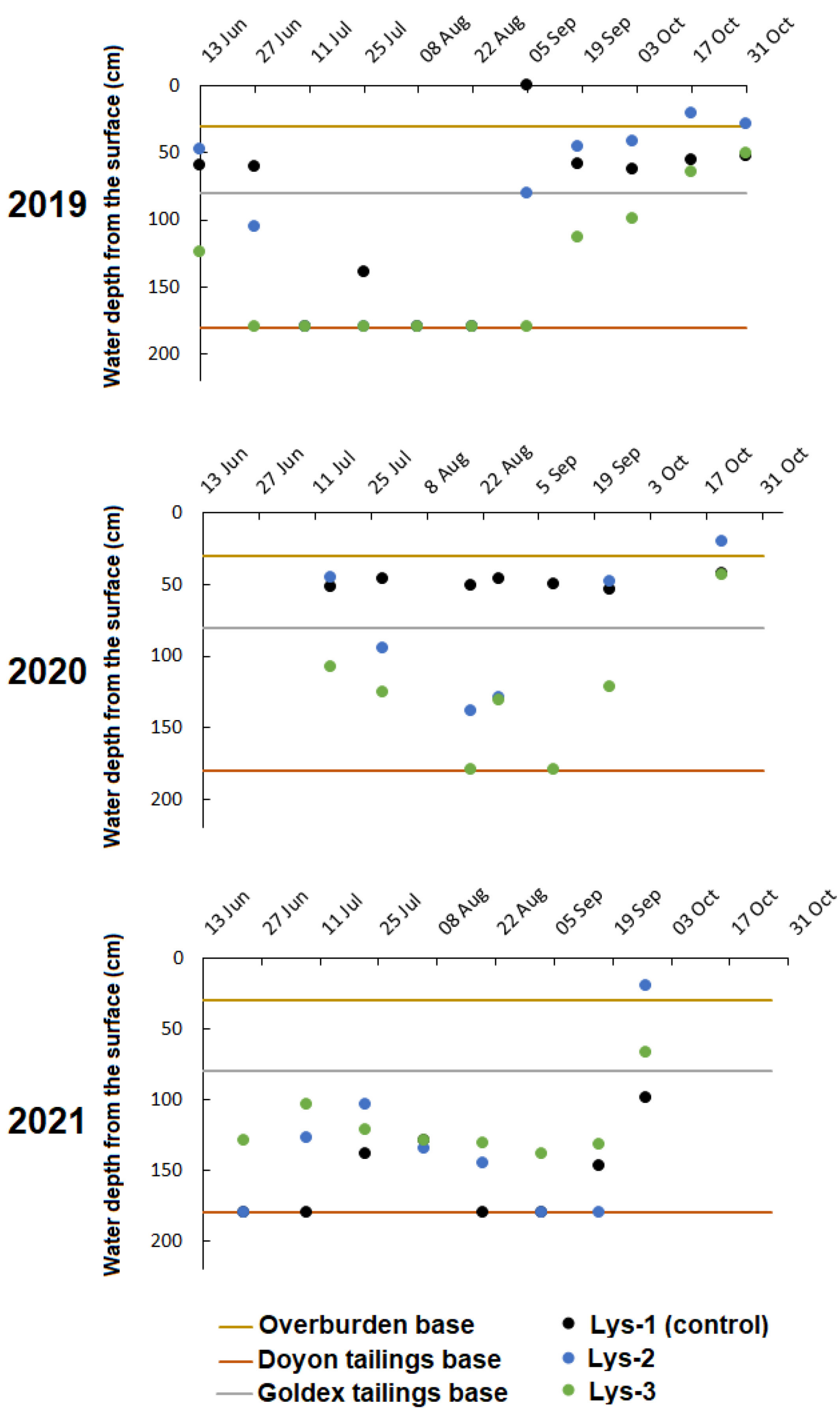

Fig. 7 Variations of the water table position for the cells 1-3

Dynamics of cumulative percolation are shown in Fig. 8. Although the trends of evapotranspiration were not so much dissimilar for different cells (data not shown), the cumulative percolations reflected a particular variability between cells. For the control cell, percolation was relatively low but still higher than cells 2 and 3 (the two vegetated cells with Goldex - overburden design), except for 2021, in which the amount of percolated water was higher for cell 3. Cell 4 had the highest cumulative percolation during all measurement periods. In this cell, the greatest percolation increase was generally observed in mid-September (there were extreme rain events around this date each year). In cell 5, the percolation varied among years. In 2019, in cell 5, the percolation increased early in the monitoring season with further negligible variations for the whole growing season. This could be because of the repeated large rain events occurred in June 2019 (Fig. 8). In 2020, the percolation had a progressive increase in this cell, however, it was very limited in 2021.

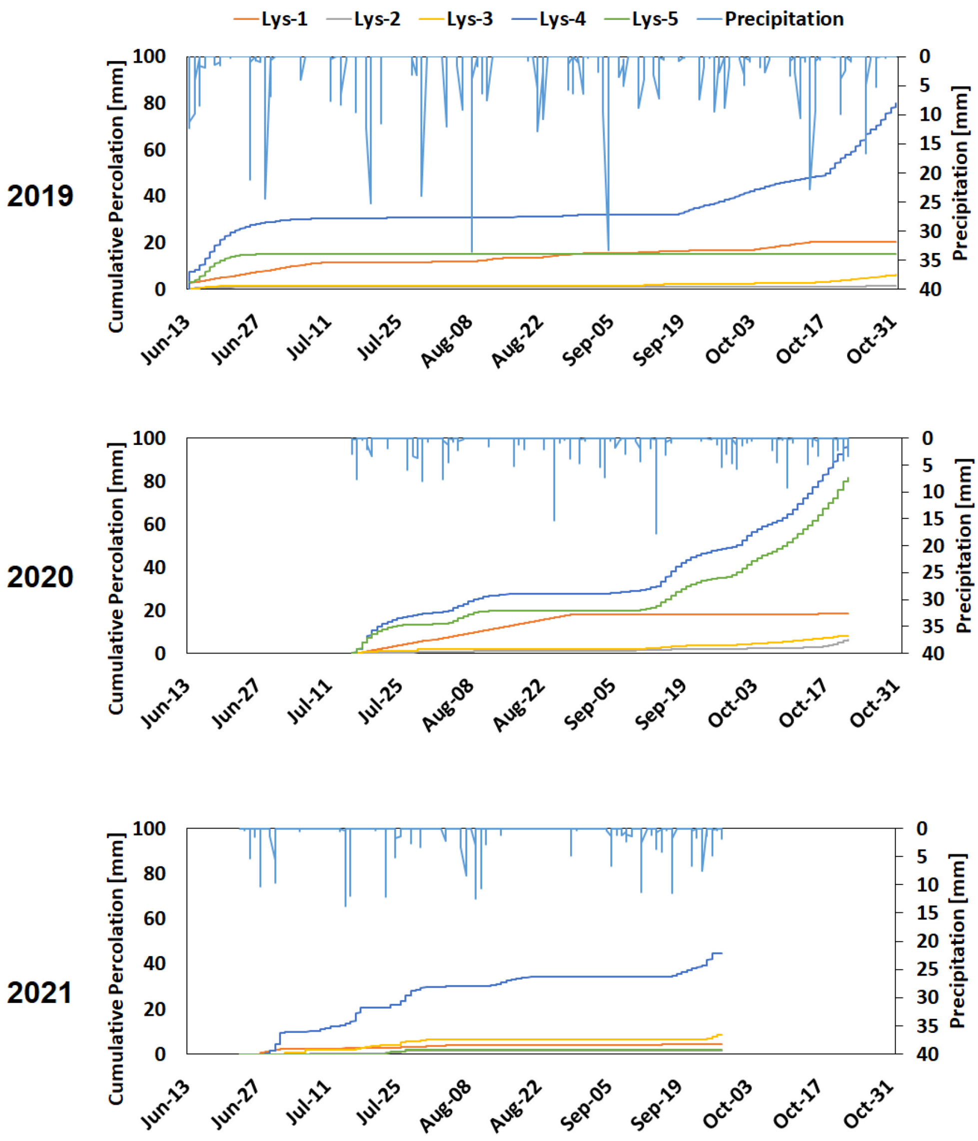

Fig. 8 Variations of cumulative percolation for the 5 cell configurations

3.2. Above-ground and below-ground vegetation development

The results of late 2021 growing season showed that the surface of cell 2 was approximately 73% plant-covered. Results of the observation trenches illustrated in Fig. 10 also showed that the roots in the cell with herbaceous vegetation were too shallow to reach the Goldex layer.

Fig. 9 illustrates the growth indicators for the willows planted in lysimeters 3-5. As can be seen, willows in cell 5 had the highest development of aerial parts. Willow roots in cell 3 reached the top 20 cm of the Goldex layer (Fig. 10) while in cells 4 and 5, it remained limited to the additional layers on top of the Goldex tailings.

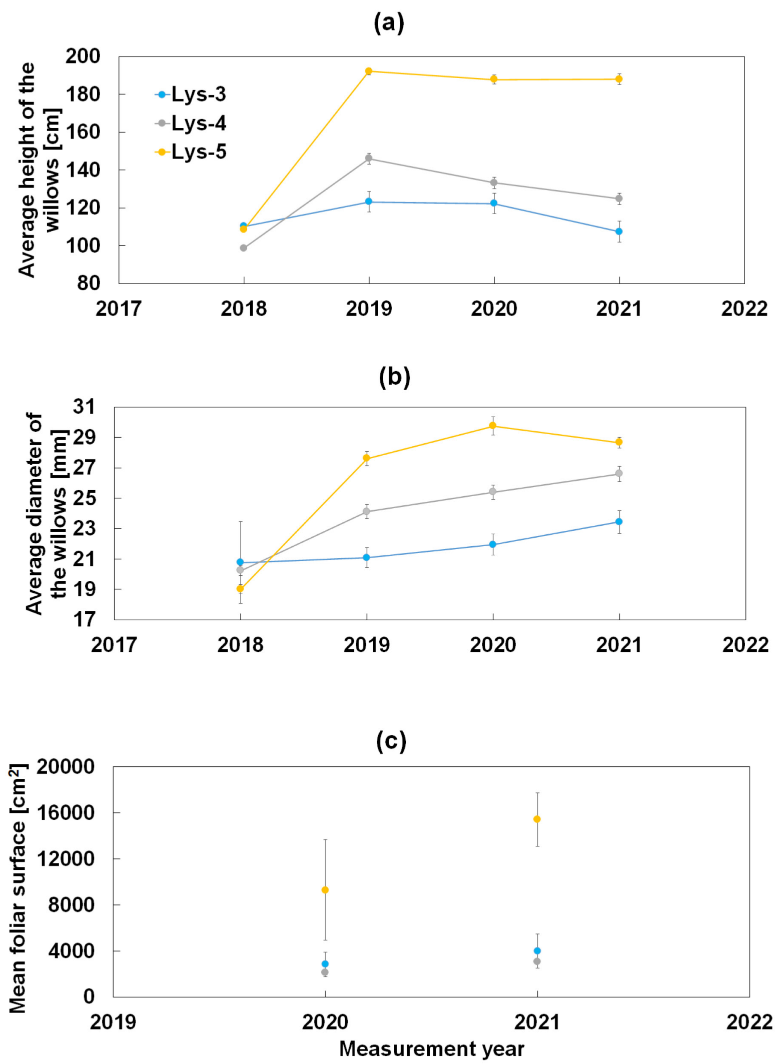

Fig. 9 Variations of average a) maximum heights (n=61, 98, and 100 for cell 3-5, respectively), b) basal diameters (n=61, 98, and 100 for cell 3-5, respectively), and c) foliar surface (n=3) for willows planted in lysimeters 3-5

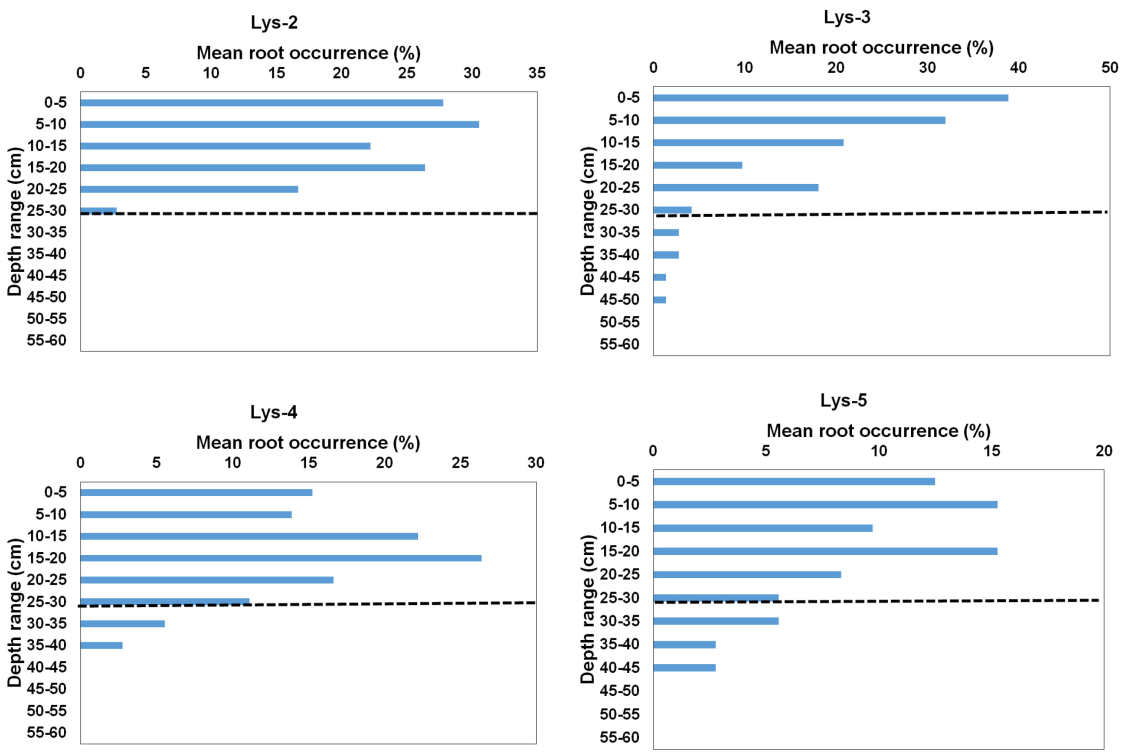

Fig. 10 Root profiles in vegetated cells based on observation trenches, values are means (n=4), the dashed lines represent the interface between the overburden and the lower layer

4. Discussion

4.1. Effect of vegetation on the relative share of water balance components

Contrary to hypothesis 1, as the global season pie charts showed (Fig.4), the evapotranspiration similarly remained the dominant water balance component for all cells despite the addition of vegetation. The reason for higher share of water storage in 2020 and 2021 is the difference in the corresponding water balance measurement period. The relative storage measurement in 2019 was started on June 13, which was earlier than 2020 and 2021, therefore the water storage in the system had been generally higher in 2019 due to the snow thaw process.

Moreover, percolation of cell 5 has been remarkably lower in 2021, which can be explained by the increased leaf area of the 4-years-old willows (15425 cm^2) that could have facilitated a higher evapotranspiration contribution. Additionally, the extremely low hydraulic conductivity in HDS layer which is induced by its physical characteristics (Van Riper Consulting et al. 2004) and also actively growing roots might have prevented deep percolation of precipitation water (Ng et al. 2019b).

Generally, based on the observations in the current study, the vertical development of the willow roots in the three year-period was lower than the amount witnessed in the literature (Cunniff et al. 2015; Guittonny-Larchevêque and Lortie 2017), which could be explained by several factors. In both studies, the willows were applied on a poor quality material (mine waste rocks in the 2017 study vs. overburden, sludge, and desulfurized tailings in the current study) with lack of organic matter, deficiency of nutrients/soil organisms, and possible elevated electrical conductivity in water which could severely restrict rooting (Handel et al. 1997; Sheoran et al. 2010). But waste rocks have lower water holding capacity than the materials used in the current study, and lack of moisture content in the plant's immediate substrate could have encouraged its roots to develop deeper in search for available water (Fontana et al. 2020). In our case, since there is nutrients deficiency, the plants were expected to develop extensive fine roots to explore deeper in the host material to mitigate the existing stress (Guittonny-Larchevêque and Lortie 2017; Świątek et al. 2019; Świątek and Pietrzykowski 2021), however, the presence of highly water-saturated layers may have acted as a growth barrier (Figs. 5 and 6, the Goldex layer). In other words, reduction in available oxygen concentration around the willow root's elongation zone could have diminished the root growth pressure (Visser et al. 2003).

4.2. Effect of using different vegetation type for the revegetation cover

Comparing data for cell 2 and 3, where herbaceous seeding and woody plants were applied, the percolation was evidently higher for cell 3 in 2021, inferring that less water percolated in a herbaceous cover in that year (Fig.4). In cell 2, the greater shading of soil surface via herbaceous vegetation compared to the willows might have led to higher water storage. This could also be observed in the higher degree of saturation in the overburden layer in cell 2 (Fig. 5).The water loss by evapotranspiration of willows and herbaceous plants might seem similar but the difference comes from the fact that evaporation at the soil surface is less restricted by willows (lower shading and being more distant from the soil surface) while denser and closer-to-the-soil cover of the herbaceous plants restricted evaporation (Forsling 1931). Moreover, the total leaf area of the willows on cell 3 is lower than what is expected from other studies (Tharakan et al., 2005), and this might explain why the willows have a lower-than-expected contribution to evapotranspiration in this cell. Accordingly to the second hypothesis, results of the present study were consistent with previous research showing that we could expect a higher soil moisture content in herbaceous covered soils compared to woody vegetation (Özkan and Gökbulak 2017). Soil moisture decreased in the deeper soil layer under willow plants due to water uptake while moisture content remained stable in the subsoil of herbaceous plant because of shallower root distribution (Fig. 10).

The water table in cell 2 was generally higher than that of cell 3 for all three measurement years. The effect could be explained by the deeper roots and the larger zone of influence for willows on root water uptake than the grass species (Ng et al. 2019a). Root observations in trenches (Fig. 10) indeed confirmed that the maximum rooting depth of the herbaceous vegetation in cell 2 was too shallow to reach the Goldex layer (maximum 30 cm, i.e. limited to the overburden layer).This was also seen in previous studies (Özkan and Gökbulak 2017). Generally, based on the results, the herbaceous vegetation had less impacts over the cover's performance as the degree of saturation in the Doyon tailings did not fall below 86% during the three measurement periods, whereas in presence of the willows, it reached as low as 33% (Lys-3, year 2019).

4.3. Effect of using an additional layer between the overburden and the functional layer (Goldex tailings)

Despite their similar thicknesses of materials, differing effects between cells 4 and 5 could be justified based on the texture of the additional layer (fine HDS layer vs. coarse CBL). In presence of coarser CBL between the overburden and the Goldex tailings layers, capillary break effects were anticipated against both infiltration and evaporation. Moreover, adding a fine-grained HDS over the Goldex layer was expected to better support the water storage in the cell. Based on the observations, however, percolation has been generally higher in presence of an additional layer (with the exception of lysimeter 5 in 2021) and the water level positions for both cells were lower than that of lysimeter 3 (at the bottom of the cells or nearly during the three growing seasons). In lysimeter 4, the capillary barrier effects in both downward and upward directions were effective based on the moisture content data (Fig. 5) and caused a discontinuity between the overburden and the Goldex (Goldex sublayers non-reactive to precipitation variations and relatively invariable in degree of saturation during the measurement periods). Nevertheless, in contrary to what was expected in hypothesis 3, this effect was not sufficient to support a higher water storage and water table level in this cell. The dynamic percolation has been relatively high in cell 4 for all measurement years (at least 3 times greater than that of cell 3). Thus, it seems that in lack of capillary continuity with the evaporative surface, water stored in the Doyon tailings flowed by gravity to the bottom of the cell rather than staying in the materials. In cell 5, since the vegetation was smaller in 2019, water loss was rather via evaporation; whereas in 2020, it was mostly shifted into deeper layers in form of percolation; then in 2021, when willows had better aerial shape, the water was largely lost through evapotranspiration: the behaviour of this cell was less predictable among years.

Moreover, in cells 4 and 5, the roots did not colonize the Goldex layer, whereas in cell 3, their occurrence was observed in top 20 cm of the Goldex layer (Fig. 10), potentially able to pump up the water from deeper horizons (hydraulic lift, (Mendel et al. 2002), especially in warmer parts of the measurement period (Fig. 5, Lys-3). Root observation trenches revealed that using the additional layers over the Goldex layer could successfully limit the penetration depth of the willow roots towards the functional (Goldex) layer. Yet, the results showed that low water level in these cells can impact the performance of the cover to limit oxygen diffusion and there is the need for some additional measures in order to keep the water table sufficiently elevated in such configurations. If the design of the reclaimed tailings facility implies impervious dikes and/or foundation or any other proper way to conserve percolation water in the system, the water table should remain high and support the cover's performance.

It is worth mentioning that the higher mean root occurrence observed in the fine-grained HDS layer (Fig. 10) could be justified by its unique physical and chemical characteristics including the ultra-fine particle size, alkaline pH and traces of nutrient contents. Since some organic flocculants are used in the HDS process (Dinu et al. 2014; Demers et al. 2015a), some residual organic components might end up in the final sludge (Aubé 1999) which could favor root development in this material. In Doyon-Westwood HDS plant, the *Magnafloc* flocculant with an anionic polyacrylamide chemical nature ($-CH_2CHCONH_2^-$) is used which could cause traces of N in the final sludge.

According to the dynamic data for cells 4 and 5 (Fig.8), percolation was lower in the cell with the fine-textured HDS layer and there was a bigger share for evapotranspiration. As can be seen in Fig. 9, the above ground development of the willows in lysimeters 3-5 in terms of both height and basal diameter followed the order Lys-5 > Lys-4 > Lys-3. This could somehow explain the higher evapotranspiration in cell 5 compared to lysimeter 3 and 4.

5. Conclusions

Based on the three-year monitoring study over the five instrumented cells, the findings could be summarized as follows:

- Vegetation influenced the contributions of percolation and water storage in the water balance of the cells. The main water balance component in both presence and absence of vegetation was the evapotranspiration.
- As hypothesised, herbaceous vegetation developed shallower roots than the willows, had lower evaporation rather than greater transpiration from the willows, supported a generally higher water table position and higher saturated Doyon tailings during all monitored growing seasons. The willows' development was probably lower than in more favorable contexts.
- Generally, an additional layer caused higher percolation in the cells. In contrary to what was expected, the addition of a capillary break layer could not maximize the water storage as the results showed that a significant fraction of the precipitated water percolated out from Lys-4. So, with this design implying a CBL above the functional layer, it would be much important to conserve deep infiltrated water in the system with semi-permeable dikes, impervious foundation, etc. in order that this water feeds the water table.
- Moreover, the hypothesized high degree of saturation in tailings layers in cell 5 was not present. The degree of saturation in the Doyon tailings was below 85%, which corresponds to a too deep water table level and indicates possible oxygen ingress in the reactive tailings. In 2021, since the planted vegetation had better development on this configuration with HDS sludge, the stored water could have been pumped up by actively growing roots and largely evapotranspirated through the leaves.
- Based on this study, the best option for vegetated layers above this kind of oxygen barrier cover system was found to be the herbaceous plants. If we would like to consider woody plants, a capillary break layer and some additional arrangements such as dikes or impervious foundation should be implemented to conserve water in the system, so that the water table is kept high and supports the efficiency of the cover. It should also be noted that the current work was performed using young vegetation and model plants tolerant to flooded soils with maximum anticipated effects on the water balance in a short-term study period. The results may change with longer time frames, from site to site, with a coarse-grained functional layer combined to EWT, and for other species. However, our results give an idea of how the vegetation reacts to this type of reclamation cover in a humid climate,

and help for a better vegetation selection to ensure its long-term performance. Future investigations are still needed on the effects of mixed vegetation types, efficiency of the above-mentioned water conserving arrangements such as dikes and impervious foundations in the system, root colonization effects on hydrogeological properties of the construction materials, and prediction of the long-term influences of the vegetation on the water balance.

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