THE DRAINAGE OF PEATLANDS:
impacts and rewetting techniques

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PREFACE

The goal of this literature review is to provide a permanent tool for understanding how drainage impacts peatlands and what techniques can counteract these effects. Literature on the subject of drainage is vast and over 166 scientific publications were reviewed for this document. These original publications should be consulted, especially for technical details on the construction of dams.

In this review special attention was paid to delimiting the direct impacts of drainage and rewetting. Many other human interventions can have an impact on peatlands, for example adding fertilizer, agriculture, and restoration after peat extraction. The results presented in this document therefore reflect the direct and indirect impacts of drainage.

Because each peatland is unique due to its geographical position, composition, hydrology, topography, age, as well as the type and degree of degradation, the repercussions of drainage vary from one peatland to the next. However, all affected peatlands are disturbed to some extent by drainage. In Quebec, especially in the south of the province where pristine peatlands are becoming rare, it is important to measure the human impacts on peatlands as these peatlands provide many important ecological functions.

THE IMPORTANCE OF PEATLANDS

Because the ecosystem functions of peatlands are becoming increasingly valued at the global level, interest in conserving and restoring peatlands is growing.

Peatlands occupy 4 million km^2 of the Earth's surface. Canada alone contains 28% of these portions (Lappalainen, 1996). Peatlands play an important role in many biogeochemical cycles, notably the carbon cycle, which regulates the Earth's climate. Peatlands are also well known for their ability to filter water when they are located at low portions of catchment areas and can form important sources of fresh water in certain geomorphic locations (Joosten and Clarke, 2002). Additionally, peatlands offer a unique habitat for diverse species of flora and fauna, which have adapted to this acidic, low-oxygen environment. Peatlands increase regional biodiversity as Calmé et al. (2002) showed using the example of birds.

In peatlands, because vegetation production is greater than decomposition, carbon is accumulated in the form of peat. This environment is known as a carbon sink. The weak decomposition rates is a result of several factors: the acidification of the environment by *Sphagnum*, the limitation of oxygen diffusion in deeper peat layers (Clymo, 1992), as well as low temperatures which create a minimal microbial activity in deeper peat layers (Chapman et Thurlow, 1998). Peatlands store more than one third of the planet's carbon in these organic soils (Gorham, 1991).

THE PRINCIPAL TYPES OF PEATLANDS IN NORTH AMERICA

Two main types of peatlands are prevalent in North America: ombrotrophic and minerotrophic peatlands. The ombrotrophic peatlands, also called bogs, are the peatlands which are dominated by *Sphagnum*. Since these peatlands are typically raised above the surrounding landscape, their only nutrient input is from precipitation and atmospheric deposition. This is why these peatlands are poor in nutrients and minerals (Payette, 2001; Figure 1).

The minerotrophic peatlands, also called fens, are located in the lowest part of a catchment basin and receive, along with atmospheric precipitation, groundwater. These peatlands are richer in minerals (Ca, Mg, Na, K) and have a pH more neutral than bogs. They are principally dominated by brown mosses and graminoids (Payette, 2001; Figure 2).


PHOTO : Josée Landry

Figure 1. Ombrotrophic peatland (Miscou, New Brunswick).


PHOTO : Vicky Bérubé

Figure 2. Minerotrophic peatland.

THE DIPLOTHELMIC NATURE OF PEATLANDS

By definition, when a peatland contains two distinctive layers of soil, it is defined as a diplothelmic peatland. The position of the water table enables us to define the two layers called the acrotelm and catotelm (Ingram, 1978).

In the upper layer, the acrotelm, the water level fluctuates. The porosity of this layer allows vast amounts of water to be stored. It is composed of live and slightly decomposed vegetation and its depth can vary from 5 to 50 cm (Price et al., 2003). Production and decomposition rates are highest and the microbial populations are very active. The production of biomass helps keep the water level close to the surface and limits fluctuation (Price, 1996), a phenomenon which can be easily observed when comparing a milled peatland without vegetation cover with a pristine peatland. In this layer the hydraulic conductivity, a parameter which governs the movement of water, is highest (to the order of 1 to 2.5 cm/s) while in the catotelm there is very little water movement (from 10^{-5} to 10^{-4} cm/s). The less decomposed the peat has larger pores and, therefore, the water movement is generally more horizontal (Boelter, 1965).

The notion of an acrotelm and catotelm was developed for *Sphagnum*-dominated peatlands (bogs and poor fens). For fens, especially graminoid-dominated fens, this diplothelmic soil formation is less apparent. Due to the layers of leaves created by the graminoids each season, the fens surface can swell when there is an abundance of water and shrink when there is less water. This capacity allows the water level to stay relatively stable and close to the surface (Ingram, 1983).

The catotelm is the layer located below the acrotelm. Peat accumulation occurs in this layer as the decomposition rate here is very low. Accumulation rates vary from 0.5 to 1 mm per year. The low decomposition rate is due to cold and anaerobic conditions which result in low microbial activity. The microbes in the catotelm consist mainly of methanobacteria, methane-producing bacteria which are abundant in wet environments. There is little to no water level fluctuation in this layer as it is constantly saturated with water. Because this layer contains older, more compact peat (Rydin et Jeglum, 2006), the hydraulic conductivity is much lower (Boelter, 1965), meaning there is little water movement.

The diplothelmic nature of peatlands regulates the water retention capacity and water movement within the environment. This only applies to pristine peatlands, because as soon as there is human intervention, i.e. drainage, the acrotelm is lost. A disturbed peatland only has one layer (the catotelm) and becomes a haplothelmic peatland (Ingram, 1978). All changes to the balance between the acrotelm and catotelm inevitably disturb the hydrology of the peatland, thereby impacting the flora and fauna which colonize the surface (Cagampan and Waddington, 2008).

WHY ARE PEATLANDS DRAINED?

Peatlands are drained for several reasons: to stabilize the substrate for building or road construction, to increase the soil productivity for agriculture or forestry (thereby eliminating anaerobic conditions) or for increasing the capacity of soil to support heavy machinery for industrial activities (peat and petroleum extraction). Figure 3 presents an example of a drainage ditch in a peatland.

Urban and industrial developments are often the reason for draining peatlands. In Canada it has been estimated that between 80 to 98 % of the wetlands located around large urban centers have been lost. In a 40 km radius from urban centers less than 0.2 % of wetlands remain (Federal, Provincial and Territorial Governments of Canada, 2010)

Canada is a global leader in the production of horticultural peat (Daigle and Gautreau-Daigle, 2001). To date, the area of peatland which has been drained in Canada for peat extraction is circa 24,000 ha (Environment Canada, 2010). In Québec approximately 6,000 ha have been drained for the extraction of horticultural peat. Approximately 70,000 ha of peatlands in Québec have been drained for forestry. Peatlands are also drained to transform wetlands into land suitable for agriculture. In Québec, circa 11,000 ha of peatlands are used for agriculture (Poulin et al., 2004).

PHOTO : Gabriel Caisse

Figure 3. Example of a drainage ditch in a peatland.

PHOTO : Line Rochefort

THE IMPACTS OF DRAINAGE

THE DISTANCE AFFECTED BY A DRAINAGE SYSTEM IN A PEATLAND

The efficiency of a drainage system in a peatland is a function of the slope of the peatland (Stewart and Lance, 1991), the age of the drainage ditches, their placement, direction and depth (Braekke, 1983), as well as the distance between ditches (Ahti, 1980; Belleau et al., 1992; Holden et al., 2004). The soil structure and the peat's hydraulic conductivity govern the water's horizontal and vertical movement within the peatland and are also important elements (Boelter, 1972; Armstrong, 2000). The distance from the drainage which affects the peatland is difficult to define, as it varies greatly from one site to another. As a general rule the dewatering (Rothwell et al., 1996) and increased flow (meaning a loss of water; Ahti 1980) of a drained peatland are inversely proportional to the space between the ditches. The influence that a drainage system will have is also a function of the type of impact anticipated. The distance of influence will be generally greater on the vegetation and the upper peat layer (acrotelm) than the lower layer (catotelm) where there is a subtle lowering of the water level.

THE DISTANCE OF DRAINAGE IMPACT ON THE ACROTELM

Depending on the composition and the structure of the peat, the drainage ditches can impact great distances from drainage installations. A study by Belleau et al. (1992) showed that the frequency at which the water level was found to be below the root zone (20 cm) was 100% at 10 m from the ditch, 70% at 20 m from the ditch and 40% at 30 m from the ditch, compared with 23% of the time in part of the peatland which had not been drained. Another study by Poulin et al. (1999) showed that drainage can impact vegetation up to 60 m from drainage ditches in peatlands of Québec and New Brunswick. For peatlands which are situated on top of sand deposits, drainage impacts have been observed up to 150-200 m from drainage ditches (Trettin et al., 1991).

THE DISTANCE OF DRAINAGE IMPACT ON THE CATOTELM

The impact on the catotelm is equally variable according to the peatland and the characteristics of the drainage ditches. Boelter (1972) studied two peatlands in Minnesota and found that the degree of decomposition of the residual peat greatly influences the drainage impact distance. A drainage ditch that was 2 m deep and 2.5 m wide on a peatland with a thick layer of slightly decomposed peat influenced the water level up to 50 m from the ditch. While a on a peatland with highly decomposed peat which was more compact and had a lower hydraulic conductivity, a smaller drainage ditch (1.5 m deep and 2 m wide) influenced the water level only within 5 m of the ditch.

Prévost et al. (1997) found that draining a forested peatland near Rivière-du-Loup lowered the water level up to 15 m from the drainage ditches. In another forested peatland in Lotbinière County, Belleau et al. (1992) found that the water level was affected more than 30 m from the drainage ditches. At this distance, the water level was on average 22 cm lower than a peatland which was not drained. Roy et al. (2000) observed that the water level was affected by drainage at more than 60 m from ditches in a forested peatland in Québec.

As shown, the distance affect by drainage can vary greatly. Table 1 provides an overview of the distances affected by drainage for the actotelm and catotelm as well as the literature source.

Table 1. Distance affected by drainage for the acrotelm and catotelm in drained peatlands.

Effect on acrotelm	Effect on catotelm	Reference
	10 m	Van der Schaaf (1999)
	15 m	Prévost et al. (1997)
	25 m	Landry and Marcoux (2011)
	5 to 50 m	Boelter (1972)
	60 m	Roy et al. (2000)
	40 m	Marcotte et al. (2008)
30 to 50 m		Rothwell et al. (1996)
30 m		Belleau et al. (1992)
60 m		Poulin et al. (1999)
110 to 135 m		St-Arnaud et al. (2009)
150 to 200 m		Trettin et al. (1991)

IMPACT OF DRAINAGE ON WATER CONTENT

Although distances affected by drainage vary greatly, one of the first observable impacts is a lowering of the water table after the diplothelmic peatland structure has been disturbed (Braekke, 1983; Lieffers and Rothwell, 1987; Stewart and Lance, 1991; Roulet and Moore, 1995; Rothwell et al., 1996; Silins and Rothwell, 1999; Van Seters and Price, 2002; Price 2003; Holden et al., 2006). There are greater fluctuations in the water level (Van Seters and Price, 2002; Holden et al., 2006). The older the drainage installations are, the greater the water level fluctuates (Strack et al., 2008). Hence, during periods of drought, the water level drops lower in the peat profile. During periods of heavy rain, the water level rises more quickly. In a drained peatland in the Bas-Saint-Laurent of Québec, the water level fluctuations were 67% greater than those of a natural peatland (Van Seters and Price, 2002). Figure 4, taken from Price et al. (2003), illustrates the differences in water table height and fluctuations among natural, drained and rewetted areas in a large peatland near Lac Saint-Jean, Québec.

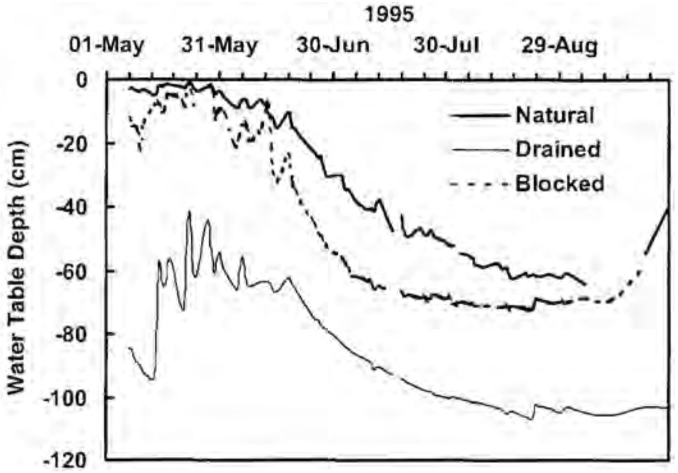

Figure 4. The average water table in a natural (thick line), drained (thin line) and rewetted (dotted line) parts of a large peatland near Lac Saint-Jean (Québec). Figure from Price et al. (2003).

The lowering of the water level and a series of other mechanisms related to drainage entail considerable water loss. In the upper peat layer (first 10 cm), the water content can decrease by 20 to 29%, depending on the distance to the drainage ditch (Prévost et al., 1997). For example, 10 m from the drainage ditch, the water content in the upper layer of the peat can exceed 73% before drainage and 44% after drainage.

In a drained peatland, the drier conditions in the upper peat layers change the hydraulic structure by, among others, decreasing the size of the pores. These changes can favour capillary movement of the deep waters towards the surface (Hobbs, 1986; Price et Whitehead, 2001), which entail a substantial loss of water due to evaporation. These drier conditions favour the proliferation of trees which in time can exacerbate the drying of the peatland (Van Seters and Price, 2001; Hökkä et al., 2008; Fay and Lavoie, 2009). The colonisation of trees on drained peatlands can increase water losses due to evapotranspiration by more than 25% and water interception could increase by 32% (Van Seters and Price, 2001).

Water circulation within a drained peatland is greatly modified, which influences its ability to retain water and the quantity of water that leaves the peatland. Annually, the amount of water that leaves a drained peatland is clearly greater than an intact peatland (Paavilainen and Päivänen, 1995; Holden et al., 2006). After a rain event, the runoff from a drained peatland continues to flow for a longer period of time than runoff from an undisturbed peatland because a drained peatland has a lower water table (Burke, 1975). Much of the runoff water from a drained peatland is groundwater, while runoff from undisturbed peatlands is mainly made up of surface runoff (David and Ledger, 1988; Holden et al., 2006).

The latency period between the initial drainage, which suddenly creates a large amount of runoff, and the annual increase of runoff per surface unit can be several years (Holden et al., 2006). Therefore, even if no changes are noticeable in runoff during the first years of drainage, the repercussions of drainage may come later.

IMPACT OF DRAINAGE ON WATER RETENTION TIME

In certain countries, one of the desired consequences of draining peatlands is flood reduction in adjacent lands. Not surprisingly, Finland, the Netherlands, Ireland and Great Britain are countries with large areas of highly drained peatlands. Traditionally, these peatlands were drained for agriculture, forestry and energy, but also to prevent flooding in the surrounding landscape (Holden et al., 2004). The hydrology of drained peatlands is complex and literature contradicts itself, depending on the author's field of interest (Holden et al., 2004).

Undisturbed peatlands can retain large quantities of water after a rain event, as long as they were not already completely saturated. When a peatland is saturated with water, the excess water leaves the peatland as surface water runoff (Holden and Burt, 2003). The retention time of rainwater before overflowing occurs, depends on the saturation level of the peatland, the type of peatland, the vegetation on the surface and the topography (Holden and Burt, 2003; Holden et al., 2004). In general, if a peatland is saturated, the surface runoff begins soon after the rain event. However, during long periods of drought, the groundwater flow to the receiving streams is minimal (Price, 1992; Holden and Burt, 2003).

Generally, it is expected that digging drainage ditches reduces the surface water flow in a peatland (Holden et al., 2004). On a drained peatland the majority of the peat profile is not saturated most of the time because the drainage ditches have lowered the water level. In certain cases, it is in this part of the profile where the greatest water retention capacity is located (Price, 2001), and could help to diminish the surface water runoff for a short period of time during a rain event.

Although one part of the peat profile can retain water relatively effectively, a certain quantity of water entering a drained peatland is diverted directly to the drainage ditches (David and Ledger, 1988). This water is thereby not held within the peatland and quickly flows off the peatland (David and Ledger, 1988; Holden et al., 2006).

Over the long term, drainage can change the structure of the soil considerably and might even lead to the creation of subterranean canals. This phenomenon can also occur in undisturbed peatlands, but becomes much larger and dense after significant drainage. The water circulates in a much greater quantity in the subterranean canals and in the altered macropores of a drained peatland as compared to an undisturbed peatland (Holden et al., 2006). In certain cases, especially sites that have been drained for a very long time the structural changes caused by the drying out of peat are irreversible (Egglesmann et al., 1993).

According to the drainage technique used, the type of peatland, its properties and placement in the landscape, draining a peatland can provoke more flooding or less flooding. Here are some reasons which might explain why floods and runoff flow would diminish after drainage:

1) Decrease in surface runoff due to a greater water retention capacity of the upper peat level (Paavilainen and Päivänen, 1995; Holden et al., 2004).

2) A greater capacity to store water in depressions due to the subsidence of the peatland (Holden et al., 2004).

3) An increase in evapotranspiration due to changes in the vegetation growing on the surface (Van Seters and Price, 2001; Holden et al., 2004; Fay and Lavoie, 2009).

4) An increase in evaporation of surface water which accumulates in ditches (Holden et al., 2004).

5) A significant lowering of the hydraulic conductivity which diminishes horizontal and vertical water movement (Van Seters and Price, 2002).

6) The amount of water in a drained peatland can change and diminish according to the landscape surrounding the peatland. For example, when a a non-saturated zone which has the capacity to store the runoff from the drainage ditches before the runoff reaches zones at risk is situated at the foot of drainage network of peatland, there is less risk of flooding (Lane et al., 2003).

Here are some reasons which could explain an increase in flooding and runoff from a drained peatland:

1) An increase in the canalization of precipitation which flows directly into the drainage ditches and exports precipitation directly out of the peatland (David and Ledger, 1988; Paavilainen et Päivänen, 1995; Holden et al., 2004).

2) The water is no longer retained in natural depressions of the peatland and is exported directly in the ditches (Holden et al., 2004).

3) When vast drainage networks are dug, much of the vegetation is removed, therefore the evapotranspiration in these areas is reduced (Holden et al., 2004).

4) Exposure and dumping of groundwater which was previously retained in a closed system (Holden et al., 2004).

5) A subterranean canal network and the macropores are formed in peat that favours the removal of large quantities of groundwater out of the peatland (Holden et al., 2006).

6) When the drainage network is situated at the foot of a saturated area and the hydraulic conductivity between the saturated area and the drained peatland is high. Consequently, the water would be removed by the drainage ditches very quickly, up to two times more quickly than in the saturated environment (Lane et al., 2003).

IMPACT OF DRAINAGE ON THE STRUCTURE OF THE PEAT DEPOSIT

The water retained in an undisturbed peatland is equivalent to 90% of their weight and 300% of their volume (Hobbs, 1986). Therefore, the more a peatland loses water, the more it loses volume. When water which is normally retained in the pores of peat is drained, the structures dry and shrink. It is possible that when peat dries that it becomes hydrophobic and is, therefore, incapable of going back to the initial humidity levels (Egglesmann et al., 1993, which was referenced in Holden et al., 2006).

Because most of the peat profile in a drained peatland is aerated, the oxygenation rate of the peat is much higher than the rate found in an undisturbed peatland. Therefore, there is a substantial loss of peat volume and increase in compaction. The density related to the surface layer (first 50 cm) can be twice as high as the density of the surface layer of an undisturbed peatland. In a peatland of the Bas-Saint-Laurent in Quebec, the density of the surface layer from a drained peatland was 0.13 g cm^{-3}, compared with 0.7 g cm^{-3} from an undisturbed peatland in the area (Van Seters and Price, 2002; Figure 5). Water movement is limited by the increase in peat density and the resulting decrease in hydraulic conductivity. Hydraulic conductivity in a drained peatland can be up to three times lower than in an undisturbed peatland (from 4.1 x 10^{-5} cm s^{-1} in an undisturbed peatland to 1.3 10-5 cm s^{-1} in a drained peatland). Higher density also diminishes the peatland's ability to store water and reduces its availability for plants (Price, 1997; Van Seters and Price, 2002).

PHOTO : Steve Henstra

Figure 5. Surface layer of a drained peatland in comparison with an undisturbed peatland. The samples were taken from the same sector of a peatland in the Bas-Saint-Laurent (Québec).

In the lower peat layer (catotelm) below the water table compaction also occurs in drained peatlands. Because the upper peat layer is denser and because the water level is no longer maintained close to the surface, this layer becomes heavier and loses its floatability. The upper layer compresses the lower peat layer. The compaction of a large part of the peat profile along with the loss of water volume contributes to subsidence of the peatland (Rothwell et al., 1996; Minkkinen and Laine, 1998; Price and Schlotzauer, 1999; van der Schaaf, 1999; Price et al., 2003). Price and Schlotzauer (1999) estimated the short-term subsidence of a peatland in the Lac-Saint-Jean area of Québec. The total subsidence was between 6.5 and 10 cm (per year). The majority of the subsidence was due the volume loss caused by the compaction of 3.5% of the peat deposit above the water level, which is equivalent to a subsidence of 6 cm. The subsidence in peatlands that have been drained over a long period of time can be even greater. Van Seters and Price (2002) measured a total subsidence of 80 cm for a peatland in the Bas-Saint-Laurent, Québec that had been drained for 57 years. The extent of subsidence is correlated with the thickness of the peat column before drainage (Minkkinen and Laine, 1998). The more peat that had accumulated before drainage, the greater the tendency for subsidence after drainage.

IMPACT OF DRAINAGE ON PEAT TEMPERATURE

The numerous changes in the structure of the peat disturb its capacity to store and transmit heat. In the surface layer (the first 10 cm) near the drainage ditches, the maximal seasonal temperature increases by 3-4 °C (Lieffers and Rothwell, 1987; Prévost et al., 1997). In spring, the roots of vascular plants warm up more quickly in drained peat because it is more aerated. Contrary to the surface temperature, the temperature in the deep peat layers is lower in a drained peatland than in a natural peatland (Prévost et al., 1997). Because the upper layer, the acrotelm, has low heat conductivity and a low heat of combustion, it acts as insulation. Therefore, drained peatlands are frozen longer than natural peatlands (Price, 2001).

IMPACT OF DRAINAGE ON DECOMPOSITION RATES

The increase in temperature and aerated zone influences the decomposition rate of the surface peat (Clymo, 1992; Chapman and Thurlow, 1998). In an undisturbed peatland the water is maintained close to the surface, within the acrotelm. Thus, the majority of the peat deposit, the catotelm, is permanently saturated, meaning the decomposition rates are very low. In that way peat accumulates, leading to the accumulation of carbon, since the biomass produced is greater than that lost to decomposition. In *Sphagnum*-dominated peatlands the peat accumulates at 0.5 to 0.6 mm per year (Lappalainen, 1996).

In a drained peatland the majority of the peat profile is aerated. The diffusion of oxygen in the upper layer of a drained peatland (0 to 40 cm) is 1.4 to 1.9 times higher than the same zone in an undisturbed peatland (Silins and Rothwell, 1999). These particular conditions and the vegetation changes in turn modify the microbial communities, including bacteria, fungi, and mould (Jaatinen et al., 2007; Andersen et al., 2010). The new microbial communities found in the constantly aerated peat layers decompose organic material more quickly (Prévost et al., 1997; Minkkinen et al., 1999). The decomposition of organic material in the aerobic zone is 50 times faster than in the anaerobic zone (Clymo, 1983).

The decomposition potential in a peatland is strongly influenced by the peat's physiochemical properties and by the surface vegetation which changes according to the amount of drainage (Andersen et al., 2010). These changes in the decomposition process also result in consequences for maintaining ecosystem functions, because functions for carbon accumulation are changed. According to Andersen et al. (2006), stable hydraulic conditions and sufficient phosphorous, characterize restored and undisturbed peatland can improve carbon and nitrogen fixation, contrary to conditions encountered in non-restored peatlands (drained).

IMPACT OF DRAINAGE ON CH_4 AND CO_2 EMISSIONS

In the carbon cycle two gases are very important: CO_2 (carbon dioxide) and CH_4 (methane). The dynamics of these two greenhouse gases are influenced by several factors. To start with, the intrinsic properties of the peatland will have a large impact on the cycle of these elements: the type of peatland (ombrotrophic or minerotrophic; Moore and Dalva, 1993; Martikainen et al., 1995), its microbial composition, its chemical composition, and the structure of the soil (Nykänen et al., 1998). The climate also greatly impacts the balance of these gases (Nykänen et al., 1998). As a general rule, undisturbed peatlands in temperate regions emit little CH_4 into the atmosphere. In Québec ombrotrophic peatlands emit on average 1 to 4 g m^{-2} $year^{-1}$ (Moore and Knowles 1990). On top of natural factors, the anthropogenic disturbances, such as the intensively of drainage and the number of drainage ditches change the proportions of CO_2 and CH_4 emitted by the peatland (Roulet et Moore, 1995; Minkkinen et Laine, 2006). For example, increasing the temperature in the upper peat layer increases the loss of these two gases (Moore and Dalva, 1993; Nykänen et al., 1998). The lowering of the water level during drainage can provoke the emission of CO_2 and CH_4 stored in water pores of peat due to the diffusion power of these gases when the pores are filled with air (Moore and Dalva, 1993). After drainage the greater variation in the water level influences these two gases (Moore and Dalva, 1993).

Several studies show that CO_2 emissions (Moore and Dalva, 1993; Silvola et al., 1996) generally increase and CH_4 emissions generally decrease (Glenn et al., 1993; Moore and Dalva, 1993; Martikainen et al., 1995; Nykänen et al., 1998) in drained peatlands. Draining decreases the thickness of the anaerobic zone, where methane is produced and increases the aerobic zone, where CO_2 is emitted and CH_4 consumed. Moreover, the smaller the anaerobic zone of the peat profile, the more the quality of the substrate diminishes for microorganisms which produce CH_4. The process of CH_4 production in peatlands is very well explained in a literature review by Lai (2009).

In an undisturbed ombrotrophic peatland in Ontario where the water level is high and stable (-1 to -3 cm), the quantity of CO_2 emitted is on average 6.1 mmol m^{-2} day^{-1} and the quantity of CH_4 is 2.1 mmol m^{-2} day^{-1}. When the water level fluctuated from -5 to -67 cm, the quantity of CO_2 increased to 140 mmol m^{-2} day^{-1}, while the quantity of CH_4 was slightly reduced to 0.36 mmol m^{-2} day^{-1} (Blodau and Moore, 2003). Studies carried out in Finland on long-term drainage indicate a decrease in the contribution of these two gases to the balance of greenhouse gases (Minkkinen et al., 2002). Even if the quantity of CO_2 increases, the decrease in CH_4 compensates (Minkkinen et al., 1999).

Although drainage can reduce the emissions of CH_4 in a drained peatland, the drainage ditches are a considerable source of CH_4. In a drained peatland where there is water in the drainage ditches, the decrease in CH_4 by the drying out of the peatland can be counter balanced by the CH_4 emissions from the drainage ditches (Roulet and Moore, 1995; Minkkinen and Laine, 2006). The CH_4 emissions from drainage ditches filled with water can reach anywhere from 182 to 600 mg m^{-2} day^{-1} (Minkkinen and Laine, 2006). The CH_4 emissions which come from drainage ditches are accentuated by water movement, the presence of nutrients, and by increased temperature (Roulet and Moore, 1995). According to a study carried out in Ontario, Roulet and Moore (1995) concluded that the distance between the drainage ditches in a forested ombrotrophic peatland determined the CH_4 of the entire system. Because forested ombrotrophic peatlands emit little CH_4, digging drainage ditches which are less than 38 m apart, results in an increase in CH_4 compared with the undisturbed state. It should be noted that when drainage ditches are deep, it is possible that they will reach the mineral soil layer, which will result in an increase in nutrients in the water which in turn favours the production of CH_4.

IMPACT OF DRAINAGE ON DISSOLVED ORGANIC CARBON

In peatlands on top of exchanges of carbon gases (CO_2 and CH_4), carbon is also exported out of the ecosystem in its dissolved form in water: dissolved organic carbon (DOC). The production of DOC is regulated by the production and decomposition rates of the plants. It is normally present in natural ecosystems. The concentration of DOC in ombrotrophic peatlands (average is 30 mg L^{-1}) is much higher than that found in undisturbed rivers (7 mg L^{-1}) or in well oxygenated lakes (2.2 mg L^{-1}). The DOC is naturally exported out of intact peatlands towards the receiving stream at rates that vary from 5 to 40 g m^{-2} $year^{-1}$ (Thurman, 1985).

The DOC consists of a variety of molecules composed of organic carbon which have a diameter which is less than 45 µm (Thurman, 1985). This composed group is made up of small molecules like simple acids, but is also composed to more complex and, thus recalcitrant, substances such as humic substances. Humic substances include humic and fluvic acids and which are colored compounds (Figure 6).

Drainage ditches lower the water level which increases the concentration of DOC in the surface water (pool water) and in groundwater, which is retained in the peat pores (Wallage et al., 2006; Strack et al., 2008). The quantity of DOC exported from the peatland's water towards the receiving streams is also greater (Moore, 1987; Laine and al., 1996; Wallage et al., 2006). In an ombrotrophic peatland of Sept-Îles (Québec), the DOC

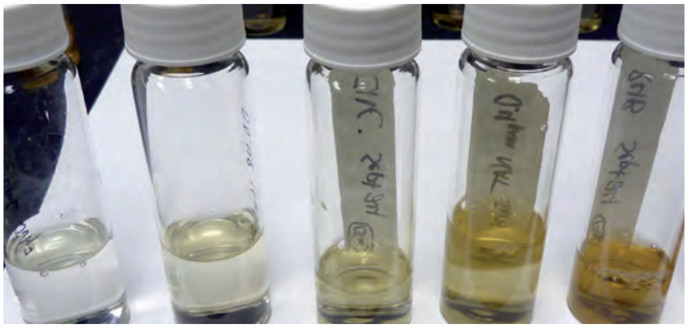

PHOTO : Yoseph Zuback

Figure 6. Water samples of different coloration according to the concentration of dissolved organic carbon (DOC). The concentrations vary from de 6 mg L^{-1} DOC (1st sample) to 75 mg L^{-1} DOC (5th sample).

before being drained varied from 23 to 34 mg L^{-1}, depending on the season. During the installation of drainage ditches, the concentration increased to 55 mg L^{-1} and thereafter varied from 35 to 43 mg L^{-1} (Moore, 1987).

The increase of DOC is not limited simply to the moment of installation and the period shortly thereafter. Strack et al. (2008) showed that even 11 years after the initial drainage the concentration of DOC in both the surface and pore water remains high. The greater fluctuations in the water level of a drained peatland are partially responsible for the elevated concentration. When the water rises after a period of drought, there is an increase in the DOC concentrations (Kalbitz et al., 2000). During periods of drought, which happen more often in drained peatlands, the microorganisms which are used to wet conditions are harmed, some use less DOC and others die. The DOC therefore accumulates in peat and is dislodged with a sudden rise in the water table. The abnormal fluctuations of the water level in drained peatlands can also entail a loss of DOC normally immobilized in the anaerobic peat layer (the catotelm of a natural peatland; Blodau and Moore, 2003). When the DOC is flushed from these peat layers, these layers are no longer saturated in DOC and the production of new DOC is stimulated (Strack et al., 2008).

Because DOC compounds are coloured, when there is an increase in their concentration, the color of the water is darker. The color of the water can have important consequences in the receiving streams. Increased DOC reduces the penetration of the light (Steinberg, 2003), which directly affects the photosynthesis of the aquatic plants. A decrease in photosynthesis inevitably leads to a decrease in oxygen availability in the water, important for aquatic fauna.

The colouration of the water can prove to be a big problem if the water draining from the peatland is treated for drinking water. This is why in some countries, like Great Britain and other countries in Europe, the companies which treat water are very interested in blocking drainage ditches (Worrall et al., 2007; Armstrong et al., 2010) and restoring the hydrology of peatlands.

On top of colouration, the DOC also has a notable influence on the chemical composition of the receiving streams by affecting the acidity and even the mobilization and the chelation of nutrients and metals. The humic substances can be an aid in transporting contaminants toward waterways because certain toxic metals are mobilized by these substances (Steinberg, 2003) and can be transported out of a peatland when it is drained.

IMPACT OF DRAINAGE ON CARBON DEPOSITS IN A PEATLAND

When a peatland is drained, it changes from an ecosystem which is extremely efficient in accumulating carbon to one that is a carbon source (Ramchunder et al., 2009). This change is brought about by a reduction in aerobic zone and an increase in decomposition. The carbon stock, which is the quantity of carbon that a peatland accumulates in its peat deposit and vegetation biomass, can decline (Minkkinen and Laine, 1998; Minkkinen et al., 1999) or increase (Minkkinen and Laine, 1998; Minkkinen et al., 1999), according to the availability of nutrients and the climate. A recent study proposes that changes in activity, the quantity and the composition of phenol oxidase in the peat can also be responsible for the variation in the carbon stock before and after draining (Toberman et al., 2010).

The capacity of a drained peatland to store peat is strongly correlated with the degree of subsidence, the nutrient availability and degree of afforestation (Minkkinen and Laine, 1998; Minkkinen et al., 1999). Nutrient availability, aeration, and pH control the decomposition rate and the rate of afforestation in a drained peatland. A high decomposition rate results in a loss of carbon stored in the peat. However, the decomposition also has the effect of increasing the availability of certain nutrients which favour vegetation growth. If the decomposition rate stays relatively low and the quantity of new vegetation is sufficient, a drained peatland can continue to store carbon (Minkkinen and Laine, 1996). This trend has been observed for forested bogs in Finland (Minkkinen and Laine, 1996). After drainage a significant increase in tree volume increased the quantity of organic matter rich in carbon in the soil, mainly through the growth of roots (Laiho and Finér, 1996; Murphy et al., 2009). Murphy et al. (2009) measured an increase of 740 % fine tree toots in a drained bog as compared to a similar undisturbed bog. A contribution also comes from an increase in recalcitrant litter which accumulates in the soil (Minkinnen and Laine, 1996). In fens the quantity of new organic matter in the soil can be less than the quantity of carbon lost due to higher decomposition (Minkinnen et al., 1999). There is a loss of carbon from the peat deposit of drained peatlands when the quantity of the roots and the litter do not compensate for the loss of carbon due to decomposition.

In some cases, the loss of carbon in the peat deposit can compensate for the increase of carbon sequestration caused by a better growth of aerial biomass. The richer the peatlands are in nutrients, the more the volume of the trees increases and the more this vegetation can accumulate carbon. The drained fens can support trees populations which have an excellent potential to store carbon (Paavilainen and Päivänen, 1995; Minkkinen et al., 1999). However, when the trees are cut or die this stored carbon is released. In the bogs, which are poorer, the afforestation is less and the aerial biomass does not contribute significantly to carbon storage; therefore, there can be a net loss of carbon (Paavilainen and Päivänen, 1995).

Laine and Minkkinen (1996) carried out an important study on the quantity of carbon stored in a peatland which has been drained for 30 years and an undisturbed peatland. They concluded that the undisturbed part accumulates 35 g carbon m^{-2} $year^{-1}$ more than the drained part. The undisturbed part of the peatland accumulated 21 g of carbon m^{-2} $year^{-1}$, while the drained part of the peatland lost 14 g of carbon m^{-2} $year^{-1}$.

It is more justified to compare carbon stock in peatland surface units, rather than in volume. The carbon stock in volume units can be greater in a drained peatland than an undisturbed peatland due to subsidence of the peatland which increases the carbon concentration in the peat (Minkkinen and Laine, 1998; Minkinnen et al., 1999). Therefore, it is important to be careful while interpreting data about carbon stocks between drained and undisturbed peatlands. See Figure 7 for an example of a peat deposit in an ombrotrophic peatland.

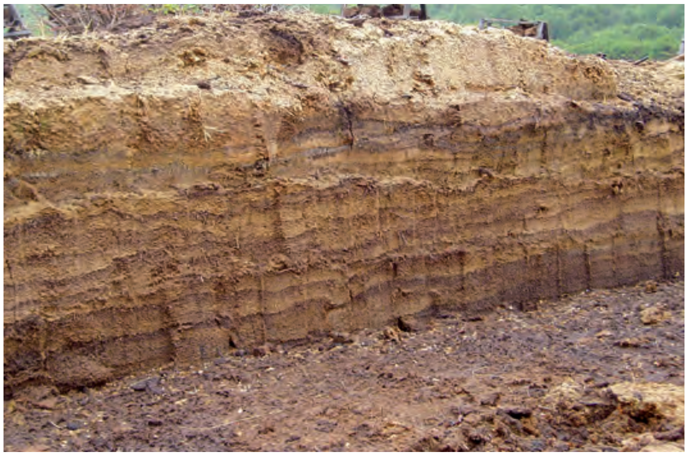
PHOTO : Line Rochefort

Figure 7. Peat deposit in an ombrotrophic peatland.

DRAINAGE IMPACT ON THE PHYSIOCHEMISTRY OF THE PEAT

It has already been noted that drainage entails accelerated decomposition and oxidation of peat, which in turn increases peat density (Wells and Williams, 1996; Sundstrom et al., 2000; Van Seters and Price, 2002). These changes in peat impact the carbon cycle and also change the rate of nutrient mineralization (Holden et al., 2004) and the redox potential (Sundstrom et al., 2000). Mineralization is a process which implies the fractionation by microorganisms of organic compounds (thus related to carbon) into more simple mineral compounds. Nitrogen and phosphorous are two nutrients essential for plant growth and are normally strongly related to carbon. These nutrients are found in great quantities in peat where drainage has lead to the breakdown of carbon compounds (Wells and Williams, 1996; Laiho et al., 1999; Sundstrom et al., 2000).

When nitrogen and phosphorus concentrations in peat increase after drainage, potassium, another important nutrient, decreases (Sundstrom et al., 2000; Andersen et al., 2011). The concentration of base cations, such as magnesium and calcium, also decrease on the surface of drained peat (Laiho and Laine, 1995; Laiho et al., 1999; Westman and Laiho, 2003). Not only is there a decrease, but the proportion of the cations in an exchangeable form, thereby able to be assimilated by plants, is also reduced (Laiho et al., 1999; Sundstrom et al., 2000). These changes in the availability of the base cations can lead to significant insufficiencies and imbalances in the element cycle (Laiho et al., 1999). Certain metals, like iron and manganese (Laiho and Laine, 1995), tend to decrease in the surface peat after drainage. The response of the total cations to the effects of drainage can vary according to the pH of the peat, the chemical composition and the density of the peat (Wells and Williams, 1996).

IMPACT OF DRAINAGE ON THE WATER CHEMISTRY COMPOSITION

The numerous modifications to peat after drainage inevitably lead to changes in the water that circulates and flows out of the peatland.

Changes in water chemistry occur either directly after drainage, over the medium-term (for example Robinson, 1980; Åström et al., 2001), or over the long-term (for example Joensuu et al., 2002).

After drainage phosphorous and nitrogen in both the organic and inorganic form (mainly $N\text{-}NH_4$) are more concentrated in the peat and are equally more concentrated in the drainage water (Miller et al., 1996; Prévost et al., 1999; Joensuu et al., 2002; Landry, 2008; Andersen et al., 2011). There is also a considerable augmentation in sulphate (Miller et al., 1996). Miller et al. (1996) estimated the amount of elements within the first meter of peat. This upper layer contained up to 20,000 kg of nitrogen, 10,000 kg of sulphur, 500 kg of phosphorus and 500,000 kg of carbon. Thus, a disturbance of this layer, even a minimal drainage disturbance, can release significant quantities of these elements into the surface runoff. The combination of these elements can contribute to the eutrophication of the receiving waters.

A site that has been extensively drained is subject to a leaching of the base cations, such as sodium, calcium and magnesium, as well as potassium (Moore et al., 1987; Miller et al., 1996; Prévost et al., 1999; Åström et al., 2001; Joensuu et al., 2002; Landry, 2008; Andersen et al., 2011). Because many cations are found in large quantities in the water, the drainage and maintenance of the drainage ditches creates an increase in the electrical conductivity of the water (Moore et al., 1987; Joensuu et al., 2002). Even certain heavy metals, like mercury (Paavilainen and Päivänen, 1995), iron and aluminum (Laiho and Laine, 1995; Paavilainen and Päivänen, 1995; Joensuu et al., 2002) and manganese (Åström et al., 2001) can be found in large quantities in the surface water and ultimately in the receiving streams.

These numerous changes can equally entail an increase or a decrease in the pH, according to the type of peatland (Laine et al., 1995; Paavilainen and Päivänen, 1995; Prévost et al., 1999; Åström et al., 2001; Joensuu et al., 2002; Westman and Laiho, 2003). These numerous changes in the chemical composition of a drained peatland can cause the modifications of the redox potential due to the exposure of the mineral substrate in the drainage ditches or due to the physical detachment of organic or inorganic particles (Åström et al., 2001).

Joensuu et al. (2002) found the increase in the suspended particles in the water as the worst consequence of drainage on water quality. Certain preventative measures can be taken at the outlet of a drained peatland, such as sedimentation basins or flood plains (see Klove, 2000, for example). However, the suspended particles are a major problem for the drained peatland runoff, either directly after the installation of the drainage ditches or after a big rain event (Francis and Taylor, 1989; Paavilainen and Päivänen, 1995; Vuori et al., 1998; Prévost et al., 1999; Åström et al., 2001; Joensuu et al., 2002; Parvey, 2006; Landry, 2008). When the drainage ditches are dug, the vegetation is eliminated and the ditch has a tendency to erode. The drainage ditches sometimes expose the peat to drought in the summer and frost heaving in the winter (Figure

8), which can also influence the stability and erosion of the ditch (Holden et al., 2007). Because there is no vegetation, there is no barrier to retain the organic and inorganic solid particles which are transported in the water flowing in the ditches (Francis and Taylor, 1989). These suspended particles are exported in large quantities to the exterior of the peatland. The increase of suspended solids can be considerable if, in addition, the mineral soil is reached at the bottom of the ditch (Åström et al., 2001). According to a study by Robinson (1980) the concentration of sediment can double after drainage and stays elevated even five years after the drainage ditches have been dug. In a case of extremely intensive drainage, the concentration of suspended solids can increase up to 50 times (Robinson and Blytt, 1982). In the study by Robinson and Blytt (1982), before drainage the concentration of the suspended solids was evaluated on average at 4 mg/L; after drainage, this concentration increased to between 30 and 150 mg/L. Big rain events can also displace impressive quantities of suspended solids, up to an average of between 300 and 1,700 mg/L. In New Brunswick, Parvey (2006) found that 72% of harvested peatlands exceed the provincial norm of 25 mg/L, compared with 30% of undisturbed peatlands.

The suspended solids as such are very powerful pollutants because when they reach the water surface, they settle and affect the dynamics of the benthic community (Vuori and Joensuu, 1996; Vuori et al., 1998; Schofield et al., 2004). The two principal factors responsible for the impoverishment of the benthic communities are: the deposition of particle on the habitats of these communities and the movement of the

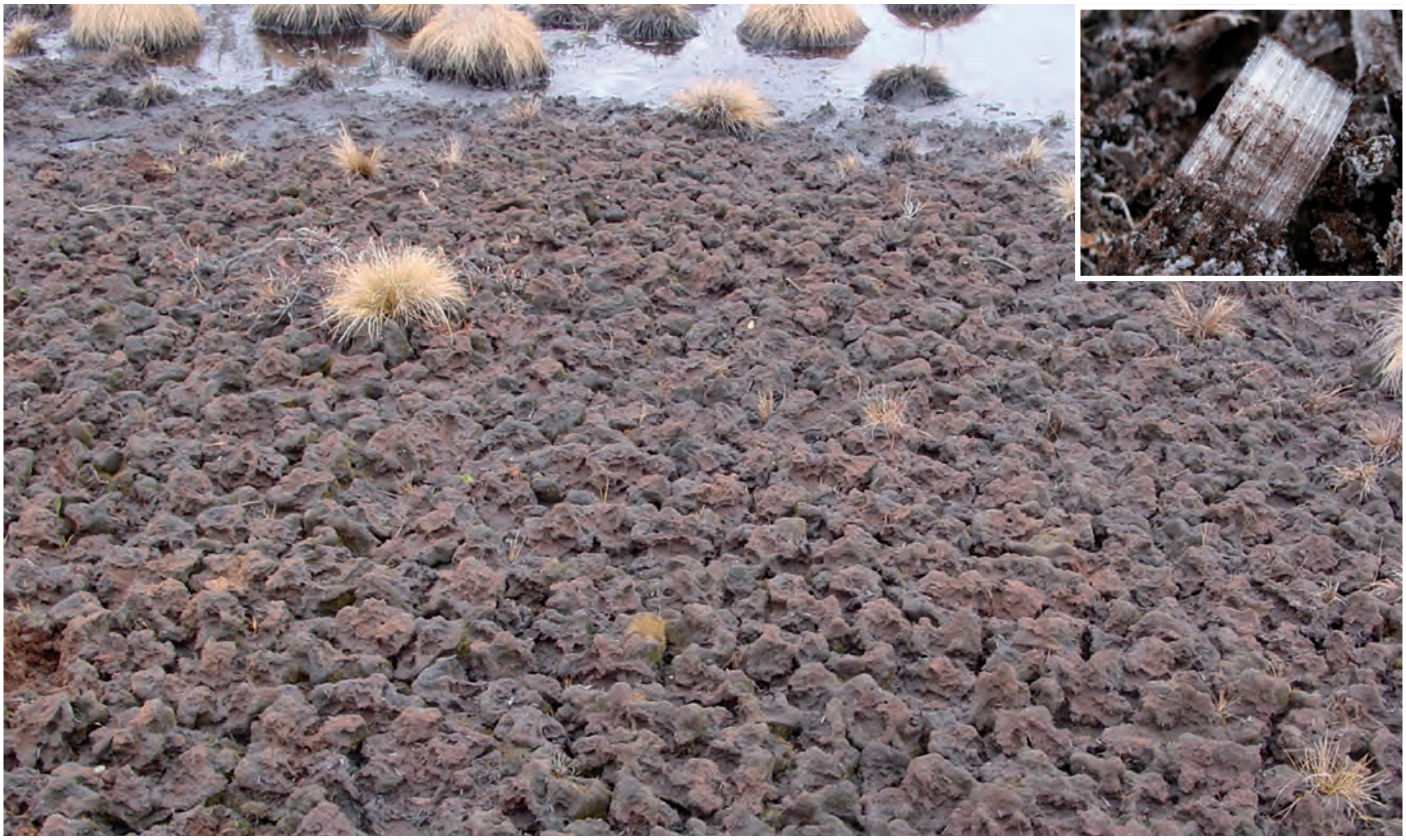
PHOTO : Vicky Bérubé

Figure 8. Frost heaving in peat without vegetation caused by the formation of crystal ice.

particles on the drainage water surface (Vuori and Joensuu, 1996). A study carried out in New Brunswick showed an important decrease in the populations of sand shrimp (Crangon septemspinosa) after their preferred habitat, sandy bottoms, was altered. When there is an addition of organic particles in the environment, the shrimp's ability to adapt for hunting as well as camouflaging from predators, is compromised. The shrimp can also be affected by indirect effects of the suspended solids, either by the production of H_2S related to the anaerobic decomposition of the peat particles or the decrease in oxygen in the environment (Ouellette et al., 2005). The suspended solids also influence the composition of algae, which in turn influences the organism that feed on them (Schofield et al., 2004).

A large quantity of suspended solids in waterways can also cause a decline in filter organisms, like mussels and oysters, because the sediments obstruct their feeding mechanisms (Aldridge et al., 1987; Strychar, 1997; Ramchunder et al., 2009). An experiment carried out in New Brunswick showed that the higher the concentration of the organic particles, the more the absorption capacity of the oyster (*Crassostrea virginica*) was diminished due to the dilution of particles easily assimilated by oysters (Strychar, 1997). Laine (2001) noted a significant impact on salmon populations. In a river fed by water from a drained peatland, which exports a significant load of suspended solids, they observed a drop in the salmon population. Additionally, the salmons of this river were smaller than those from a river which was not influenced by runoff from a drained peatland.

Indirectly, the suspended solids bring about other problems in the receiving waters. The organic part of the suspended solids is biologically active and, when they are found in waterways, oxygen is consumed for their decomposition (Paavilainen and Päivänen, 1995). The suspended solids are also a vehicle for many contaminants in waterways, such as metals (Klove, 2000) and phosphorus (Paavilainen and Päivänen, 1995). This effect is mostly evident immediately after ditching or ditch-cleaning, long-lasting effects of drainage on the solid organic matter in watercourses are generally negligible (Heikurainen et al. 1978). The increase in metals concentration can have important impacts on the food chain in the receiving waters (Ramchunder et al., 2009). The heavy metals directly affect the populations of invertebrates, which constitute the base of the food chain, as shown by Clements et al. (2000) for the mayflies.

The temperature of water that leaves a drained peatland is higher than water draining from an undisturbed peatland. According to Prévost et al. (1999), the temperature can reach 25 °C and more in summer in drained peatlands located in a temperate climate.

IMPACT OF DRAINAGE ON ANOTHER GREENHOUSE GAS: N_2O

Nitrogen oxide (N_2O) is also an important gas in a drained peatland. This gas is stimulated when a peatland is drained, especially in the minerotrophic peatlands (Martikainen et al., 1993, 1995; Laine et al., 1996; Regina et al., 1996). In a drained peatland the production of this gas is caused principally by an imbalance in the process of ammonification and nitrification. The increase of N_2O in a drained peatland is related to the type of peatland and the water level. The emission of this gas is higher in fens than in bogs, because it is increased by a large availability of nitrogen, phosphorus, calcium, and a more neutral pH (Regina et al., 1996).

In undisturbed sites the N_2O fluxes are normally very low (for 12 bog and fen sites observed values were between -30 and 200 $\mu g\ N_2O\ m^{-2}\ day^{-1}$), many bogs even sequester N_2O (Regina et al., 1996). According to collected data, there is a slight increase in N_2O in drained bogs, but in fens the increase can reach 40 times the amount before drainage (Regina et al., 1996) or on average up to 1 $g\ N_2O\ m^{-2}\ year^{-1}$ after drainage (Alm, 2010). Considering that N_2O is a greenhouse gas which is 300 times more powerful than CO_2 and 15 times more powerful than CH_4, an increase could have import repercussions on the contribution of drained peatlands to global warming. Thus, the contribution of greenhouse gases from a drained peatland, depend on changes in the ratios of the three gaseous substances: CH_4, CO_2 and N_2O (Laine et al., 1996).

IMPACT OF DRAINAGE OF THE FLORISTIC BIODIVERSITY

Drainage provokes many changes under the peatland's surface, which could create monumental changes in the vegetation that covers it. The peatland's vegetation is adapted to an environment which is constantly humid. Obviously, if drainage entails peat drying over a long period of time, there will be significant changes in the composition and abundance of vegetation (Laine et al., 1995; Laiho et al., 2003; Murphy et al., 2009; Talbot et al., 2010). The typical peatland vegetation is progressively substituted by forest vegetation (Laine et al., 1995; Minkkinen et al., 1999; Laiho et al., 2003; Pellerin et al., 2008; Kozulin et al., 2010; Talbot et 2010).

In an ombrotrophic peatland, *Sphagnum* species such as *Sphagnum papillosum* (Figure 9) are progressively replaced by forest mosses like *Pleurozium schreberi* after drainage (Laine et al., 1995; Korpela, 2004). Poulin et al. (1999) noted a significant decline in *Sphagnum* cover in 24 ombrotrophic drained peatlands in Québec and New Brunswick. Lower *Sphagnum* cover than in undisturbed reference ecosystems was notable more than 60 m from the drainage ditches. A drained site makes the establishment and survival of *Sphagnum* very difficult and generally this species will decrease in abundance after drainage (Stewart and Lance, 1991; Laine et al., 1995; Poulin et al., 1999; Talbot et al., 2010). The presence of *Sphagnum* is strongly correlated with a water level between -11 and -39 cm (Price and Whitehead, 2001; Van Seters and Price, 2002). However, the soil water pressure is a better indicator of the survival potential of *Sphagnum* on a site. Hayward and Clymo (1982) established that the pressure should be greater than -100 mb to allow for the establishment and survival of the *Sphagnum*. Below this, *Sphagnum* does not have capillary force necessary to provide themselves with water. Because *Sphagnum* does not have roots they are entirely dependent on their capacity to pump water via capillarity force. Similarly, the relative humidity of the air directly above the soil surface should reach up to 54% for a minimal period of three days to assure the survival of the *Sphagnum* mosses (L. Rochefort, unpublished data). The *Sphagnum* mosses have a very limited tolerance to desiccation (Sagot and Rochefort, 1996).


PHOTO : Gilles Ayotte

Figure 9. *Sphagnum papillosum*, a typical species in wet peatlands.

In the vegetal succession of drained peatlands, one can observe a fast and significant decline in graminoids, which are replaced by trees and bushes (Murphy et al., 2009). The ericaceous bushes, such as *Vaccinium myrtilloides* and *Ledum groenlandicum*, increase considerably after drainage (Pellerin and Lavoie, 2003; Talbot et al., 2010). While creeping ericaceous plants, like *Vaccinium oxycoccos* (Talbot et al., 2010), and low ericaceous shrubs which are shade intolerant, such as *Kalmia polifolia* (Talbot et al., 2010) and *Chamaedaphne calyculata* (Pellerin and Lavoie, 2003; Lachance and Lavoie, 2004; Pellerin et al., 2008), tend to disappear with drainage intensification and the closure of a canopy. In fens, typical fen species, such as *Potentilla palustris*, are replaced by mesic forest species, such as *Trientalis europaea* and *Rubus idaeus* (Laine et al., 1995).

After 50 years of drainage, the aerial biomass of the plants is up to seven times greater than a peatland which has not been drained and 90% of the biomass is made up of trees (Laiho et al., 2003). Afforestation is the most noticeable change when a peatland is drained (Figure 10). Lowering the water level favors the establishment and growth of trees, such as pine, birch, larch, and spruce (Lieffers and Rothwell, 1987; Prévost et al., 1997; Jutras et al., 2002; Van Seters and Price, 2002; Faubert, 2004; Murphy et al., 2009; Talbot et al., 2010). Due to the more favourable conditions, the bud-break and flowering of the dwarf birch and larch are 2 to 6 days earlier in drained peatland than in non-drained peatlands (Lieffers and Rothwell, 1987). In study by Van Seters and Price (2002), forest cover increased by 5 to 20% after a peatland in the Bas-Saint-Laurent of Québec was drained. Jutras et al. (2002) travel through 48 drainage networks of forested peatlands in Québec. After nine years of drainage the growth increase of the black spruce situated at least 5 m from a drainage ditch was 26 to 95% for the diameter and 55 to 105% for the height.

In an undisturbed peatland, the trees are normally not very productive because the soil is saturated, the temperature is low and there is a lack of nutrients (Paavilainen and Päivänen, 1995).

PHOTO : Ministère des Ressources naturelles et de la Faune, 2000

Figure 10. Aerial photo showing the influence of drainage ditch on the proliferation of trees of the peatland Grande plée Bleue (Québec).

The drainage of certain ombrotrophic peatlands for forestry use is often inappropriate, because these environments are generally very acidic and poor in nutrients. The increase in nutrient mineralization (discussed in the section: impacts of drainage on the physical chemistry of peat) in ombrotrophic drained peatlands is sometimes too small to provide adequate nutrition for trees. Therefore, the yields are too small to be economical. In which case, fertilization is added to optimize production (Aro, 2000; Renou and Farrel, 2005). However, fertilization can prove to be expensive and can contribute to the enrichment of runoff flowing into receiving waters (Cummins and Farrel, 2003).

In certain regions picking berries in peatlands is an economically important activity for local populations. Although drainage can favour the cloudberry (*Rubus chamaemorus*) and lingonberry (*Vaccinium vitis-idaea*; Figure 11) over the short-term, the vegetative succession which follows over a mid-term has negative repercussions for berry population. Drainage entails negative impacts on cranberry population (*Vaccinium oxycoccos*; Figure 11), even over short term (Paavilainen and Päivänen, 1995).

PHOTO : Gilles Ayotte

PHOTO : Gilles Ayotte

Figure 11. *Vaccinium vitis-idaea* (bottom) and *Vaccinium oxycoccos* (up), typical peatland berries.

In terms of floral diversity, the drainage of a peatland favors the arrival of new forest species. However, when a canopy is closed, the species diversity tends to diminish. There is a strong correlation between the drainage period and floral diversity of a site (Laine et al., 1995). The more afforestation is evident, the lower the species richness is for ombrotrophic peatlands (Pellerin and Lavoie, 2003; Lachance et al., 2005). The loss of these plants associated with peatlands can contribute to the decline in regional biodiversity, both in the flora as well as the fauna which finds shelter and food in peatland flora (Lachance et al., 2005).

The impacts on the fauna and flora within a peatland can also be noticed in the margin of these peatlands. The margins of the peatland (sometimes called laggs) are important habitats which contribute to the faunal and floral diversity. When adjacent peatlands are drained, important changes also occur in the laggs. Korpela (2004) noted a major increase in dwarf birch and a decrease in *Sphagnum* within in the lagg zone of a peatland.

IMPACT OF DRAINAGE ON THE FAUNAL DIVERSITY

The changes in humidity and vegetation in a drained peatland are inevitable and impact the faunal diversity. Many animals, like birds (Calmé et al., 2002) and several insects (Vespälänien et al., 2000; Spitzer and Danks, 2006; Moores, 2008; Grégoire Taillefer and Wheeler, 2010) are adapted to the particular conditions of peatlands, certain species can only survive in this environment. The beetles are a good example of adaptation and prosperity in peatlands. Lavoie et al. (1997) identified several exclusive taxons of beetles present for thousands of year in peatlands due to their unique vegetation composition, their particular microtopography and the stability of their microclimate.

Grégoire Taillefer and Wheeler (2010) carried out a study in an ombrotrophic peatland in southern Québec for evaluating the impacts of drainage ditches on a group of insects *Diptera* (*Brachycera*). This group of very diverse insects is made up of 134,000 species (Brown, 2001, as cited in Grégoire Taillefer and Wheeler, 2010) and is very important in the diet of certain amphibians, reptiles, fishes, and birds (Murkin and Batt, 1987, as cited in Grégoire Taillefer and Wheeler, 2010). The study showed that a greater distance in relation to a drainage ditch permits a higher richness in *Diptera* species and an assemblage of species different comparatively to the proximity of the ditch.

Schikora (1994 as cited in Grégoire Taillefer and Wheeler, 2010) noted important changes in the populations of spiders in drained ombrotrophic peatlands. With the vegetation changes associated with drainage, the spiders which are tolerant to sun, specialists for open peatlands are progressively replaced by those which are tolerant to shade.

Ants are also affected by drainage. Vespälänien et al. (2000) have observed that the diversity of ants was higher in a drained peatland than in a natural peatland. However, the composition of the species in these two environments is completely different. Three species of ant specialists in ombrotrophic peatlands weren't found in drained peatlands, as well as those found in natural peatlands of the study. The intensive drainage of peatlands could lead to the extinction of specialized peatland species, such as the ant species *Myrmica scabrinodis* (Vespälänien et al., 2000) and *Dolichoderus maria* (Domaine et al., 2010). In Québec *D. maria* was identified at one single location, in the Grande plée Bleue peatland located near Québec City.

PHOTO : Etienne Paradis

Figure 12. Ants from an ombrotrophic peatland in New Brunswick.

Bird populations are closely linked to their feeding habitat and their reproduction. For example, the sandhill crane needs habitats which are open and isolated, more specifically ombrotrophic peatlands or marshes encircled by a forested border (Tacha et al., 2011). Certain populations of birds need soft wet soils for feeding habitat. This is true for birds which feed on soil insects. If the soil is too hard, their beak cannot penetrate the soil. Additionally, certain populations need soils partially submerged for nesting (Tickner and Evans, 1991, as cited in Armstrong, 2000).

The afforestation of the peatlands following drainage, as discussed in the preceding section, greatly changes the structure of the vegetation composition. The open areas with mosses and ericaceous shrubs are progressively replaced with trees. In southern Québec, the loss of habitats can have important consequences for the specialized peatland birds like the palm warbler (Figure 13) and the Lincoln's sparrow (Calmé, 1998; Lachance et al., 2005) or also for the species like the upland sandpiper, which can be found in open habitats (Calmé and Haddad, 1996).


PHOTO : Etienne Paradis

Figure 13. Palm warbler, a species found in peatlands in southern Canada.

Amphibians, coldblooded animals with wet skin, are also affected by peatland drainage. The mobility and abundance of many amphibian species, like the green frog (*Rana clamitans melanota*; Figure 14) are particularly sensitive to the fragmentation of peatlands and the decrease of their habitat caused by drainage (Mazerolle, 2001, 2003). However, the drainage ditches containing water diminish this effect by providing amphibians with corridors where then can survive and move from one suitable habitat to another (Mazerolle, 2005).


PHOTO : Marie-Claire LeBlanc

Figure 14. Green frog, a species which is sensitive to the impacts of drainage on peatlands.

PHOTO : Gilles Ayotte

THE IMPACTS OF REWETTING

Because rewetting peatlands and especially the monitoring of rewetting efforts in peatland are relatively recent, few studies present the results of rewetting. However, some show interesting changes.

Blocking the drainage ditches raises the water level (LaRose et al., 1997; Price, 1997; Price et al., 2003; Holden et al., 2004; Gottwald and Seuffert, 2005; Lanta et al., 2006; Shantz and Price, 2006; Patterson and Cooper, 2007; Worrall et al., 2007) and stabilizes the water level (LaRose et al., 1997; Gottwald and Seuffert, 2005). Blocking the ditches allows for a greater water retention within the peatland and decreases the water losses from 15 to 85% (Shantz and Price, 2006; Worrall et al., 2007). Price and Ketcheson (2009) analyzed rewetting practices in Québec and concluded that the rewetting efforts in peatlands permit the progressive return of ecohydraulic functions characteristic of peatlands. Even with simple interventions, which assure a minimum water level of -50 cm below the surface, an increase in the water level of the drained peatland can be noticed (Armstrong and Rose, 1999). Roul (2004) found that blocking a main drainage ditch resulted in an increase in the water level of the drained peatland within a radius of 150 m of the blocked ditch.

While allowing the return of the water level close to the surface, blocking the ditches favors vegetation typical to peatlands and decreases the abundance of non-desirable plants or plants not typical to peatlands (Tuittila et al., 2000a; Lanta et al., 2006; Patterson and Cooper, 2007). The return of wetland hydrology is critical for peat-accumulating vegetation which allows the ecosystem to return to a carbon sink (Chimner and Cooper, 2003). The changes are not instantaneous; it is possible that one year after rewetting that no changes are apparent. Visibly changes, such as trees which die off when a high water level returns to the site, can be observed after 3 to 10 years (Kozulin et al., 2010). A study from Tuittila et al. (2000a) showed that a peatland which has recently been rewetted, the typical peatland plants return, but the floral diversity diminishes because the plants which need drier habitats disappear. However, three years after rewetting, the diversity tends to re-establish. Lanta et al. (2006) observed important changes in the vegetation composition of the rewetted site after only four years after blocking the drainage ditches. In rewetted areas *Sphagnum* (*Sphagnum capillifolium* and *Sphagnum fallax*) dominate the moss cover. As for the vascular plants *Eriophorum vaginatum* (Figure 15), *Carex canescens*, and *Vaccinium vitis-ideae*, all typical peatland plants, were present. In areas that did not benefit from the rewetting, the moss cover was dominated by forest mosses: *Dicranella heteromalla* and *Dicranum scoparium*. The return of *Sphagnum* on disturbed peatlands after restoring the environmental conditions needed for their growth was observed in Québec and New Brunswick (Robert et al., 1999; Roul, 2005). In a rewetted peatland Roul (2004) observed a decrease in the frequency of trees and the presences of ericaceous shrubs and lichens accompanied by an increase in *Sphagnum* and herbaceous plants.

PHOTO : Gilles Ayotte

Figure 15. *Eriophorum vaginatum*, typical vascular plants in *Sphagnum*-dominated peatlands.

According to the observations of Holden et al. (2007, as cited in Ramchunder et al., 2009), blocking the drainage ditches, even with weak dams, permitted a reduction of 54 times the concentration of suspended solids in the water. Eventually, blocking drainage ditches can significantly diminish the concentration of DOC and the colorization of the water (Wallage et al., 2006; Armstrong et al., 2010). Wallage et al. (2006) observed a decrease in the average DOC and coloration of 69% and 62%, respectively, when the drainage ditches were blocked. These tendencies were confirmed by a study carried out by Armstrong et al. (2010) in 32 peatlands which noted DOC averages were 28% lower.

The rewetting lowered the total respiration rate of the peatland and increases the photosynthetic capacity of the plants. These changes permit rewetted and well-vegetated peatlands to return to carbon sinks (Tuittila et al., 1999; Soini et al., 2010). However, CH_4 emissions increase after rewetting. On the other hand, the emission rates of CH_4 in a rewetted peatland are the same as those in undisturbed peatlands (Tuittila et al., 2000b). Blocking the drainage ditches in peatlands also reduces the density of the peat (Wallage and al., 2008, as cited in Ramchunder et al., 2009).

PHOTO : Flor Salvador

REMEDIATION MEASURES

CHOICE OF THE TYPE OF REWETTING INSTALLATION

Before beginning rewetting work in a peatland, it is essential to have a good understanding of the site and have decided on specific objectives. A preliminary study of the site should allow one to understand the direction and intensity of water flow, the slope, and the dimensions of the drainage ditches. These variables permit restoration efforts to be tailored to each site. The choice of installation depends equally on the initial objective, the land use history, the time since drainage ditch construction, the budget, and the accessibility and topographical constraints of the terrain.

REWETTING OBJECTIVES

It is important to decide on an objective at the beginning of a restoration and to remind oneself of this objective while the rewetting project is being carried out. In order to target an objective, a good approach is to understand the impacts created by drainage which should be alleviated for a successful restoration (Land Resources International, 2009; Eco-pulse Environmental Consulting Services, 2010). Meaning one should target the biggest problems in the peatland that should be eliminated, be it the hydrology, the ecology or the geomorphology.

For example, if a drained peatland dumps large quantities of suspended solids in the receiving waters, a central aim of restoration could be to reduce the concentration of suspended solids by adding vegetation to the dams to retain sediments and decrease the water velocity. It is useful to collect data before and after drainage for key impacts to easily justify certain objectives and be able to quantify restoration success.

It is also important to remember the final use of the site. If a site is remote and not frequently used, the aesthetics of the dams is less important than for a site that will become an ecological reserve. In order to quantify the return of an investment in a restoration project, it is important to include in the balance of the costs and benefits the return of ecological goods and services of the restored habitat (Land Resources International, 2009; Eco-pulse Environmental Consulting Services, 2010). Examples of ecological goods and services include the return of berry bushes which could be picked by the local population or the improvement of water quality which could diminish the eutrophication of neighbouring waters.

It is also important to be consistent with the environments around the peatland. It could be that there are habitats around the restoration site which are very rich in biodiversity or are unique habitats. In which case, it is important that restoration does not result in the loss of exceptional habitats by increasing the runoff or nutrients in the system (Gottwald and Seuffert, 2005).

When blocking drainage ditches, three categories of installations are possible, depending on the restoration objective and the slope (the description of work type 1, 2 and 3 have been taken for the most part from Grosvernier and Staubli, 2009).

1) **Backfilling:** Backfilling a drainage ditch is **the most effective method to raise the level** of water table level of the peatlands affected by drainage ditches. This technique, when well executed, reverses the effects of the drainage ditches and allows for the **restoration of the peatland's hydrology**. On the other hand, this technique requires a good quantity of slightly decomposed peat or other material (like sawdust) which does not affect the chemical conditions of the peatland and allows the water to adequately circulate.

2) **Dams: This technique aims at stopping the water from flowing in the drainage ditches in order to redistribute a part of the water throughout the peatland.** A priori, the smaller the slope and the higher the peat density, the more you increase the chances of a complete and successful restoration. In some cases, it could be advantageous to choose the construction of a dam, rather than backfilling. Dams allow for the formation of water surfaces in the ditches between the dams which could potentially increase the biodiversity of a site originally without pools. The dams allow the water level to rise but the dam density is important. When the dam density is too low, the effect could be localized around the dams. Nevertheless, the water which overflows from the dams in periods of heavy rain or snow melt contributes to the rewetting of neighbouring surfaces.

When the slope is practically zero (slope < 1%), it is easier to raise the groundwater table to the surface, which creates conditions which are optimal for the growth of *Sphagnum*. In such a situation it is possible to reconstruct the hydrology of a peatland divided by a drainage ditch. When the slope is between 1 and 2%, the dispersion of the water retained by the dams is limited by surface drainage. In this case, it is more realistic to envision a rewetting rather than a complete restoration of the hydrology. This approach permits, nevertheless, a partial rising of the groundwater table and creates adequate conditions for the return of *Sphagnum*. If a complete restoration is a chosen objective, with a slope of 1 to 2% it would be better to backfill the drainage ditches because a complete restoration would necessitate an enormous amount of dams. The construction of dams on a peatland with a slope greater than 2% will probably not allow restoration or rewetting to be attained. On the other hand, this technique allows for the increase of water surfaces, locally favouring the spontaneous recolonization of *Sphagnum* and offering habitats for aquatic invertebrates.

3) **Regulation devices: Installations which aim to regulate the water level in a peatland.** This technique is very useful in peatlands which have former trenches, remnants of block-cut[1] or portions of the peatland which have a relief lower than the average of the peatland (for example: former basins for cranberry farming) and which do not possess a single outlet. **Regulation devices allow the groundwater table to rise progressively, preventing sudden flooding of established vegetation.** This technique can be used when the optimal growth of *Sphagnum* is an objective, as is the case for *Sphagnum* farming (Landry and Rochefort, 2010). This technique allows not only for a better control of water contribution according to the seasons, but also according the progressive growth of *Sphagnum* in the trenches. This technique can also be useful for halting afforestation of the trenches by flooding the trees.

When the slope of a peatland is great, it is wise to combine the techniques of backfilling and dam creation. These combinations could be applied either on all ditches or certain areas which are under greater pressure like the head of a ditch or areas with higher slopes.

In order to calculate the material necessary to block the drainage ditches according to one of the three categories of techniques proposed above, it is essential to know the exact dimensions of the ditch. The measured variables are illustrated in Figure 16, taken from Grosvernier and Staubli (2009). The dimensions should not only include the height and width of the ditch, but also the thickness of the degraded peat below and on the sides of the ditch, as it is instable. It is also recommended that the ditches are surveyed to detect the presence of dead wood and roots which could harm an installation of a future dam.

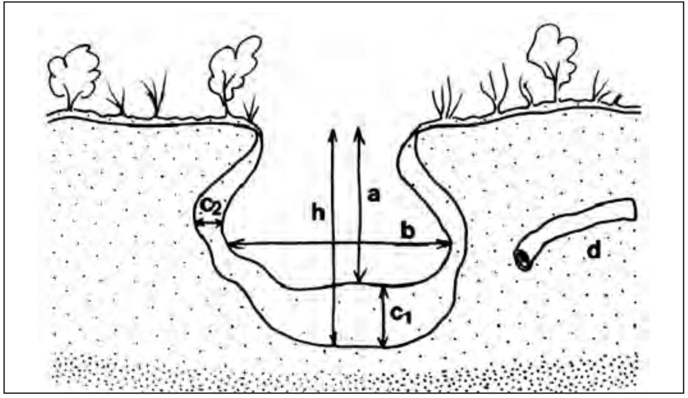

Figure 16. A vertical cross-section of a ditch: a: depth; b: width; c_1: vertical depth of degraded peat; c_2: lateral depth of degraded peat; h: height of water to be retained; d: dead wood. Figure from Grosvernier and Staubli (2009).

SITE PREPARATION AND CONSTRUCTION

Before beginning with restoration work, it is important to consult the people who live nearby or carry out activities around the peatland (for example, farmers) in order to explain the work and to create a rewetting plan which is adapted to the realities of the site. These stakeholders will be more in favour of the project if they understand it well.

It is also important to prepare precise plans and clear instructions for the workers who will work on the construction of the installations. The safe circulation of machinery is important for the safety of the workers, for the machines, and to avoid damaging the machinery. It is important to define in advance the paths for the heavy machinery, areas that should be avoided

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[1] Block-cut: A manual peat harvesting technique which consists of extracting blocks of peat with a shovel along a trench. Thus, trenches are created which could have an average of 1 m depth and be 10 to 30 m wide and up to circa one hundred meters long.

the exact site of installations and the zone from where the material should be taken. One option is to use color codes to define each zone to create an approximate plan and give this to the workers.

Ideally, it is preferable to employ construction workers who have already worked with heavy machinery in a peatland. If not, it is important to inform the workers of the peatland's structure and the instable composition of the substrate which can change within a few meters- these environments are sometimes full of surprises! When an excavator is used, avoid pivoting in place because the tracks destroy the *Sphagnum* carpets (Grosvernier and Staubli, 2009). A passage which may seem solid for a certain distance can quickly soften if precautions are not taken. When the soil is wet an efficient method of solidifying the peat is to stack branches or trunks across the road (see Figure 17 for an example).


PHOTO : Olivier Marcoux

Figure 17. Road covered with wood logs and branches to allow for passage of the machinery in the peatland Grande plée Bleue (Québec).

Assure a good surveillance of the construction site: the construction site should be supervised for a minimum of two hours each day for the entirety of the work. A telephone number should be left with workers in case of questions. It is better to be present often to avoid complications later.

During the work, be sure to have plastic containers to store the living plant material. This material can be used for the revegetation of the dams after their completion as well as the areas where peat was taken. In this way you can avoid damaging the vegetation around the perimeter of the construction zone (Grosvernier and Staubli, 2009).

TREE REMOVAL

One operation necessary for the optimal rewetting of a peatland is the removal (cutting down) of trees which proliferate around the perimeter of the ditch, a direct consequence of drainage. The species which are non-typical to peatlands, such as birch, should be removed. Sometimes the proliferation of these trees can be significant: they contribute to drying out the peatland and can become invasive. In order to minimalize the stump debris, the Peatland Ecology Research Group (PERG) cuts the trees at chest height (Figure 18).


PHOTO : Line Rochefort

Figure 18. Birch trees cut at chest level at the peatland Bic – Saint-Fabien (Québec).

Additionally, all the trees which are found in the perimeter of the construction zone should be cut down to allow for the circulation of the machinery. In the case of dam construction, it is possible to make holes where the dams are constructed. It is recommended to make the hole sufficiently big for an excavator to rotate 360° with its extended arm.

The period in which the trees are cut can influence their ability to grow back. In principal, cutting the trees can be executed just as well during a period of dormancy as during a period of growth. However, for many competitive species, like wild red cherry, mountain maple, paper birch, and the quaking aspen, a cut during the growing season (July through September) at 15 cm creates the best results (Doucet et al., 2009). During this operation the cut trees on the border of the ditch can be stripped of their branches and left on the site to help solidify the dams or to put through a chipper to fill the ditches.

BACKFILLING

Backfilling a ditch using peat

This type of backfilling means filling up the drainage ditch with peat. However, it is recommended to add dam construction simply to solidify the peat, to assure the work is sealed, and to prevent that the peat collapses when there is a big rain event (Grosvernier and Staubli, 2009). It is very important to compact the peat in the ditch with an excavator to assure the stability of the installations.

The peat used for backfilling can be imported from another peatland or from around the area of the installations. However, it should be peat which is only slightly decomposed to allow for a good integration of the walls and bottom of the ditch. This will recreate homogeneous physical conditions across the surface of the peatland. If the peat quantity is insufficient for backfilling all of the ditches, it is recommended to start with part upstream and progress towards the downstream part. It is important to backfill a ditch by creating a mound of 30 to 50 cm above the peatland level in order to take natural compaction into account (Grosvernier and Staubli, 2009). If the backfilling is limited to the level of the peatland, a new small ditch above the backfilling might form. Poorly compacted backfilling is inefficient because it does not stop water from flowing in the ditches.

On top of effective compaction, the peat must adhere completely to the walls. To accomplish this, stagnant water in the bottom of the ditch should be pumped out and the decomposed layers in the ditch should be removed (layer c_1: see Figure 16). You must remember that the layer of decomposed peat which will be removed from the ditch must be transported off the site. A large quantity of decomposed peat can become difficult to manage. If the vegetation is already established on the bottom of the ditch, this could be conserved nearby and replanted on the backfilled ditch at the end of the installations in order to stabilize the surface of the dam and to obtain a more aesthetic landscape.

Backfilling the ditch using wood sawdust

The method of backfilling with sawdust follows the same recommendations as the backfilling method with peat. The only difference is in the compaction process. It is enough to backfill with dry wood, wait until the sawdust moistens and compact it with your feet or machinery. Sawdust, when wet, is very easy to compact and, once compact, will keep its same volume (Grosvernier and Staubli, 2009). It is therefore not necessary to create mounds of 30 to 50 cm as with peat backfilling. The wood sawdust backfilled into the ditch should only come to the level of the peatland. After backfilling, as for the peat, the vegetation can be added on top of the backfill.

Sawdust is a good substitute for peat. It is organic, practically inert, does not decompose in anaerobic conditions, has a low porosity and usually inexpensive. The wood sawdust is light to transport and is, therefore, ideal for areas which are very far away (Grosvernier and Staubli, 2009). Additionally, because it can be easily transported by hand, this type of backfilling can be converted into a voluntary project for a community. Because sawdust does not compact much, the use of machinery for its compaction is not necessary.

Grosvernier and Staubli (2009) recommend relatively fine sawdust, meaning without shavings or a maximum of 50% shaving ranging from 1 to 2 cm. The tree species used is not important. According to this study, the technique remains efficient even when the slopes are greater than 2%.

THE DAMS

Many types of dams are recommended in the literature for blocking the drainage ditches. This section will present first the applicable concepts for all types of dams, be it the space between them or how to fight erosion on the edge of the ditches. First a summary description of the dams adapted for the small drainage ditches will be given: dams made of wooden planks, or of metal, of Plexiglas or corrugated plastic (single or double), peat dam with straw bales or of ericaceous shrubs. Then, a summary of the dams adapted for mid-sized and large dams will be given: wooden dam, wooden dam with backfilling, nested rigid plastic, stone gabions, and stones piles with walls.

Spacing of the dams

The budget and the initial objective will have an influence on the space between the dams. Nevertheless, the principle factor to take into account is the volume of water that should be retained and the slope (Evans et al., 2005; Armstrong et al., 2009). In the literature, there are no absolute values for the spacing between dams, however, some general guidelines are proposed.

Evans et al. (2005) and Kozulin et al. (2010) recommended a 'stairs' approach. This means that the dams are at intervals so that the top of the dam is situated slightly above the foot of the upstream dam (Figure 19). The dams are spaced in such a way that the runoff of the first dam flows into the water retained by the dam downstream. This is done to assure that the overflow water does not constantly run out onto bare peat or mineral substrate, where erosion risks may lead to a weakening of the dams. A continuous water surface should be created between the dams. Kozulin et al. (2010) recommends that the water level between the dams should be between 30 and 40 cm to avoid erosion (Figure 19).

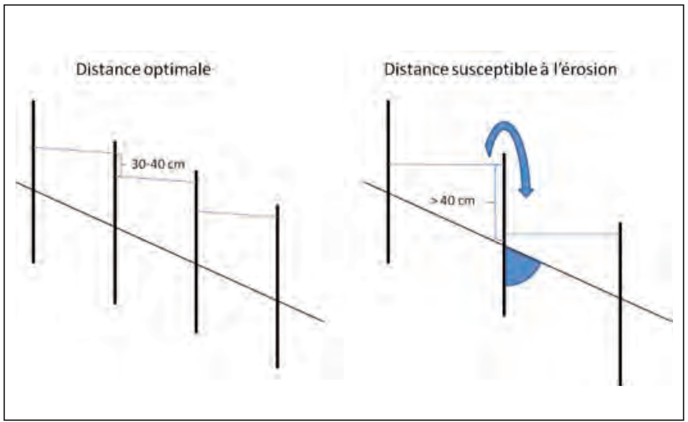

Figure 19. An optimal spacing design between dams for avoiding erosion. Adapted from Kozulin et al. (2010).

The topography of the land is important. It is not always appropriate to distribute the dams equally among themselves (Armstrong et al., 2009). If the slope in the beginning of the ditch is greater than at the end of the ditch, the first dams will be closer than the last.

Fight against erosion

Thawing and heavy rains make dams susceptible to erosion. Here are some suggestions on how to counter the devastating effects heavy rainfall can have and dams and ditches.

It is important to construct dams that exceed the width of the ditch on both sides to encourage a better redistribution of water around the dam. This is also an effective way to combat erosion of the dam walls and to make sure the water doesn't flow around the dam and return to the ditch (Armstrong et al., 2009).

When the risk of flood is high, the dams could be constructed higher and larger in order to favor the dispersion of the surface water runoff from the peatland (Grosvernier and Staubli, 2009). On the other hand, in certain situations, the rewetting must be done gradually and a surge of water onto the peatland surface or surrounding environment should be avoided. This is the case if agricultural lands and other installations are found in the area. In these cases, a plan must be made for the overflow in order to manage the occasional excess water.

A relatively simple technique for preventing overflow and erosion on the sides of the dam is to create notches on center of the dams. In general this practice is not advisable (Armstrong et al., 2009) because it leads to the erosion of the bottom of the ditch and weaken all of the dams situated downstream. Nevertheless, if this technique is used, many small notches should be used (Figure 20). Because the water will be dispersed over many small notches instead of one single one, the force of the water hitting the bottom of the ditch will be minimized.

More elaborate installations for overflow can be installed, either by constructing a wooden frame or installing an outlet pipe (Grosvernier and Staubli, 2009). On the other hand, such installations need to be maintained as time goes on to ensure their operation.

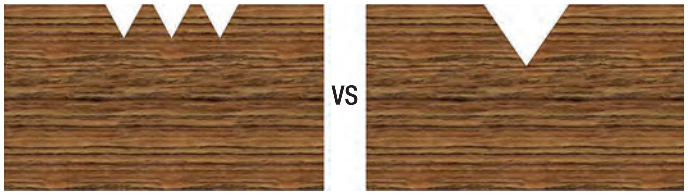

Figure 20. Several notches are recommended instead of one single notch.

In very large dams, Kozulin et al. (2010) suggested the construction of drainage culverts. They also recommended placing plate made of metal, wood or cement at the exit of the culvert in the form of a gutter to avoid the erosion of the bottom of the ditch.

In order to reduce the erosion of deep ditches that have steep walls, Armstrong et al. (2009) suggest reshaping the edge of the ditches between the dams from a right angle to 45°. When the reshaping is carried out well and vegetation is planted along the ditch edges, sediment loads, runoff, and bank erosion is reduced. Additionally, this technique can be very appropriate in habitats where abundant wildlife is found as it facilitates the circulation of large animals, for example moose.

When constructing a simple dam without filling, Armstrong et al. (2009) recommend positioning the dams perpendicularly to the ditch. When the quantity of water exceeds the capacity of dam, this configuration should stop the water from skirting around both sides of the dams and erode the edges, which could lead to the collapse of the dam.

For all dams, it is recommended to create a moderate slope of well-compacted peat upstream and downstream of the dam. Moderate slopes stabilize the structure and permit the revegeta-

PHOTO : Marie-Claire LeBlanc

Figure 21. The installation of stabilization net at the peatland Grande plée Bleue (Québec).

tion of the dam. In order to stop the peat from being eroded by the water, this slope could be covered by a stabilizing net (a mat made from coconut fibers; for example, see Figure 21). The vegetation can be introduced on top of such a net after the installations are finished. If a coconut mat is used, it is also possible to carry out vegetation plantations while including the mat. The mat should be used following the instructions of the manufacturer. You must remember that peat, even if it is well-compacted, is more instable than substrates usually used for such retention structures (for example: along the road). The long wooden stakes driven into the ground with a mallet will fasten the mats better than metallic staples usually used.

DAMS: BLOCKING SMALL DAMS

Dams using wooden planks

The dams made with wooden planks are affordable and efficient installations for shallow ditches. The standard dimensions for the wooden planks found in stores is usually 1.25 m x 2.5 m, which is why they can only be used for shallow dams. The plank should be sunk a minimum of 60 cm into the beat (if possible at least 30 cm into the mineral soil) and should as well surpass at least 60 cm on each side of the ditch to avoid water leaking through the dam (Grosvernier and Staubli, 2009; Figure 22). If the presence of deadwood makes the installation of wood planks difficult, a chain saw can be used to cut a slit in the peat in the ditch. In order to facilitate the insertion of a plank in a slit cut by the chainsaw, Grosvernier and Staubli (2009) recommended the use of a metallic support brace which will allow an excavator to be used to push the plank deeply into the peat without damaging the peat.

When the peat is very soft, Armstrong et al. (2009) recommend the use of a wooden plank rather than the surface blocking techniques (for example: straw bale and peat, discussed below). The panels can be anchored in the substrate and have less of a chance of being carried away by a big amount of water or instable peat. A small quantity of peat well-compacted and placed upstream and downstream from the plank should be planed to stabilize and cover the installation.

Dam made of metal, Plexiglas or corrugated plastic

The dams made of wooden planks can be reproduced using different materials, including metal panels, Plexiglas or corrugated plastic. According to a study by Armstrong et al. (2009), who compared 32 rewetted sites in the United Kingdom, the wooden planks were more effective than corrugated plastic. The choice of material for a dam is influenced by many factors. For example, if the rewetted site does not allow machinery access and the material must be transported by hand; it would be preferable to opt for a lighter material such as corrugated plastic. On the other hand, if the initial objective is to use only natural materials, the choice of a wooden plank would be more appropriate. The wooden planks, being more porous material, have the potential to retain more sediment and therefore create a natural filling in of the ditch upstream. Therefore, peat fills in the ditches without adding compacted peat upstream and downstream of the dam (Armstrong et al., 2009). From the aesthetic point of view, the wooden planks blend in more with the landscape. In terms of durability, the non-oxidizing metals, although the most expensive, do not crack or rot with time and are very resistant.


PHOTO : Flor Salvador

Figure 22. Installation of a wooden plank covered with a geotextile (Bic – Saint-Fabien peatland, Québec).

Dam with double panels

This technique, proposed by Grosvernier and Staubli (2009), is a variation of the panel dams. This technique is appropriate when the water column that should be held by the dam is more than 50 cm. It is enough to install two independent, perpendicular panels in the ditch 3 or 4 m from one another. The portion of the ditch between the two panels is then filled using one of the backfilling materials described above (peat or sawdust). The vegetation found at the bottom of the ditch could be recuperated before beginning work, conserved and then transferred to the filled in area after the installation is complete.

Peat dam

For a drainage ditch where the slope and water pressure are low, the construction of a peat dam is an economically viable option. The vegetation taken from the bottom of the ditch is conserved and put aside to be added on top of the dams at the end of the work. It is important to remove approximately 30 cm from the layer that covers the ditch in order to assure a better adherence between the new peat and the ditch (Kozulin et al., 2010).

The dam consists of a peat mass that has been well compacted at the bottom of the ditch forming a pile where the height is at least 30 to 50 cm higher than the rest of the peatland (Quinty and Rochefort, 2003). Kozulin et al. (2010) even recommended a height of 70 to 100 cm. The dam should also be larger than the ditch, either 2 to 3 m larger than the ditch walls (Quinty and Rochefort, 2003; Kozulin et al., 2010). The longer the dam (in the direction of the ditch), the more stable it is.

In order to assure an optimal compaction, an excavator should press each layer of peat added in the ditch. The peat used should not be the surface peat as used for backfilling. The peat used should come from greater depths, meaning more decomposed. The more the peat is decomposed, the lower the hydraulic conductivity which assures a better seal (Rochefort, 2001). Dead wood should be avoided as it can be an inlet for water infiltration (Quinty and Rochefort, 2003). Peat dams which are well constructed and placed at 50 to 75 m intervals can raise the water table level (Price, 1996; see Figure 23 for a peat dam in construction).

Dam with straw bales and branches from ericaceous shrubs

In a peatland which is drained by small ditches, one option for blocking ditches is the use of straw bales (Evans et al., 2005; Armstrong et al., 2009; Figure 24) or a bale of ericaceous shrub branches (Blanket bogs in Wales, 2011). The straw or ericaceous bales are compacted in the ditches and solidified either with the wooden logs inserted deeply into the bottom of the ditch or other types of stakes. The straw bale is, according to the region, easily accessible and affordable. Because these structures are natural, they are an aesthetically pleasing option.


PHOTO : Olivier Marcoux

Figure 23. Peat dam in construction at the Grande plée Bleue peatland (Québec).

It is not the straw which will block the water, but rather the sediments that accumulate in the straw bale which permit an effective rewetting. According to Armstrong et al. (2009), the rate of success for this technique is comparable to the success rates using wooden planks. The authors strongly recommend this technique when the peat at the bottom of the ditch is dry. In this situation the straw bale will accumulate the sediments during the rewetting process and will adapt to changes in the consistency of the peat. On the other hand, a dam constructed for being watertight, like a wooden plank dam, will have a more difficult time adapting to the changes in volume of peat when it is flooded. The risk of failure is thus higher. As specified by Evans et al. (2005), it is important to assure the absence of pesticides in the straw in order to avoid contamination.

Dam of logs

Dams made of wooden logs are strongly discouraged (Grosvernier and Staubli, 2009). In order to execute this technique, the logs are piled horizontally or placed side by side vertically in the ditch. The logs stacked up on each other do not ensure a good seal (Figure 25), it is the peat that accumulates around the logs that allows water to be retained. In order to improve the seal of the dams, a geotextile can be added to the dam. PERG experimented with this technique to rewet a fen in the Bas-Saint-Laurent region of Québec. More than four hours was needed for the construction and the adjustments of the dam using small logs, while the construction and installation of five other subsequent dams using wooden planks took only one hour per dam, including the addition of peat upstream and downstream from the installation as well as replacing vegetation.


PHOTO : Geneviève Allard

Figure 24. Straw bales


PHOTO : Flor Salvador

Figure 25. Dam made of wooden logs: a technique which is not recommended.

DAMS: BLOCKING MID- TO LARGE-SIZED DITCHES

Dam using wooden planks

This technique consists of piling wooden planks either horizontally or vertically and nailing them together. Sometimes the individual insertion of the planks can be difficult and can have bad results if the substrate is heterogeneous and involves dead wood (field observations by Olivier Marcoux; Figure 26). If the construction is done manually, Kozulin et al. (2010) recommends laying a tree trunk at least 30 cm in diameter at the bottom of the ditch and to attach the planks vertically to assure better stability. To make this task easier, if machinery is available the dam can be constructed before in front of the installation in the ditch (Figure 27).


PHOTO : Olivier Marcoux

Figure 26. The technique of a vertical dam by individual insertion; observation of the openings between planks.


PHOTO : Olivier Marcoux

Figure 27. Dam of wooden planks.

As with all the preceding dams, the planks have to be inserted into the peat as deeply as possible at the bottom of the ditch and into the walls of the ditch (at least 60 cm) to assure the solidity of the structure and avoid erosion (Grosvernier and Staubli, 2009). In order to assure the seal of the installation a geotextile or a polyethylene sheet should be installed in such a manner that the upstream face of the installation is completely covered to prevent leaks. The dimensions of the planks can vary, however, the thicker the planks are, the more resistant they will be. A little quantity of peat well compacted and placed upstream and downstream of the dam will cover and solidify and the installation.

When the dams cannot be constructed ahead of time and transported, the material of choice are tongue and groove planks where the ends are bevelled. Bevelled planks, thanks to their tongue and groove edges, fit one into another ensuring optimal sealing. Due to the bevelled edges, the planks, when they are driven into the peat and reach the underlying mineral soil, are firmly pushed against each other. In order to avoid dislocation, Grosvernier and Staubli (2009) recommend the use of boards installed horizontally on each side of the dam and fastened with a clamp to ensure that the boards for the dam are aligned. These boards could be inserted on either side of the dam after construction. In order to assure the solidity of the dam the lateral and vertical anchorage can be added (Figure 28).

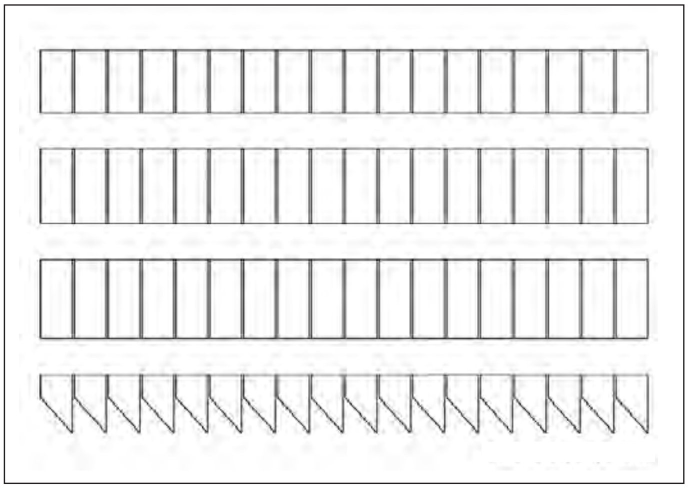
PLAN : Olivier Marcoux

Figure 28. A diagram of a vertical dam with horizontal reinforcement.

Kozulin et al. (2010) suggest another configuration (Figure 29). With this technique, the insertion of the planks begins in the center and progressively moves to each side. The center of the dam is lower which allows for a certain quantity of water to circulate. This type of configuration is recommended for ditches with a width of approximately 2 m or the water pressure is strong and the water flow is high (up to $2\ m^3\ s^{-1}$).

The dams must be made sufficiently large to avoid erosion of the banks. This means for a dam that is 2 m wide, 1 m should be added to each side of the ditch on the banks (Kozulin et al., 2010). It is important to probe the bottom of the ditch before dam installation beings in order to find the optimal place for to place the dam, meaning the place where there is the least amount of dead wood or roots. The roots and dead wood situated on the surface can be cut using a chain saw. If the water pressure is too strong, it is possible to double the walls with backfilling in the middle, as was done for the double wooden plank dam. Because it is not easy to insert all of the planks at the same depth, at the end of the installation, the tops of the planks can be evened off with a chain saw. Solidifying the installation with peat slopes upstream and downstream of the installation permits the stabilization of the structures.

Double wooden dam with backfilling

The dams made of wooden planks can be doubled to provide more solidity. When a double dam is constructed on dry ground, before being installed into the ditch, it can be made in two sections: a lower section and a higher section. Figure 30 is a construction diagram of double wooden dam constructed for a drainage ditch where the water pressure was high and the dimensions were 3 m width by 1.75 m depth to the mineral soil. The dams are kept together by the planks nailed and attached to the structures in the form of a U for more stability (Figure 31). The base is installed solidly at the bottom of the trench and is compacted. After the upper section is added and solidified using nails and then backfill. The stages and the necessary material for this type of dam are very well described in the interim report 2010 for the rewetting project in the southern section of the Grande plée Bleue peatland near Québec City (Landry and Marcoux, 2011). For all large-sized horizontal dam, you must alternate the joints between the planks to prevent the dam from splitting in two.

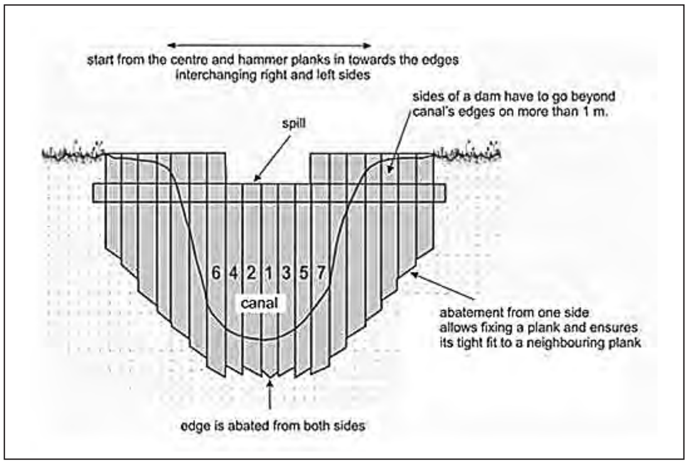

Figure 29. Vertical dam constructed starting from the center and lower in the middle to counter the effects of water pressure and allow water to pass. Figure from Kozulin et al. (2010).

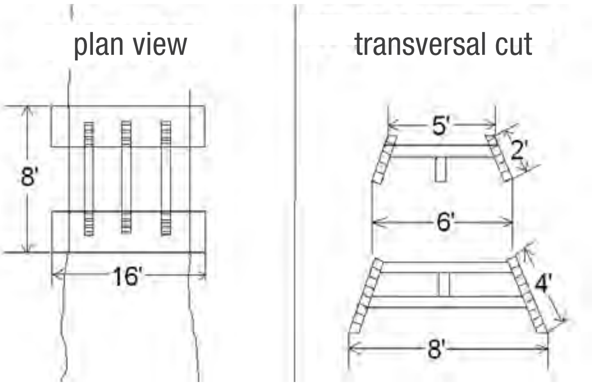

Figure 30. Construction plan for a double wood dam. A traversal cut of the left represents the two sections of the constructed dam separately and assembled in the ditch.

PHOTO : Olivier Marcoux

Figure 31. U structure for stabilizing the stakes.

Plastic piling dam

This technique, comparable with the wooden dam technique, is for blocking large ditches but with different material. Because this material is very resistant, this technique is recommended for ditches that store much water, like the sloped peatlands or also for a principal ditch into which the secondary ditches flow (Armstrong et al., 2009). This type of dam should be inserted as deeply as possible into the mineral soil in order to be efficient and to avoid leaking. It is equally possible to double the dam for more solidity. The plastic dam does not trap sediments as efficiently as the wooden dams or the straw bale dams. The water accumulates upstream of the installation which creates movement and dislodges the sediment as they accumulate, keeping them suspended in the water (Evans et al., 2005). Consequently, when installed by itself, this type of dam is the least discrete because it is not camouflaged by the peat as quickly as the dams made of natural material that is more porous. Therefore, it is important to cover the dam with compacted peat upstream and downstream from the installation for a more aesthetic dam.

Stone gabion

A stone gabion is a solid structure that can be constructed in a drainage ditch which reaches the mineral soil layer (Figure 32). As is the case for the straw bale technique, it is not the stones as such that stop the water from circulating, but more the peat which settles and will block the spaces between the stones. It is important to choose acidic stones so that the water chemistry of the peatland is not completely changed. The stones are kept together using metal cages which are welded together, thus forming a solid wall to retain large quantities of water. This option could be interesting to use for the large ditches which have eroded down to the mineral soil. On the other hand this option can be expensive if the material must be transported onto the site. According to Evans et al. (2005), a stone wall may also require rigorous maintenance.


PHOTO : Line Rochefort

Figure 32. Stone gabions (South Africa).

Dams made using stones piles with walls

Kozulin et al. (2010) suggest another type of large dam for big drainage ditches. The first step is to place a wooden dam perpendicularly to the ditch. This dam must be inserted very deeply (minimum of 8 m depth). At each side of the dam, a pile of peat is placed sloping away from the installation over a distance of 5 to 20 m. After this, a layer of stones at least 20 cm thick is added to the two slopes of peat. At each extremity of the construction, one dam is installed to ensure that the rock walls do not collapse.

DEVICES FOR WATER REGULATION

Wooden regulation tank

A regulation tank is used when the water is being channeled towards a single outlet. This technique permits a progressive input of water into the system via an outlet pipe. The water can be controlled either from above with a series of planks stacked up which can be added or removed depending on the height desired (Figure 33) or controlled from below by an outlet door which can open (Figure 33). The regulation tanks are more effective when used in small ditches. They can be used for larger-sized outlets when they are combined with a dam (Grosvernier and Staubli, 2009) or are improved by adding wooden planks as seen in the second tank of Figure 33. The first tank of Figure 33 also has wooden planks on each side to stop erosion, but they are buried in the peat to create a more aesthetically pleasing result. The tanks must be solidly fastened to the walls and the bottom of the ditch to avoid leaking. For more stability, the inside of the tank can be partially filled with rocks or the tank could be solidified with pieces of metal. For installing this dam an excavator is necessary.


PHOTO : Marlies Hähni

PHOTO : Josée Landry

Figure 33. Regulation tank being controlled from above (1st photo), installed to block a basin in Sainte-Marguerite peatland, in Québec. A regulation tank controlled from below (2nd photo), installed to block a basin in Shippagan (New Brunswick).

Cement water control construction

Grosvernier and Staubli (2009) propose a cement chamber model with a control valve. Kozulin et al. (2010) propose cement culverts with a control system. These two models fill the same objectives as the regulation tank, but they are much more complex and more expensive to carry out. However, they are very solid and can manage large volumes of water. They should be installed ideally on a mineral substrate with the help of a hydraulic engineer.

REMOVING MATERIAL FOR BACKFILLING AND SOLIDIFICATION

When a peatland's hydrology is being restored, it is important to develop a strategy for obtaining the material in a way that will have the lowest impact possible on the environment. The best material in acidic peatlands is, without a doubt, peat. This resource is not only available in the field, but it also has the appropriate pH which means that the chemical properties of the peatland will be kept intact. The material used for backfilling work in a ditch should be weakly decomposed surface peat to insure water circulation and to return to a hydrology more 'normal' (Grosvernier and Staubli, 2009). While if the material is needed to make the dam leak-proof or stabilize the dams, it is better to use peat which is more decomposed and more impermeable than the peat from the surface (Armstrong et al., 2009).

When excavating peat for rewetting purposes one highly recommended technique is to dig out pools upstream from the dams (Figure 34; Armstrong et al., 2009; Grosvernier and Staubli, 2009). These pools create a kind of retention basin which reduces the velocity of the water when it suddenly becomes abundant, which would lower the risk of erosion (Armstrong et al., 2009). From an ecological point of the construction of pools is desirable because they increase the floral and faunal diversity of the site (Poulin et al., 2002; Fontaine et al., 2007). The construction of a series of small pools which hold smaller quantities of water is better than big pools which have the potential to collapse more easily (Evans et al., 2005).

PHOTO : Olivier Marcoux

Figure 34. Creating a pool allows for the collection of peat material for the construction of a peat dam at the Grande plée Bleue peatland (Québec).

Aside from peat, other materials for backfilling can be used. Sawdust, an inert organic material, can be an interesting alternative. Because wood sawdust can be mixed with wood chips, this type of material can be interesting for eliminating wooden logs left on the site after cutting down trees during site preparation.

For a more solid filing, rock can be used to backfill certain dams and tanks. However, it is important to avoid using rocks which are calcareous as this could change the chemical properties of the peatland. For example, initially clay would seem to be an interesting material as it is extremely impermeable, but its use must be limited because it is generally basic and contains many minerals. An excess of minerals and alkalinity is harmful for the growth of *Sphagnum*.

PRACTICAL RECOMMENDATIONS APPLICABLE TO ALL TECHNIQUES

Here are some recommendations which apply to all the dam or backfilling construction techniques :

- The work should be carried out during the driest period of the year. If the work must be carried out during a humid period or if the water is permanently in the ditches, it is necessary to evacuate the water using a pump to assure a better adherence of the dams. It may be necessary to construct a temporary dam upstream and downstream from the dam to divert the water into a secondary ditch to allow the construction in dry conditions (Grosvernier and Staubli, 2009; Kozulin et al., 2010).

- Avoid working in period of frost: the peat and clay are very difficult to manipulate and their structure is not very stable.

- When constructing large dams of wood with peat, it may be necessary to add stones or cement to solidify the structure and counteract the floatability of the structure.

- It is advisable to use types of wood that are stable and do not rot easily, such as cedar, hemlock, jack or red pine, and the larch (Ministère des Ressources naturelles du Québec, 1997). Spruce is also a good choice and is less expensive. Avoid using birch and poplar, as they tend to rot more easily.

- When dams are made of wood, it is important to minimize the risk of rotting. The wood's contact with oxygen should be limited by keeping the water level so high that the installations are submerged in water or adding well-compacted peat upstream and downstream from the installation (Grosvernier and Staubli, 2009). The revegetation of the installations creates a more aesthetically pleasing result and contributes to the creation of new habitats.

- In order to improve the impermeability, a geotextile can be added to all installations (Figure 35).

PHOTO : Flor Salvador

Figure 35. Installation of a geotextile at the base of a future dam at the peatland Bic – Saint-Fabien (Québec).

CONCLUSION

The drainage of peatlands is a widely used technique which entails numerous impacts on the peatland. These impacts are well documented in the literature. However, a range of techniques exist to return a normal functioning peatland. In order to guide the participant in the choice of a technique which will block drainage ditches in a peatland, we have created a flow chart to help in decision-making (Figure 36). It should be noted that the recommendations given by this tool do not take budget into consideration. Nevertheless, it gives a good starting point for successfully rewetting a peatland.

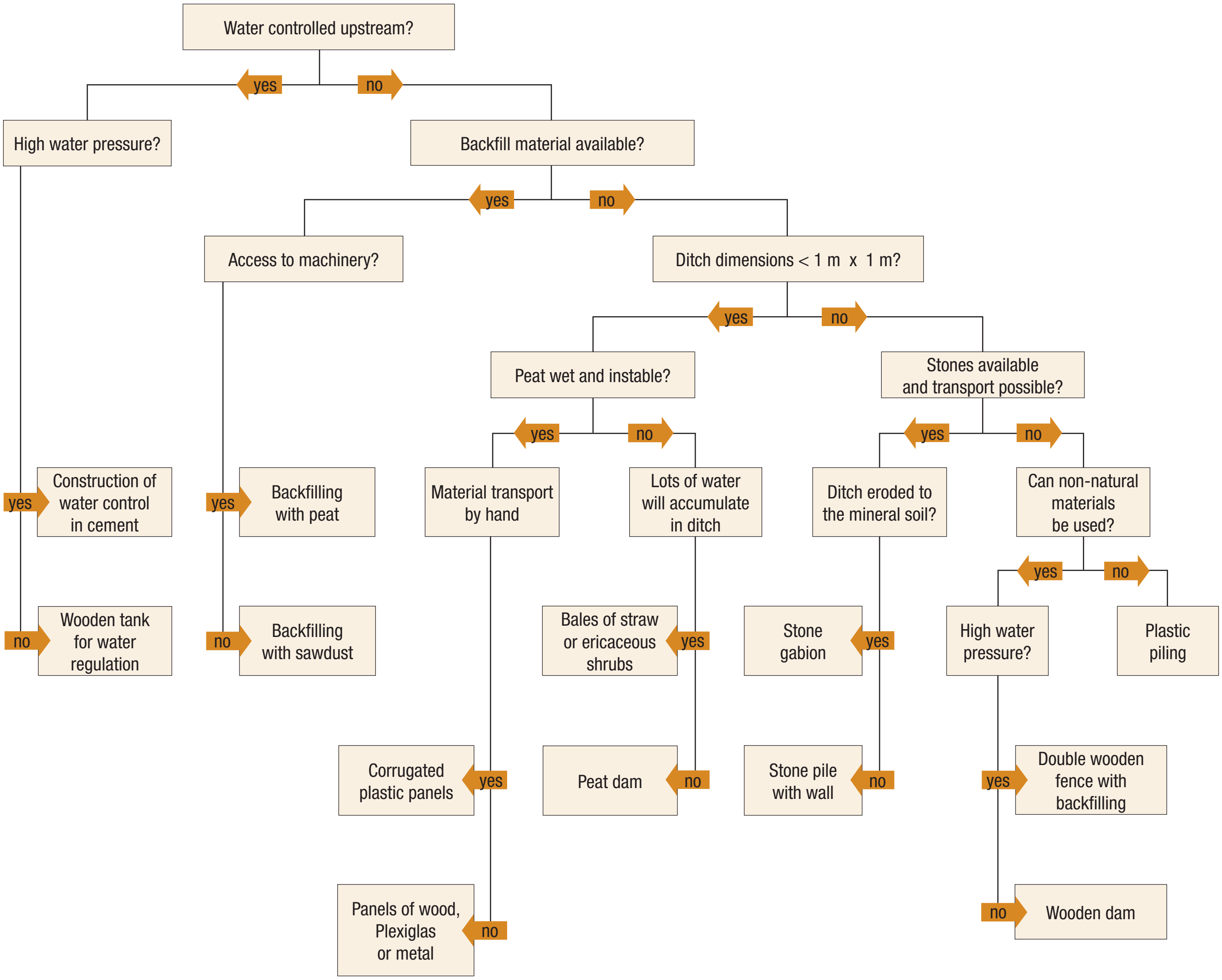

Figure 36. Flow chart to help in decision-making for blocking drainage ditches in peatlands.

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