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in

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Characterization of bogs and their role in CO_2 storage

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Ai miei genitori.

Anche in questo percorso mi avete sostenuta

dandomi forza, volontà e coraggio.

Vi ringrazio ancora una volta per

essermi sempre stati vicini e

per aver creduto in me,

quando io non ho saputo farlo.

Ancora una volta, devo tutto a voi.

Grazie.

Contents

Abstract

This study aims at analyzing peatlands, specifically alpine peat bogs, and how climate change can affect the development of these environments. Therefore, it has been used a computer model (DigiBog), created by Baird et al. (2012), thanks to which it is possible to study peatland development over time. Once understood the model and verified its functionalities, we applied it to the selected case study, which is an Alpine peatland located near Misurina lake (Italy). In order to do so, we collected field measurements to constrain the model for the actual geometry of the study site, as well as soil samples to obtain soil properties used as inputs in the model. Meteorological data were provided by ARPAV, thanks to the presence of a meteorological station near the Misurina lake. Finally, to understand how climate change may affect the development of this type of environments, we consider the forecasts of the Euro-Mediterranean Center on Climate Change (CMCC), with Representative Concentration Pathways (RCP) of 8.5. This scenario, in fact, which is the worst-case scenario provided by the IPCC (International Panel on Climate Change), appears to be the most realistic, because today other scenarios are outdated, given the current conditions of emissions and mitigation (Schwalm, Glendon, and Duffy, 2020). In order to give a better context to the work done, a general description of the peat bogs and their importance from the climatic point of view was first introduced; then DigiBog, with which the maps were created, was described in detail. It is clear that the study of peatlands is fundamental, because it allows to understand how they can develop under specific conditions, and how they will adapt to future

climate scenarios worldwide. From the outputs obtained through DigiBog it is possible to understand that the model is able to represent in a fairly true way the real growth of the peatland, therefore it can be considered a valid tool to obtain data on the development of peatlands.

Chapter 1

Introduction

1.1 What are peatlands

Peatlands are a terrestrial ecosystems that have been formed from 10-40 thousand years ago, and they are a distinctive wetland type, characterized by the accumulation of partially decayed organic matter, forming layers of peat (Charman, 2009). In a peatland, the many layers of peat are spongy and saturated with water: due to this condition, the production of organic matter exceeds the degradation rates, resulting in an accumulation of peat. The substrate saturated with water is the predominant factor for the formation of peat, which is an organic material of vegetable origin resulting from the accumulation of undecomposed substances. The water in fact reduces the presence of oxygen, which is used for the metabolism of decomposers (bacteria, fungi and other microorganisms). Therefore, in living peatlands, the production of organic matter exceeds the degradation rates (as mentioned earlier), resulting in a positive carbon balance (Hans Joosten). Specifically, as the International Peatland Society points out, a wetland is a landscape experiencing high amounts of water at the surface, either permanently or for considerable periods in the years. Waterlogging can be by fresh or saline water and in some cases the surface can be permanently flooded.

A general definition of peatlands is any ecosystem where peat has accumulated to a depth of $>$ 30-40 cm (Charman, 2009), and in accordance to the International Peat Society, peat is the surface organic layer of a soil that consists of partially decomposed organic matter, derived mostly from plant material, which has accumulated under conditions of waterlogging, oxygen deficiency, high acidity and nutrient deficiency. Another definition of peat derived from FAO and US soil classification, according to which peat is organic soil with a thick A horizon (Histosol). As specified above, peatlands is a specific type of wetlands with the unique potential to accumulate dead organic matter as peat, often to considerable thickness; peat accumulates as a result of an imbalance between plant productivity and decay (Charman, 2009).

Peatlands, moreover, are a living ecosystem with two fundamentals needs: water and plants. Through photosynthesis plants extract carbon dioxide from the atmosphere and store it as carbon compounds, like starch and carbohydrates. The carbon dioxide is stored as carbon in the soil, and because the peat is permanently saturated with water, the carbon will not be converted into greenhouse gasses. Peatlands can be classified in two categories: bogs and fens. Bogs are Ombrotrophic system that receive water and nutrients only from atmospheric sources (e.g. rainwater).These environments are hydrologically isolated from the adjacent landscape and this results in low pH, low nutrient (Charman, 2009). Fens are Minerotrophic system and they also receive atmospheric water but are in addiction affected by runoff or groundwater that has been in contact with mineral soils, and is therefore enhanced in nutrients and of higher base status and pH (Charman, 2009).

Peatlands occur in every climatic zone and continent, but as peat only accumulates in areas with excesive moisture, the distribution of peatlands is deeply affected by climate (Joosten, 2015). In the boreal zone peatlands contain 7x more carbon per ha than other ecosystem, while in the tropics 10x more carbon (Joosten, Sirin, et al., 2016, Joosten and Couwenberg, 2008). The total area globally is around 4 million km^2 (Lappalainen, 1996), making them 70% of natural freshwater wetland or 3% of the land surface of the Earth; in contrast, forests cover 30% (10 times more)(Figure 1.1). Trees can hold the carbon in the short term, but there is a need to consider what happens to these trees in the long term. If trees continue growing, obviously they can continue to absorb carbon, but eventually trees will die or be cut down and the carbon they seized during their lifetime will be released back into the atmosphere. Bogs are more a long term type of game, where they can hold carbon for thousand of years. In fact forests are important for the climate, but peatlands are even more important because they can contain more carbon and they can do so for longer than forests; peatlands account for more than 1/3 of the carbon stock, holding more than 30% of the Earth's carbon in the soil. In fact peatlands can contain 550Gt of carbon in their soils and this is the equivalent of the 75% of carbon contained in the air, equal to all terrestrial biomass and 2x the carbon stock in the total forestal biomass of the world (Joosten and Couwenberg, 2008).

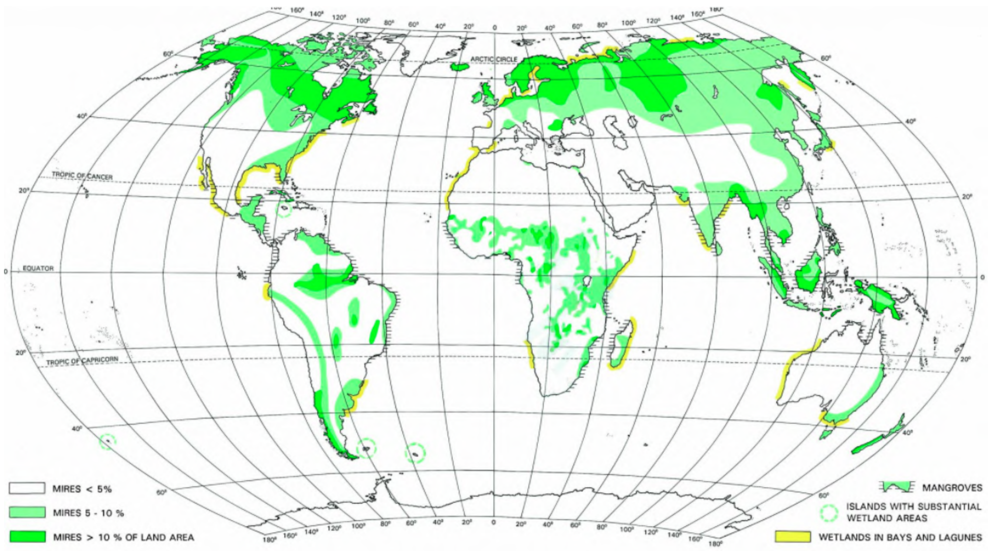


Figure 1.1: Global peatland distribution expressed as a proportion of the total land surface. (Lappalainen, 1996) [Reproduced with permission from the International Peat Society]

Peatlands include landscapes that are still actively accumulating peat (mires), others that are no longer accumulating and do not support the principal peat forming plants (e.g. *Sphagnum spp.*), and peatland used for economic uses such as agriculture, forestry and excavation for energy generation, horticulture and other human activities.

As Charman writes (Charman, 2009), in terms of aerial extent, most peatlands occur throughout the northern mid to high latitudes (Figure 1.1). The remainder occur principally in the intertropical zone, especially in Southeast Asia. However, mapping of peatlands is defective in tropical wetland regions, and the complexity of landscape and habitat types in areas such as the Amazon makes a precise assessment of peatland extent rather difficult. Despite these likely sources of error, the global extent of peatlands is approximately 400 million ha; the largest areas are in North America and Europe and Russia, each with approximately 175 million ha (Charman, 2009).

As explained before, peatlands are very old ecosystems, existing already for thousands of years and they're also special ecosystems with a very peculiar biodiversity that enabled them to sequester carbon and to live for thousands of years. As Evans writes in his studies (Evans, 2013), an approach used to describe peatland landscapes recognizes three scales of interest: the microtope, the mesotope and the macrotope (Ivanov, 1981; see table 1.1).

Table 1.1: Table from Evans, 2013. Source: Modified from Ivanon, K., 1981. Water Movement in Mirelands (Translated from the Russian by Thompson, A. and Ingram, H.A.P.). Academic Press, London.

Classification of scales of mire landform	
Microtope	"A part of the mire where plant cover and all other physical components of the environment connected with it are uniform." (Ivanov, 1981)
Mesotope	Isolated mire massifs with distinct patterns of microtopes and a single center of peat formation.
Macrotope	Complex mire massif formed from the fusion of isolated mesotopes through peat growth.

Evans, 2013 continues by saying that the mesotope is the scalee of the peatland landform type, so a raised bog or a patterned fen is a mesotope. Macrotope are amalgamations of peatlands landforms into peatland landscapes, and the microtope represents the fine-scale geomorphological detail. Peatland are similar to depositional landforms in that they are accreted above the preexisting land surface. In the case of an active peatland, the accretion is typically a function of *in situ* accumulation of organic litter. The controls on peatland growth are therefore a function of site conditions rather than of site erosion, but in common with depositional landforms, peatland forms are to some degree derived from, and constrained by, the antecedent landscape (Evans, 2013).

We can also have another kind of classification as Charman suggested in one of his articles (Charman, 2009), and we can see it in figure 1.2. Charman designed this classification on the approach of Lindsay (Richard, 1995) and recognized six mire types based on landscape position: raised mire, blanket mire, basin fen, valley mire, floodplain and sloping mire (Figure 1.2)(Evans, 2013).

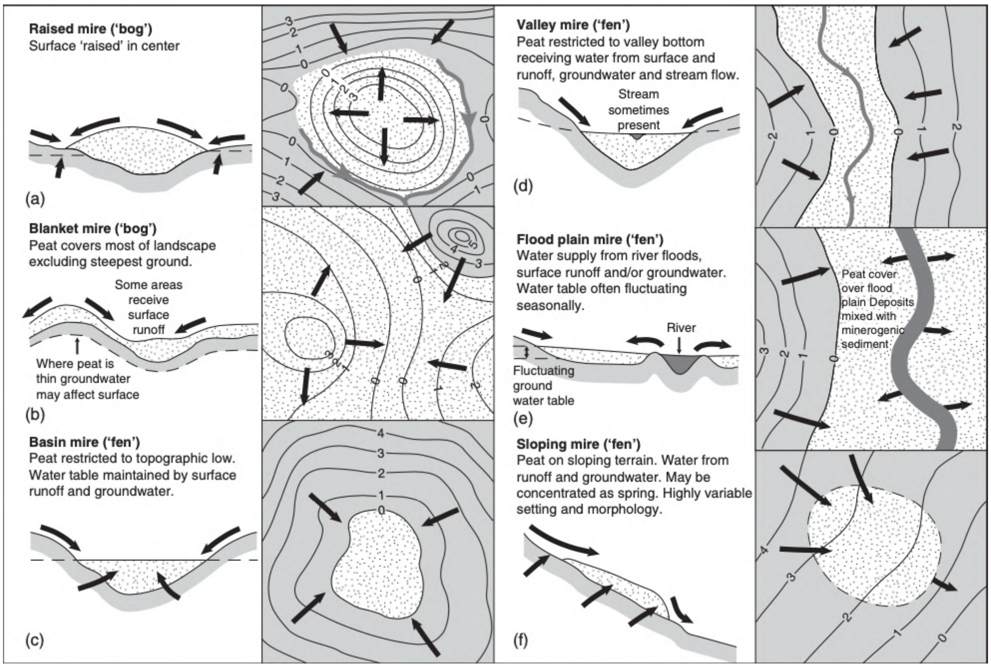


Figure 1.2: Figure from Charman, 2009. Schematic cross-sections and plan views of the main hydromorphological peatland types.

In this study we are interested in Alpine peatlands, because they are rarely studied environments and very important from an ecological and environmental point of view. As mentioned before, bogs are generally found in temperate climates and in Italy this type of conditions, thanks to the orographic increse of precipitation and the decrease of the temperature linked to the altitude, are realized mainly on the reliefs and, subordinately, in the pre-alpine areas with high rainfall. The study site is located nearby the Lake of Misurina, a natural Apline lake, which is located 1754 m above sea level in the district of Auronzo di Cadore (Belluno, Veneto, Italy).

Figure 1.3: Figure of the peatland near the lake of Misurina, Auronzo di Cadore; 15/09/2020; Francesca Aldi.

1.2 Raised Bogs

The raised bogs were the earliest types of peatland ecosystem to be studied (Ingram, 1982), so they're the world's oldest living, near-natural ecosystems and are the largest bogs in the northern hemisphere. These bogs, when mature, are above the water table; we can find raised bogs in cold temperate climates where rainfall is abundant and regular, especially in the northern hemisphere.

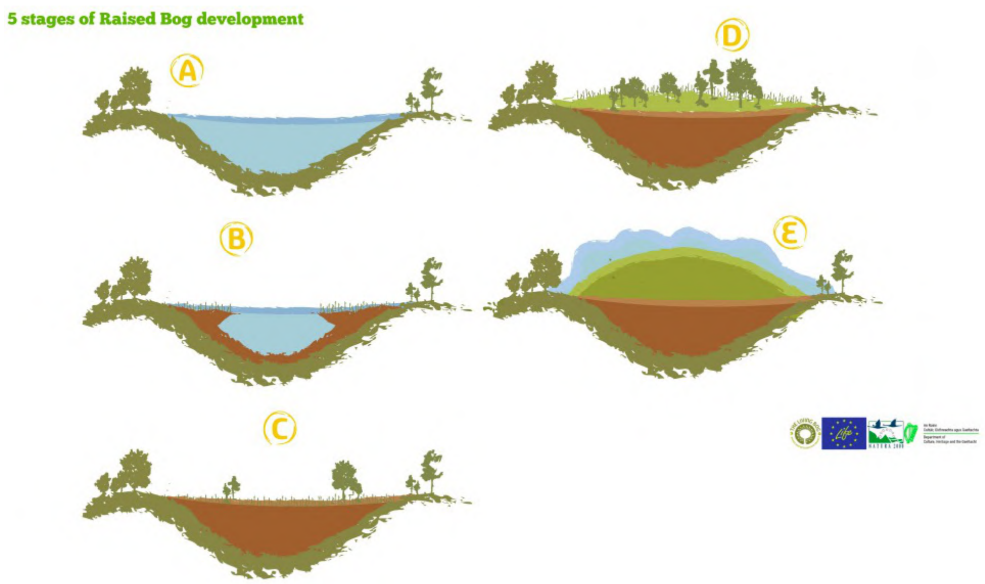


Figure 1.4: Figure from "The Living Bog". Evolution and formation of a raised bog. [Reproduced with permission from "The Living Bog"].

We can find raised bogs in the midlands and it has been estimated that at one time, this type of bog covered a million acres of land but today, less than 1% of these bogs remains as active, living bog (from The Living Bog, 2016). As the project "The Living Bog" underlies, raised bogs began to develop 10,000 years ago in hollows occupied by shallow lakes (Figure A). Thereafter, the land was washed by nutrient-rich ground water and the anaerobic conditions occurred. At first, reed beds evolved but they died off and their dead residue began to amass (Figure B) and a fen appeared. Other types of vegetation began to grow around the fen, such as Rushes, grasses, wild-flower and trees and eventually died as the fen peat was accumulating (Figure C). The layers of fen peat thicken, so that the roots of plants growing on the surface were no longer in contact with calcium-rich groundwater; the only source of minerals for plants became the rainwater, which is very poor in minerals (Figure D). Raised bogs plant species, such as *Sphagnum mosses* began to invade and eventually the fen became a raised bog. The *Sphagnum mosses* can survive on mineral-poor rainwater alone and the spongy-peat which forms over the fen is above the influence of groundwater. The fen plants are replaced completely by plants which can survive in the much poorer, acidic conditions and as the mosses accumulate and plants die, a raised bog is born (Figure E).

1.3 The Importance of Peatland in Climate Change

Peatlands are very important from a climate perspective because, as noted earlier, they can store giga tons of carbon dioxide underground. Estimates suggest that peatlands can contain twice as much carbon as is found in all the world's forests. In a study done by the University of Plymouth (Sustainable Earth Institute, 2018), they estimated the CO_2 storage of Fox Tor Mire (located in Dartmoor, in the county of Devon, England); this mire has an extension of 58.3 ha and can accumulate 565 t of CO_2 annually, and give the peat volume this mire stores 88000 t of CO_2. This is just an example of the large volume of CO_2 that can be stored inside bogs scattered all over the world.

The greenhouse effect is a threat to the living condition on Earth, however peatlands can help to slow down this process; in fact peatlands act as an efficient storage of CO_2, as specified before, and the more CO_2 they can put into storage, the more stable our climate will become. It takes thousands of years to grow these water-thick layers of peat, but drainage is one of the most destructive processes of peatlands. When a peatland is drained, the peat is exposed to oxygen and microbes attack the stored carbon and as a result carbon is oxidized to carbon dioxide and released into the atmosphere. Drained peatlands released a large amount of CO_2 and have the same negative impact on climate as coal-fired power plant, oil-fired heating and petrol powered cars. 60% of peatlands in Europe have been drained; the situation is a little better in the Nordic and in the Baltic regions, because just below half of the peatlands in these countries have been drained. On a global scale, however, 15% of all peatlands has been drained and this has had a serious effect on the global climate balance because drained peatlands are responsible for 5% of the total CO_2 released through human activity. Sequestration and long-term storage of carbon require permanent waterlogging (as said before) and if peatlands are drained they became an important sources of CO_2 and N_2O; it has been estimated that degraded bogs release more than 2Gt of CO_2 per year worldwide (Joosten, Sirin, et al., 2016). The causes of this losses are several:

- Fire (especially in South Est Asia)
- Agricolture
- Land use
- Drained peatlands.

Draining, fertilizing and tilling are the most effective ways to enhance peat oxidation and degradation; unfortunately drainage is a process that is done all over the world, in fact agricolture requires drainage, and this process causes the *"Devil's cycle"* of peatland utilisation (Joosten, Sirin, et al., 2016; see figure 1.5). Drainage can cause subsidence, because the peatland dries out and release large amounts of carbon into di atmosphere; as a result, the soil surface level falls as a result of compaction, consolidation, and volume loss due to drainage (or deforestation) and peat erosion.

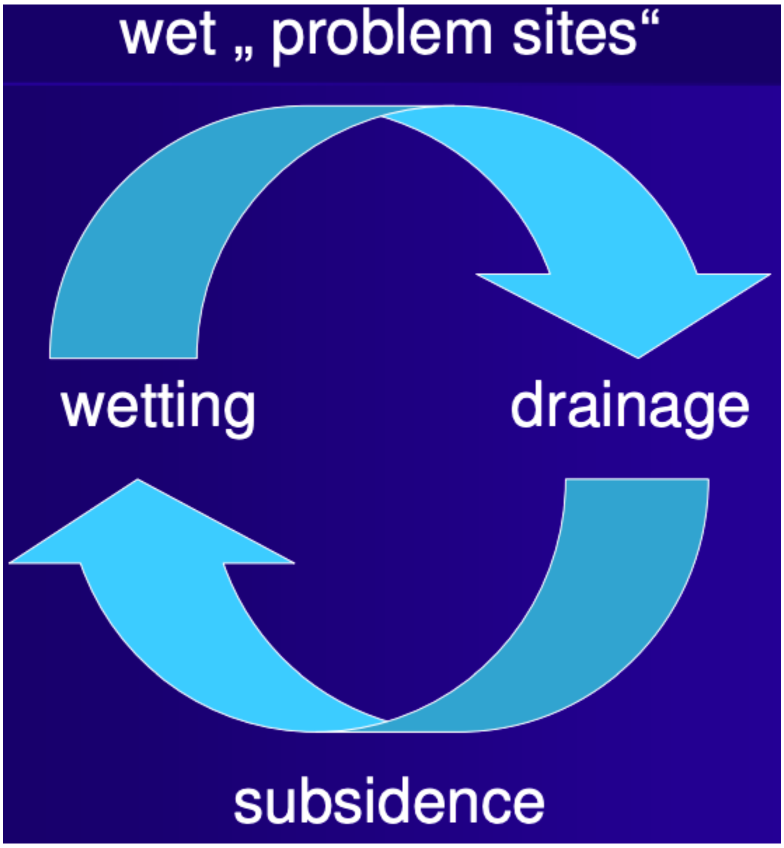


Figure 1.5: Figure from Hans Joosten. The "Devil's cycle".

1.4 Objectives of the research

The presented thesis shows the analysis of an alpine peatland, located near the Lake of Misurina (Belluno, Italy).

Before studying the development of this peatland, a detailed description of the computer model used to generate the outputs (DigiBog) is made. The aim of this study is therefore to analyze the growth of the peatland of interest through DigiBog, using at first the recorded data of temperature and precipitation of Misurina, in the current climatic conditions.

Once the peatland profile is obtained under current climate conditions, temperature and precipitation data from Euro-Mediterranean Center on Climate Change (CMCC) forecasts are used to understand how the peatland may grow under critical climate conditions.

The thesis is structured in four chapters: the first one is dedicated to an introduction describing peatlands and their importance in climate change. The second chapter describes the computer model used to produce the graphs of the peatland considered in the study. The third chapter shows the results obtained from the simulations and their analysis, comparing them also with results obtained in other studies. Lastly, the last chapter contains the conclusions of the thesis.

Chapter 2

Methods and Materials

Table 2.1: Description of mathematical symbols used in this thesis.

Symbol	Description	Value	Unit of measurement
q	Discharge rate		LT^{-1}
Q	Fluid flow rate		L^3T^{-1}
A	Section where the fluid passes		L^2
K	Hydraulic conductivity		LT^{-1}
h	Elevation of the water table over the datum		L
t	Time		T
d	Flow thickness		L
κ	Depth-averaged hydraulic conductivity under the water table		LT^{-1}
s	Drainable porosity	0.3	*Dimensionless*
P	Rate of rainfall addition to the water table		LT^{-1}
E	Rate of evaporative (or transpirative) loss of water from the water table		LT^{-1}
U	Rate of precipitation	0.3	LT^{-1}
L	Lateral extension of the modelled bog	500	L
H	Height of water table		L
p	Net rate of litter production by peatland plants	8640	$ML^{-2}T^{-1}$
z	Water table below the peat surface		L
B	Bog surface height		L
α	Rate of decomposition		T^{-1}
m	Peat mass		M
m_0	Initial mass		M

Table 2.2: Description of mathematical symbols used in this thesis.

Symbol	Description	Value	Unit of measurement
ox	Proportion of layer above WT		$Dimensionless$
an	Proportion of layer below WT		$Dimensionless$
Δt_e	Length of ecological timestep		T
α_{an}	Anoxic decomposition	0.001	T^{-1}
α_{ox}	Oxic decomposition	0.035	T^{-1}
ρ	Dry bulk density	1000	ML^{-3}
Q_{10}	Temperature sensitivity	3	$Dimensionless$
a	Hydraulic conductivity parameter	1586.87	LT^{-1}
b	Hydraulic conductivity parameter	8	$Dimensionless$
θ	Proportion of the layer's original mass which has not been lost to decomposition	$Dimensionless$	
T_{BC}	Baseline temperature	6.29	C
T_W	Mean weekly air temperature		C

2.1 DigiBog

The aim of this thesis is to study the future development of a peatland under the influence of climate change, through the use of the model DigiBog; this model was originally created by Paul J. Morris, Andy J. Baird, Lisa R. Belyea (Paul J. Morris, 2009). DigiBog is a model that describes bogs and ombrotrophic peatlands, simulating the accumulation of peat, in times that can vary from decades to millennia. This model has two versions: 1D or 2D/3D and the second version combines the peat storage model of version 1D and a model based on water flow physics to simulate peat bog growth on a landscape scale. DigiBog is a tool that can be used, for example, to understand the impact that a future change in clamate may have on peat and consequently on the entire peat bog. DigiBog can then be used to make predictions on bogs, to understand whether an increase in temperature or a decrease in precipitation can adversely affect the CO2 storage capacity.

As noted by A.J Baird, P. Morris, and L. Belyea, 2012, there is a conceptual structure at the basis of the model, that we can seen in figure 2.1.

The principal module at the basis of the model is the hydrological module: this model simulates the movement of underground water in response to water exchanges with the atmosphere and therefore also simulates the spatial distribution of the water table in the simulated peat bog (A.J Baird, P. Morris, and L. Belyea, 2012). As can be noticed in the figure 2.1, many submodels are included in the general model structure (plant-succession submodel, plant litter production submodel, decomposition submodel and hydraulic proper-

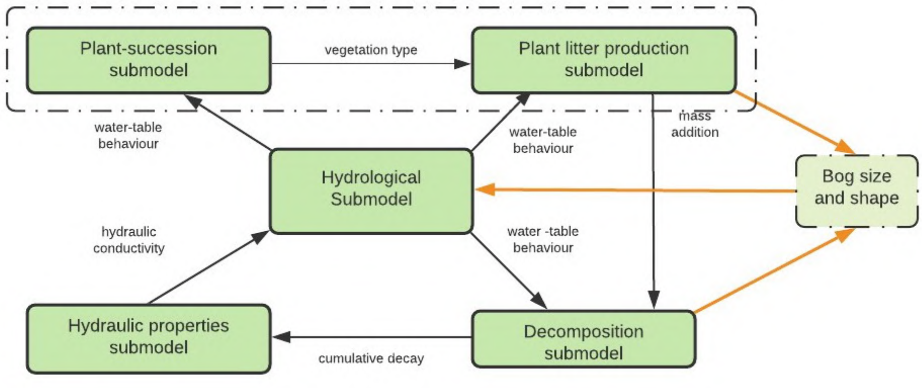


Figure 2.1: Representation of DigiBog as a conceptual model; scheme adapted from A.J Baird, P. Morris, and L. Belyea, 2012.

ties submodel) and two of these interact directly with the shape and the size of the bog, which in turn has a direct connection with the hydrological module: in fact, the processes in the conceptual model (water flow through the bog, plant succession, the rate of litter production, peat decomposition and changes in peat hydraulic conductivity) are all mediated by the shape and size of the bog (A.J Baird, P. Morris, and L. Belyea, 2012).

We must also describe the geometry that takes into consideration DigiBog during the simulations, because it controls how the submodels inside DigiBog connect and interact with each other. DigiBog describes a bog like a grid, represented by columns of peat connected with each other, where every column is formed by vertically stacked peat layers.

As described in the paper by P. J. Morris, A.J. Baird, and L. R. Belyea, 2012, in figure 2.2, the bog is represented by white and light grey columns, while the dark columns are not used. So, the light grey columns represent the boundary columns and in this example currently only Dirichlet's boundary

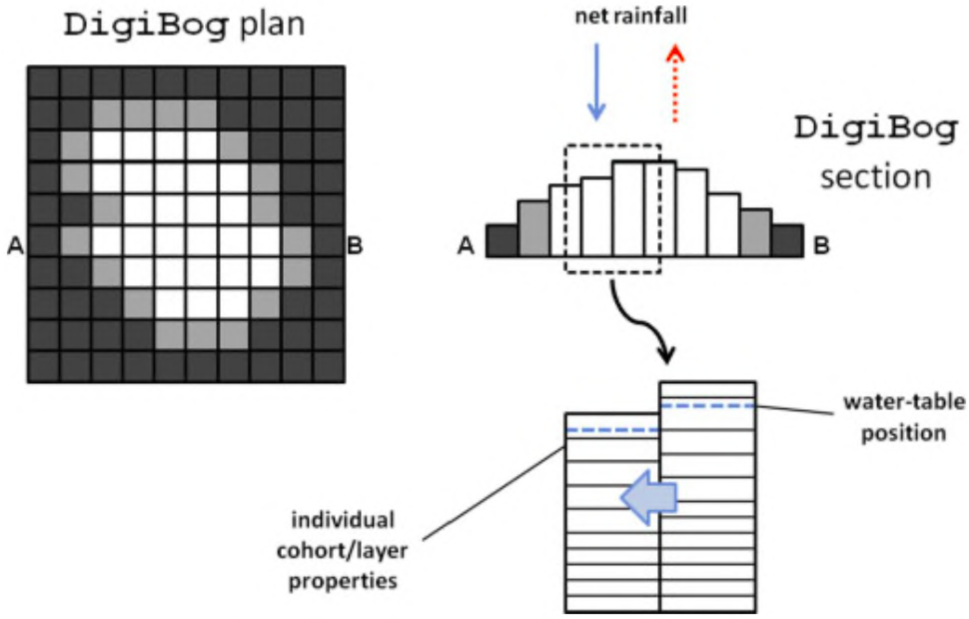


Figure 2.2: Representation of a bog according to DigiBog geometry. Thin blue arrow indicates rainfall additions to the water table (P); broken red arrow indicates evapotranspiration losses (E); thick blue arrow indicates direction of inter-column groundwater movement for the water-table geometry shown. P. J. Morris, A.J. Baird, and L. R. Belyea, 2012.

conditions are used in this model; this means that a bog represented in DigiBog is like being disaggregated into many square-sectioned peat columns, in a framework in x-y directions. The dimensions in plan of the columns are the same for all columns and in both horizontal directions and the length of each side of the column is referred to in the model with the wording "spatial step" (Paul J. Morris, 2009). Each column is further divided into a series of layers, as we said before, and this can be seen in the detail of figure 2.3 and every columns has its own values for K (permeability), s (effective porosity), thickness and any other property that must vary in three dimensions.

Water, in this representation, can move between columns and the water table, instead, can rise or fall in the various layers that compose the column

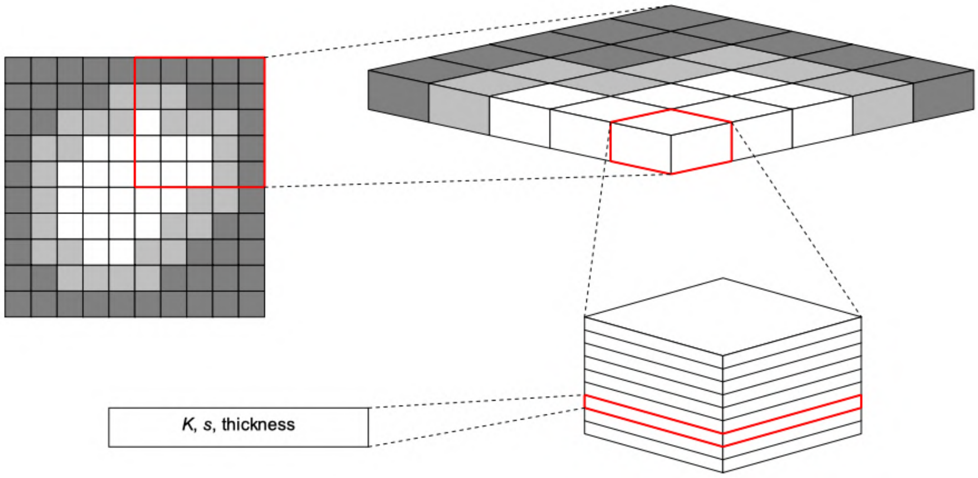


Figure 2.3: Representation of columns in a bog in DigiBog; each layers has its own properties like K, s or thickness. Image taken from Paul J. Morris, 2009.

(P. J. Morris, A.J. Baird, and L. R. Belyea, 2012).

DigiBog consists of two principal Fortran codes, as said before: the main and the hydrological submodels. The hydrological submodel is the first to run, since many of its functions are called from the primary main. The hydrological submodel, as we explained before, simulates the movement of the underground water and for this model it has been assumed that the flow present below the water table is horizontal. This assumption is called the approximation of Dupuit-Forchheimer (D-F), therefore the flow is strictly 2D in both horizontal directions (P. J. Morris, A.J. Baird, and L. R. Belyea, 2012). Moreover the flow in the undergound water is mediated by hydro-physical properties of the bog, and the most important ones are:

- Hydraulic conductivity, or permeability K (with dimension LT^{-1});
- The effective porosity, s (dimensionless).

K is defined in the Darcy law, as hydraulic conductivity (LT^{-1}), which can be defined in an isotropic medium as the specific flow rate per hydraulic gradient unit, and is scalar that expresses the ease with which a fluid is transported in interstitial spaces. As defined in Freeze and Cherry (Freeze and Cherry, 1979), hydraulic conductivity is a function not only of the porous medium but also of the fluid that passes through it. The hydraulic gradient, on the other hand, is the parameter that quantifies the driving force that allows water to move from one point to another of the aquifer overcoming the resistance opposed by the ground. Moreover, Darcy's law says that the discharge rate q is proportional to the gradient in hydraulic head and the hydraulic conductivity $q = \frac{Q}{A} = -K\frac{dh}{dl}$, where q is the discharge rate (LT^{-1}), Q is the fluid flow rate (L^3T^{-1}), A is the section where the fluid passes (L^2), K is the hydraulic conductivity, h is the hydraulic head (L), l is the distance in the direction of water flow (L) and $\frac{dh}{dl}$ is the hydraulic gradient (dimensionless).

The main purpose of the hydrological submodel is to calculate the spatio-temporal dynamics of water table behaviour within the modelled bog in order to inform DigiBog's other submodel. As described in the paper P. J. Morris, A.J. Baird, and L. R. Belyea, 2012, water flow is simulated using a finite-difference solution of a 2D formulation of Bussinesq's equation (cf. McWhorter and Sunada, 1977):

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\kappa(d)}{s(d)}d\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\kappa(d)}{s(d)}d\frac{\partial h}{\partial y}\right) + \frac{P(t) - E(h,t)}{s(d)} \tag{2.1}$$

Where h is the elevation of the water table (L) over the datum, t is time

(T), x e y are the horizontal distances, d is the flow thickness (L), κ is the depth-averaged hydraulic conductivity under the water table (LT^{-1}), s is the drainable porosity (dimensionless), P is the rate of rainfall addition to the water table (LT^{-1}) and E is the rate of evaporative (or transpirative) loss of water from the water table (LT^{-1}).

Equation (2.1) describes flow in the two horizontal directions and allows the water table to change over time. With regard to the calculation height of the water table, there is an equation that calculates each timestep Δt:

$$H_t = H_{t-1} + \Delta t \left(\frac{U - K(H_{t-1}) \frac{H_{t-1}^2}{L_{t-1}^2}}{s} \right) \tag{2.2}$$

Where U is net precipitation rate (precipitation - evapotranspiration; LT^{-1}), K is the depth-averaged hydraulic conductivity below the water table (LT^{-1}), L is the lateral extension of the modelled bog, from the centre to the margin (L), and s is the drainable porosity (Paul J. Morris, 2009).

The hydrological submodel produces a series of outputs:

- **Altitude/height of water table, H (x,y).** This parameter describes the elevation of the water table over the impermeable base of each columns of the bog, at the end of every hydrological cycle; so it indicates the final position of the water table.

- **Stationary state/water table depth, d (x,y).** This parameter is similar to the one described above, but in this case the water table depth is expressed as depth in relation to the peat surface, which is almost never contiguous between neighboring columns. This measure identifies with more simplicity the availability of moisture at the surface of a column, at the contrary of H that didn't provided this kind of information. This value, like H, does not consider the behaviour of the water table.

- **Moisture of the stationary state/Time out layer, w (x,y).** This parameter is the proportion of each layer that is below the aquifer at the stationary state at the end of a hydrological cycle (this is the interval used by the model in its hydrological flow calculations and is expressed in minutes; fine minutes is a sensible maximum timestep to use). This value is useful because the decay submodel works layer by layer, in the sense that each layer that is inside a column lose an amount of mass at the end of an interval of ecological time (like the hydrological timestep, this is the interval used by the model in its ecological calculations.), at a speed that is determined by the quality of the single layer peat and by the available amount of oxygen.

The outputs generated by the hydrological submodel will also be used in the main module. DigiBog is a model that describes the growth of a bog, so it doesn't only take into account the hydrological part but also other mechanisms related to the formation of the bog itself, like for example the production of litter. As described by A.J Baird, P. Morris, and L. Belyea, 2012, the production of litter is expressed by p $(ML^{-2}T^{-1})$, that represents the net rate of litter production by peatland plants; a new layer of litter is added at the rate p to each column at the start of each subsequent year depending on the mean oxic zone thickness (z) and mean annual temperature (T_{mean}) (D. M. Young et al., 2016):

$$p = 0.001\left(9.3 + 1.33z - 0.022(100z)^2\right)^2(0.1575T_{mean} + 0.0091) \qquad (2.3)$$

Which is valid for $0 \text{ m} \leq z \leq 0.668$ m, while $p = 0$ where $z > 0.668$ m. In this equation z is expressed in cm and the equation that describes it is: $z = B - h$; where B is the bog surface height and h is the water table elevation. It can be seen from equation (2.3), if z has positive values the water table is below the peat surface, while negative values of z occur when the water is stagnant and therefore when the water table is above the peat surface.

Regarding the decompositional submodel, DigiBog implements the equations present in Clymo (1984) assuming that the rate of loss is directly proportional to the amount of material remaining (Clymo, 1984):

$$\frac{dm}{dt} = -\alpha m \qquad (2.4)$$

Where t is time and α is the rate of decomposition (T^{-1}); integrating the previous equation in time we have:

$$m = m_0 e^{-\alpha t} \qquad (2.5)$$

The equation (2.5) describes an exponential decline of the amount of mass remaining from a cohort with an initial mass m_0 (P. J. Morris, A.J. Baird, and L. R. Belyea, 2012). But to calculate the decay of each layer of peat, another equation had to be used, because with DigiBog the remaining mass within a cohort or layer follow an exponential decline for each ecological time phases (P. J. Morris, A.J. Baird, and L. R. Belyea, 2012). In addition, we must consider the fact that, always in the decomposition submodel, there are two decomposition rates acting along the peat profile:

- α_{ox}, for oxic conditions, used for layers above the water table;
- α_{an}, for anoxic conditions, used for layers below the water table.

Layer thickness is calculated by dividing its mass by a constant value for dry bulk density ρ. Depth-integrated oxic and anoxic decomposition of each layer takes place subannually according to the proportion of the layer above (ox) or below the water table (an), the value of the decay parameters (oxic (α_{ox}) and anoxic (α_{an})), and the temperature sensitivity Q_{10}:

$$m_t = m_{t-1}\left[\left(ox \cdot e^{-\Delta t \alpha_{ox,T_{BC}} Q_{10}^{(} T_W - T_{BC})/10}\right) + \left(an \cdot e^{-\Delta t \alpha_{an,T_{BC}} Q_{10}^{(} T_W - T_{BC})/10}\right)\right] \tag{2.6}$$

Where m_t is the peat mass (M) in any layer during timestep t (-), T_W is the mean weekly air temperature, T_{BC} is the baseline temperature, 6.29°C used to derive the productivity function described in equation (2.6); ox is the proportion of that layer which is above the steady-state water table during the previous timestep (-), an is the proportion of that layer which is below the steady-state water table during the previous timestep (-), and Δt is the length of the ecological timestep (T)(D. M. Young et al., 2016). In this way, each layer of peat is controlled according to how much mass remains in the layer in proportion (indicated with the letter θ, that represents how much mass remains in each cohort or layer as a proportion) to what was originally there at the time of the first formation (P. J. Morris, A.J. Baird, and L. R. Belyea, 2012). Within the main, an initial layer of mineral soil is also set between the impermeable bottom of the bog and the actual peat accumulation. This layer is necessary for the functioning of the model, because it allows to simulate a flow in the underground; the thickness is set to 20 cm, we notice that in the comment of the main (where this value is inserted) and in the article by D. M. Young et al., 2016 is written a thickness of 2 cm.

At the end we have to consider the relation that DigiBog considers among the ecological and hydrological processes in the form of hydrophysical submodel; we hypothesize that peat decomposition creates a decompression that affects the size of the pore diameters effective in transmitting water, making them smaller; but there is also another hypothesis: independently of the degree of decomposition, the mass density remains the same, because compression corresponds to a loss of mass. The radius r (L) of the most water-conductive pores might reasonably be represented as an exponential function of θ. Poiseuille's law describes the area-averaged flow of water through a capillary tube as a function of the energy gradient driving flow and the square of tube radius. If such a relationship holds for pores in peat soils, we may write: $K \propto r^2$, Assuming, as argued above, that r is an exponential function of θ we can write: $K \propto (\alpha e^{(\beta\theta)})^2 = \alpha e^{(b\theta)}$; where α (LT^{-1}), β and b (dimensionless) are parameters and $b = 2\beta$. This equation can give a possible relation between idraulic conductivity and θ (P. J. Morris, A.J. Baird, and L. R. Belyea, 2012).

The hydrological model requires information on what happens at the boundary of the modelled area; in our study, DigiBog Hydro (the hydrological model) was used to represent the flow of water through a raised bog on a hillslope, so it is necessary to know what happens at the boundaries (at the upslope boundary and at the downslope boundary). From figure 2.4 it can be noticed that the peatland in DigiBog is considered as a set of columns separated from each other, as explained at the beginning of the paragraph. The specific application of DigiBog to our study site (see paragraph 2.4.1).

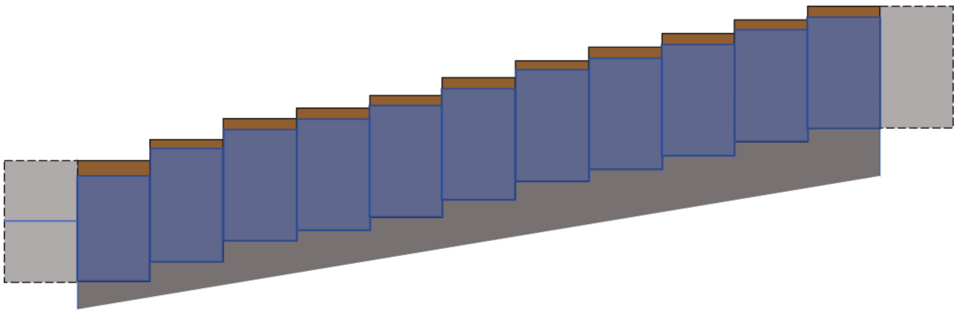


Figure 2.4: Representation of a peatland on a hillslope, with the boundary condition columns. On the left there is the stream where the water drains.

2.2 Study site and samplings

The study site is located near the lake of Misurina (46°34'55"N 12°15'14"E), in the fraction of Auronzo di Cadore, Veneto. This region is located at middle latitudes and in a transition zone between the central-European area, where the influence of great western currents predominates, and the south-European area, dominated by the action of subtropical and Mediterranean anticyclones.

There are two types of factors that determine the climate of the region:

- **Macroscale - Continental level**

  - Transitional position between the central European continental area and the Mediterranean area;
  - Influence of "source regions" of air masses (continental, maritime and its variants) and atmospheric circulatory structures (westerly currents, subtropical anticyclones, etc.).

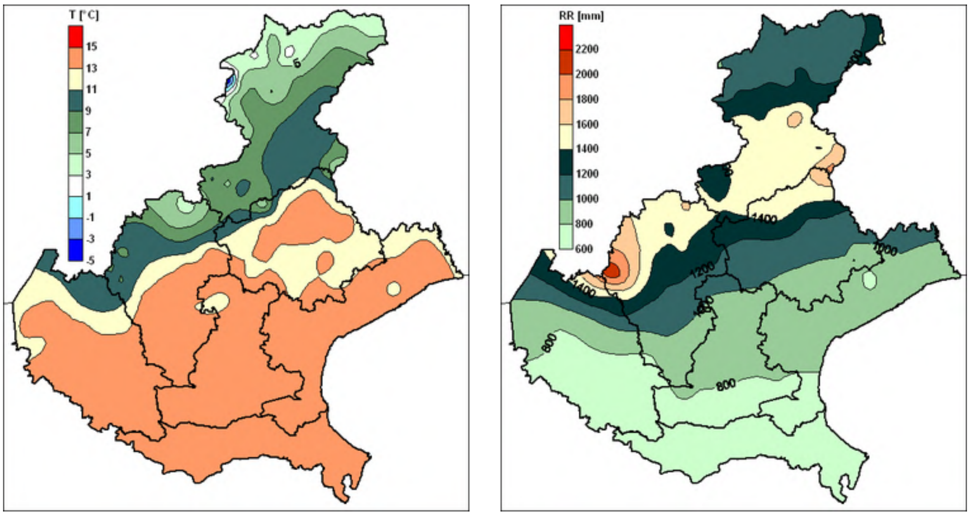
- **Mesoscale and Microscale - Regional and Sub-Regional level**

  - Collocation in the padano basin;
  - Northern mountainous areas with complex orography, affecting circulation and atmospheric variables (solar radiation, temperature, relative humidity, precipitation, wind);
  - Adriatic Sea and Lake Garda that mitigates temperatures;
  - Different use of territory that influence the climate, originating real "microclimates".

ARPA Veneto has analyzed the averaged values of mean temperatures and annual precipitation on the regional territory from 1985 to December 2009; they have created two maps, one of mean isotherms and one of mean isohyets. The isotherms and the isohyets are curves that graphically display, through different colours, areas characterized by the same averaged temperatures and the same averaged amount of precipitation respectively.

Thanks to these maps, it is possible to highlight in Veneto three main mesoclimatic zones:

- Lowland;



(a) *Map of mean temperatures (isotherms).*
(b) *Map of mean annual precipitation (isohyets).*

Figure 2.5: Maps of isotherms and isohyets; by ARPAV.

- Prealps;
- Alpine sector.

According to these maps, our bog is part of the Alpine sector; in this zone the mesoclimate is characterized by relatively hight precipitation but generally less than 1600 mm per year, with seasonal highs often in late spring, early summer and autumn. The mean temperatures have variable averages between 7°C and -5°C (variable mean values) and monthly average values below zero in the winter months.

In the territory near Misurina there are the optimal climatic conditions to allow the presence of peat bogs.

The studied raised bog is presented in figure 2.6; a portion of the bog was selected because was surrounded by drainage ditches, so that they could act as a natural boundary of our bog.

Figure 2.6: Satellite view of bogs near the Lake of Misurina; scale 1:2000. Elaborated with QGis.

The study site is located on a sloping terrain, where the highest part is to the east and the lowest part is to the west. At the lowest part of the bog, there is a drainage channel that runs along the bog (Figure 2.6). The bog of interest has a total length of 113,5 m, with a perimeter of 275,1 m and an area of 2367 m^2. Being an alpine bog and being in an area with slope, it can be imagined that it has an influx of water from the mountains to the east, bringing water in the spring and summer as the ice melts; therefore in this type of bog, not only precipitation and evapotranspiration should be considered, but also an influx of extra water coming from uphill. However, the presence of a small drainage channel at the upper east boundary of the study probably prevents large infiltration from uphill, so that we set a no-flux boundary along this side.

During the field work, it was decided to proceed with soil sampling of the bog, both to analyzed the samples in the laboratory but also to know the depth of the bog itself. The sampling was done with a peat corer using a wet/waterlogged soils auger, with a diameter of 2.5 cm and a length of 50 cm; it was decided to sample the peatland along transects (See figure 2.7).

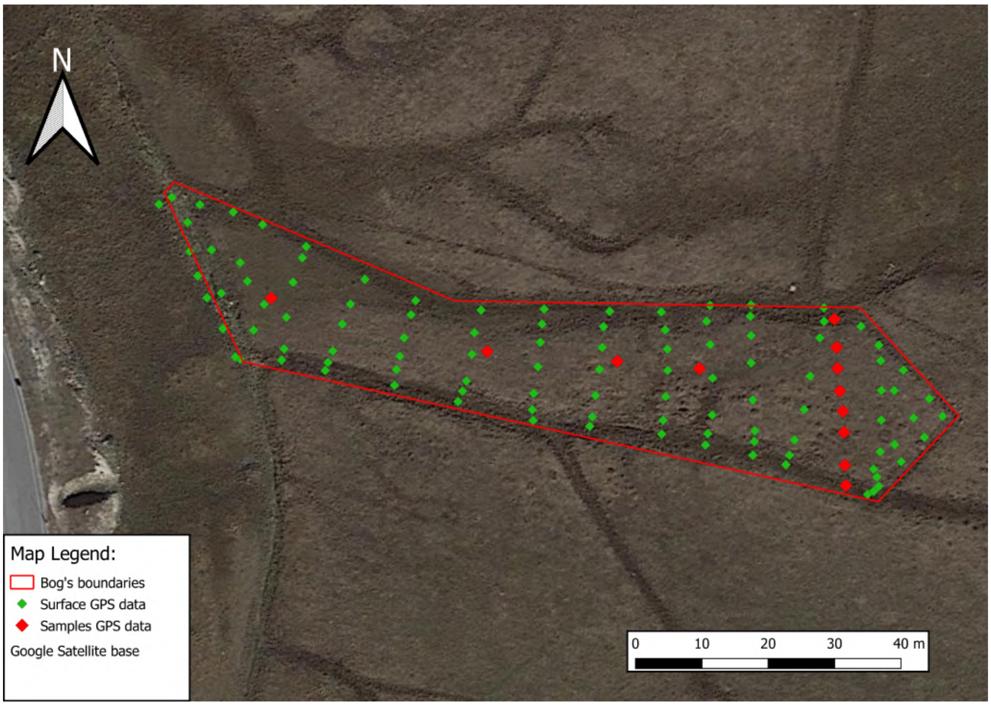


Figure 2.7: Satellite view of the bog with all the samples taken during the field work (red diamonds) and GPS data (green diamonds); scale 1:500. Elaborated with QGis.

A total of 12 locations were sampled; for each sampling the core was divided into plastic bags, each containing 50 cm of soil. Each bag then was named with the sampling site number and the portion of soil sampled and was added to remind us of the length of the sampling. After the sampling, it was used a GPS (antenna: Leica Viva GS14- Smart antenna GNSS; camp controller: Leica Viva CS15) to map the sampled points but also to map additional points, in order to delimit our entire bog and also to get altitude information. In addition another map was created to highlight which GPS points were used in the model to get the profile of our bog (See figure 2.8), but also to calculate the height of the peat accumulation (by subtracting the altitude of the bog bottom from the altitude measured by GPS).

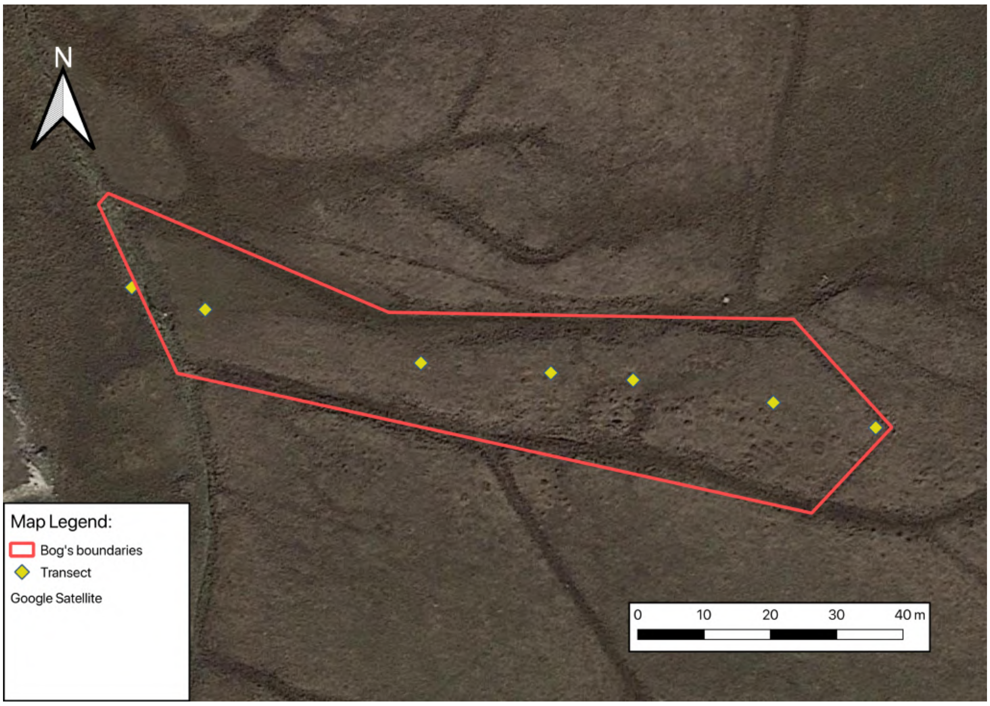


Figure 2.8: Satellite view of the bog with the GPS points used in the model; scale 1:500. Elaborated with QGis.

Thanks to the use of the GPS, a map representing the surface of our marsh was also created (See figure 2.9); as shown in the figure's legend, the different heights of the bog are represented.

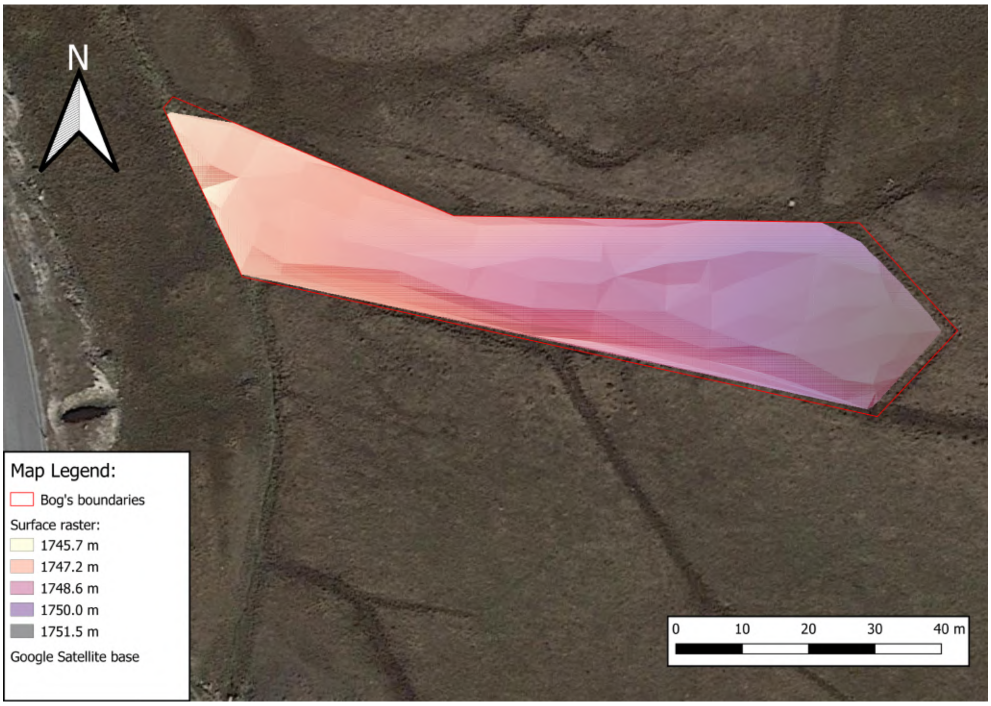


Figure 2.9: Satellite view of the bog's surface with the digital elevation model overimposed; scale 1:500. Elaborated with QGis.

QGis was used to generate the maps; to create the raster Surface we used a TIN interpolation (Triangular Irregular Network), using as extension the boundaries of the peat bog (Liang and Wang, 2020).

2.3 Laboratory analyses

This chapter of the thesis describes the analytical procedures that were used for the analysis of the organic matter and organic carbon of the samples taken on the field. Specifically, the bulk density and the Loss of Ignition (LOI) were determined. The bulk density is an important indicator of the quality of the soil, and its measure is one of the quantitative methods usually used to evaluate the grade of soil compaction. The bulk density of a soil is defined as the mass of dry soils (in the oven at 105°C) per units of volume, i.e. the total volume of soil, or rather of its mineral and organic components, and of the pores occupied by the air in it. This mathematical relationship expresses in a synthetic way the relationship between solids and voids in an unitary volume, providing an indirect indication of the total porosity, according to the relation:

$$porosity\% = 100 - \left[\left(\frac{\rho_b}{\rho_r} \right) \cdot 100 \right] \quad (2.7)$$

Where ρ_b and ρ_r (gcm^{-3}) are the apparent density and the real density of the particles respectively. Therefore the lower the apparent density values are, with the same real density, the greater the porosity will be.

The Loss Of Ignition (LOI) is a method for determining the organic matter content of a soil, where a dried sample of soil is subjected to high temperature in a muffle furnace in order to oxidize all of the organic matter; the loss in weight after cooling then gives the organic matter content.

In order to determine the bulk density, for each sample of volume V (calculated based on the probe used in the field), one should weight an aluminum

(a) *Aluminum cup weighed before weighing soil sample.*

(b) *Open oven with aluminum cup.*

(c) *Oven at 105°.*

cup (M_c), then transfer the sample into the cup and place the sample in the oven with a temperature of 105°C for at least 24h. If the samples are very wet and humid, they must be kept in the oven for at least 36 hours or 48 hours to dry completely. To verify that the sample is dry, it is necessary to check the weight of the samples after 24h and after 36h (or even more if the sample keeps changing weight).

After that time in the oven, the samples must be weighed again to get the final weight and to be able to calculate the bulk density. The weight of the sample plus the cup (M_s + M_c) must then be taken and the mass of the sample M_s = (M_s + M_c) - M_c can be calculated. The Bulk Density is calculated by dividing the dry sample mass M_s (g) by the volume V (cm^3) of the original sample. To see the results of the experiments, see figure 2.14.

Sample	Core drill diameter	Segment_1	Segment_2	Segment_3	**Total_length**
	cm	cm	cm	cm	**cm**
Site_1	2,5	50	47	30	**127**
Site_2	2,5	50	47	42	**139**
Site_3	2,5	50	47	34	**131**
Site_4	2,5	50	50	23	**123**
Site_5	2,5	50	26	0	**76**
Site_6	2,5	50	50	26	**126**
Site_7	2,5	50	50	5	**105**
Site_8	2,5	50	5	0	**55**
Site_9	2,5	50	50	5	**105**
Site_10	2,5	50	50	27	**127**
Site_11	2,5	50	50	44	**144**
Site_12	2,5	50	4	0	**54**

Figure 2.10: Initial sample data with the total length.

Sample	Volume_1	Volume_2	Volume_3	**Total_volume**
	cm^3	cm^3	cm^3	**cm^3**
Site_1	245	231	147	**623**
Site_2	245	231	206	**682**
Site_3	245	231	167	**643**
Site_4	245	245	113	**604**
Site_5	245	128	0	**373**
Site_6	245	245	128	**619**
Site_7	245	245	25	**515**
Site_8	245	25	0	**270**
Site_9	245	245	25	**515**
Site_10	245	245	133	**623**
Site_11	245	245	216	**707**
Site_12	245	20	0	**265**

Figure 2.11: Initial sample data with the total volume.

To determine the Loss of Ignition, it is necessary to start with the soil samples that have been dried to calculate the Bulk Density. At this point, each oven-dried sample must be taken and placed in an electric grinder; each ground sample was stored in plastic bags, with the date of grinding and the sample number written on it. After grinding all the samples, the crucibles should be weighed to the fourth decimal digit (M_{cru}) and put about 10 g of sample; the crucibles should be left in a desiccator for 30 minutes and after this time they should be put in a furnace. For the furnace, the temperature should be increased gradually (100°C every hour) up to 450°C and the crucibles should be left at that temperature for 8 hours (See figure 2.12). After the 8 hours, the crucibles should be weighed again (the ashes will then also be weighed; see figure 2.13). To see the results of the experiments, see figure 2.15.

Figure 2.12: Example of a furnace with crucibles.

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(a) *Crucible n°1.* (b) *Crucible n°2.*

(c) *Crucibles.*

Figure 2.13: Example of crucibles with samples after 8 hours in the furnace.

Name	(Mc)	(Mc + Ms) 1	(Mc + Ms) 2	Ms = (Ms+Mc)-Mc	(Ms/V)
1.1	13	28,8	28,4	15,4	0,025
1.2	13,2	33,5	33	19,8	0,032
1.3	6,8	21,2	20,9	14,1	0,023
2.1	13,2	34,6	34,1	20,9	0,031
2.2	13,2	31,9	31,5	18,3	0,027
2.3	7	26,1	25,6	18,6	0,027
3.1	13,2	32,5	32,1	18,9	0,029
3.2	13,2	34	33,5	20,3	0,032
3.3	6,9	24,8	24,5	17,6	0,027
4.1	13,2	35,4	34,9	21,7	0,036
4.2	13,1	35,5	34,9	21,8	0,036
4.3	7	20,1	19,7	12,7	0,021
5.1	13,3	28,3	28	14,7	0,039
5.2	7	19,7	19	12	0,032
6.1	13,3	35,5	35,8	22,5	0,036
6.2	13,3	37,8	38	24,7	0,040
6.3	6,9	23,2	23,2	16,3	0,026
7.1	13,2	37,7	38,1	24,9	0,048
7.2	13,1	39,4	39,6	26,5	0,051
7.3	13,1	16,6	16,7	3,6	0,007
8.1	13,1	30,8	30,9	17,8	0,066
8.2	6,9	10,6	10,6	3,7	0,014
9.1	13,2	35,1	35,2	22	0,043
9.2	13,2	38	38,2	25	0,049
9.3	9	13,2	13,2	4,2	0,008
10.1	13,2	37,2	37,4	24,2	0,039
10.2	13,2	31	31,3	18,1	0,029
10.3	9,1	19,4	19,5	10,4	0,017
11.1	13,2	36,6	36,8	23,6	0,033
11.2	13,2	41,6	41,7	28,5	0,040
11.3	13,3	54,5	54,6	41,3	0,058
12.1	13,1	43,7	43,9	30,8	0,116
12.2	9	11,8	11,9	2,9	0,011

Figure 2.14: Bulk Density calculation table. M_c: weight of the aluminum cup; M_s: weight of the sample; M_s/V: Bulk Density.

Name	CW	SW	CW+SW	CW+SW a.f.	SW a.f.	% Ash	% LOI
1.1	57,5136	10,0283	67,5419	58,3318	0,8182	8,1589	91,8411
1.2	55,2885	10,008	65,2965	56,0897	0,8012	8,0056	91,9944
1.3	56,0688	9,0161	65,0849	56,9177	0,8489	9,4154	90,5846
2.1	55,0951	10,0044	65,0995	56,2545	1,1594	11,5889	88,4111
2.2	56,0688	10,3944	66,4632	56,9641	0,8953	8,6133	91,3867
2.3	55,2879	10,2633	65,5512	56,5569	1,269	12,3644	87,6356
3.1	54,6746	10,1085	64,7831	55,6938	1,0192	10,0826	89,9174
3.2	55,0942	10,0486	65,1428	55,8188	0,7246	7,2110	92,7890
3.3	55,0939	10,0485	65,1424	56,618	1,5241	15,1674	84,8326
4.1	55,2874	10,0967	65,3841	56,2716	0,9842	9,7477	90,2523
4.2	54,6749	10,4621	65,137	55,3681	0,6932	6,6258	93,3742
4.3	56,0682	10,0644	66,1326	58,5824	2,5142	24,9811	75,0189
5.1	57,5133	10,0612	67,5745	58,8136	1,3003	12,9239	87,0761
5.2	55,2873	10,0861	65,3734	56,8116	1,5243	15,1129	84,8871
6.1	55,0944	10,0247	65,1191	56,1449	1,0505	10,4791	89,5209
6.2	54,6753	10,0505	64,7258	55,5229	0,8476	8,4334	91,5666
6.3	31,0149	10,0922	41,1071	33,1056	2,0907	20,7160	79,2840
7.1	50,8498	8,519	59,3688	51,9471	1,0973	12,8806	87,1194
7.2	55,2876	10,0701	65,3577	56,0527	0,7651	7,5977	92,4023
7.3	57,5132	3,6612	61,1744	57,9877	0,4745	12,9602	87,0398
8.1	56,0684	10,1146	66,183	57,4889	1,4205	14,0441	85,9559
8.2	55,0944	3,939	59,0334	56,1578	1,0634	26,9967	73,0033
9.1	54,6753	10,2328	64,9081	55,709	1,0337	10,1018	89,8982
9.2	66,7701	10,2371	77,0072	67,4798	0,7097	6,9326	93,0674
9.3	50,8485	4,2935	55,142	51,1677	0,3192	7,4345	92,5655
10.1	31,0145	8,317	39,3315	31,9582	0,9437	11,3466	88,6534
10.2	57,5132	10,1054	67,6186	58,3811	0,8679	8,5885	91,4115
10.3	55,2877	10,1953	65,483	57,1222	1,8345	17,9936	82,0064
11.1	54,6751	10,1115	64,7866	55,8896	1,2145	12,0111	87,9889
11.2	55,0944	10,732	65,8264	56,6311	1,5367	14,3189	85,6811
11.3	56,0685	10,4423	66,5108	61,0746	5,0061	47,9406	52,0594
12.1	50,8483	10,0555	60,9038	53,8935	3,0452	30,2839	69,7161
12.2	31,0149	2,9648	33,9797	32,0988	1,0839	36,5590	63,4410

Figure 2.15: Initial sample data with the total volume.

2.4 DigiBog data preparation

To monitor growth of Misurina bog through DigiBog, some changes have been made to the default model which can be downloaded for free from the site of the University of Leeds, under the section "Resources". With this download comes the two Fortran codes (the hydrological submodel and the main) and five .txt input files that the model use to generate the output files, that have been described in the paragraph 2.1; the input files are:

- Information (010-DigiBog-BB-INPUT-information)
- Net rainfall (020-DigiBog-BB-INPUT-net-rain)
- Temperature (030-DigiBog-BB-INPUT-temp)
- Column status (040-DigiBog-BB-INPUT-column-status)
- Base altitude (050-DigiBog-BB-INPUT-baltitude)

All parameters used to calculate the values to be included in the simulations (such as temperature and precipitation) were taken from the ARPAV website.

2.4.1 Column status

This file provides 81 values, because the Hydrological submodel works with a grid (representing the bog) built with 27 columns and 3 rows (for a total of 81 cells (27x3)). When the Hydrological submodel runs, it starts reading from the first column in the lower right corner, as shown in the figure 2.16.

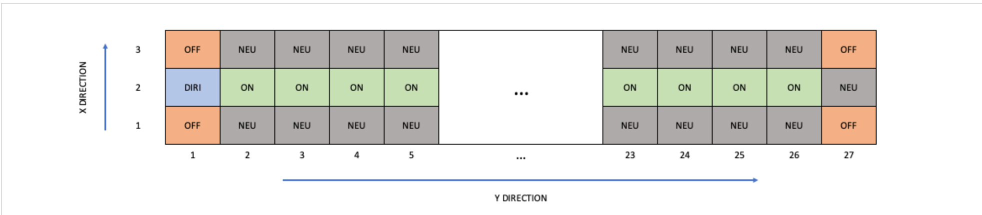


Figure 2.16: The Hydrological submodel setup showing the columns and the rows of the peatland.

First there is one "OFF" column and are 25 columns labeled with "NEU", corresponding to no flux. the columns labeled with "NEU" represents boundary conditions in which flow is specified and specifically here it stands for no-flow (including zero flow); "NEU" stands for Neumann boundary condition. After, there are 27 columns labeled with "ON" that represent a strip of hillslope from the hillslope divide (left) to a stream at its base (right); in the Hydrological submodel is necessary to know what happenes at the upslope boundary and what happenes at the downslope boundary (a stream). The column labeled with "DIRI" represents a specific water level on the model boundary rather than a flow across a boundary, which in this case is set zero; "DIRI" stands for Dirichlet boundary condition. Instead, Moreover, the strip of "ON" columns follows the gradient, so it is also assumed there is no lateral hillslope flow, and this is ensured by having "NEU" cells either side of the

"ON" cells. The Hydrological submodel requires that all model domains are square or rectangular in shape, which leaves four corner cells as shown in figure 2.16; These must be included in model input and output files, but, because these are unused, they are denoted as "OFF" and this label means that the part of the model that calculates water flows between cells ignores them (A. Baird, Gill, and D. Young, 2020).

2.4.2 Information file

This file contains nineteen parameters, that guide the bog's development. These parameters remain fixed and are used to describe the main characteristics of a peatland, such as the oxic and anoxic decay constants, run time, and mean annual temperature. In this thesis, only some of the parameters contained in this file were modified, because the others were considered valid and in agreement with the type of peatland taken into account in the study. In the table 2.3 there are the parameters used for the first run in Misurina, with the current weather conditions.

As shown in the table table 2.3, some parameters have remained unchanged, like oxic decay base, anoxic decay base, bulk density, porosity, x extent and y extent; while others have been changed, in order to insert a value that reflects the real situation in Misurina, such as temperature and model run time. Other parameters have remained unchanged because it has been determined that they are close to the values found by the analysis carried out in the laboratory, such as the bulk density; but others are not modifiable, such as x extent and y extent, because fixed values that are used

Table 2.3: Principal parameters used in the simulations of the thesis.

Parameters	Values	
Oxic Decay Base α_{an}	0.035	*Unchanged*
Anoxic Decay Base α_{ox}	0.001	*Unchanged*
Bulk Density ρ	0.1	*Unchanged*
Porosity s	0.3	*Unchanged*
Mean Annual Temperature C	4.07	*Changed*
Model Run Time y	1000	*Changed*
x Extent	27	*Unchanged*
y Extent	3	*Unchanged*

for the construction of the model grid, as will be seen in the description of the input file "Base altitude".

2.4.3 Temperature and Net rainfall

The file "020-Net Rainfall" contains 260 thousand values of net rainfall (in cm/y), defined as weekly rainfall (in cm/y) minus the evapotranspiration (in mm). To calculate this parameter the daily temperature values of Misurina were considered, with a dataset from 2010 to 2020. This dataset includes daily temperature for each month of the year; the weekly average temperatures were then calculated, to obtain 52 total values for each year of the dataset. At this point 260 thousand values were obtained, repeating the values of the 10 years of the dataset.

This procedure has been reproduced also for the precipitation of Misurina, calculating the weekly sum of precipitations measured dily for 10 years, hence obtaining the 52 values corresponding to the weeks. The values, originally in mm/y, were then transformed to cm/y. At the end of these calculations, in order to calculate the net rainfall needed for the model, we calculated the evapotranspiration using the formula of Thornthwaite.

$$ET_p = 16N_m\left(\frac{10\bar{T}_m}{I}\right)^2 \tag{2.8}$$

Where N_m is the maximum number of light hours, $\bar{N}$, times latitude Φ considered divided by 12; specifically there are:

$$\bar{N} = \frac{24\omega_s}{\pi} \tag{2.9}$$

$$\omega_s = cos^{-1}[-tan(\Phi)tan(\bar{\delta})] \tag{2.10}$$

$$\bar{\delta} = 0.409sin\left(\frac{2\pi}{365}D_{15} - 1.39\right) \tag{2.11}$$

Where D_{15} is equal to the Julian day corresponding to the 15th day of the month considered. Moreover $\bar{T}_m$ is the average weekly temperature:

$$\bar{T}_m = \frac{1}{7}\sum_{i=1}^{7}\left(\frac{T_{MAX,i} + T_{MIN,i}}{2}\right) \tag{2.12}$$

I is known as the heat index for the year in question:

$$I = \sum_{m=1}^{52}\left(\frac{\bar{T}_m}{5}\right)^{1.514} \tag{2.13}$$

Lastly:

$$a = 6.75x10^{-7}I^3 - 7.71x10^{-5}I^2 + 1.792x10^{-2} + 0.49239 \tag{2.14}$$

Finally, the evapotranspiration was subtracted from the precipitation to obtain the net rainfall. It was observed that the Thornthwaite formula tends to overestimate potential evapotranspiration in warm months.

2.4.4 Base altitude

In this last input file, there are always 81 values, like the previous file, because these two files work together, so for each column status there is a value of the height of the base of the Misurina peat bog. Starting from known depth data (acquired as explained in section 2.2), the Misurina bog was divided in 26 equidistant points; the first point (representing the stream at the base of the peatland) has been assigned the zero quota (reference zero equals to 1745.386 m above m.s.l.). Of the remaining points, starting from the known heights, elevations calculated by linear interpolation were assigned.

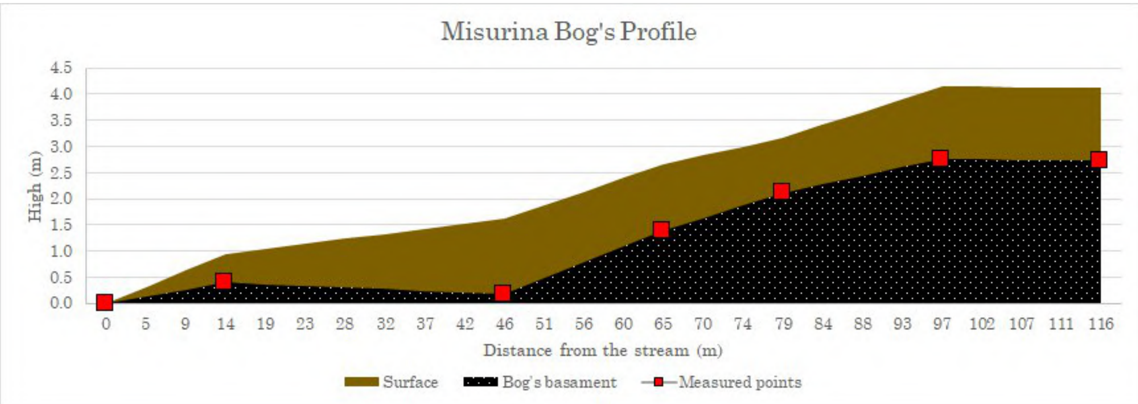


Figure 2.17: The bog's profile with the sampled points.

2.5 CMCC data

In this thesis, it was also decided to analyze the development of the Misurina peat bog under different climatic conditions, as mentioned above. In particular, it was chosen to consider a particular configuration specific for Italy given by the Regional Climate Model COSMO-CLM, developed by the Euro-Mediterranean Center on Climate Change (CMCC)(Zollo, Rillo, and Bucchignani, 2016). The data were processed through DataClime, the service designed to provide climate analysis using both the high-resolution climate projections developed by CMCC and those made available through other projects and programs. CMCC provides three periods (2021-2050; 2041-2070; 2070-2100) and two Representative Concentration Pathways (RCP) scenarios; the maps that are generated indicate anomalies in terms of mean values referenced to the 1981-2100 period (Euro-Mediterranean Center on Climate Change, 2020). RCPs are climate scenarios expressed in terms of GHG concentrations rather than in terms of emission levels. The number associated with each RCP refers to the Radiative Forcing (RF) expressed in units of watts per square meter (W/m^2) and indicates the magnitude of anthropogenic climate change by 2100 relative to the pre-industrial period (Euro-Mediterranean Center on Climate Change, 2020). Among IPCC climate scenarios, CMCC proposes two scenarios, as mentioned above:

- **RCP8.5** (No mitigation): growth of current emissions. This scenario assumes, by 2100, atmospheric CO_2 concentrations tripled or quadrupled (840-1120 ppm) compared to pre-industrial levels (280 ppm);

- **RCP4.5** (Strong mitigation): assumes implementation of some initiatives to control emissions. A stabilizing scenario is considered: by 2070 CO_2 emissions fall below current levels and atmospheric concentrations stabilize and by the end of the century, at about double pre-industrial levels (Euro-Mediterranean Center on Climate Change, 2020).

For the simulations of this thesis the RCP8.5 scenario was chosen, and the period 2071-2100 (Schwalm, Glendon, and Duffy, 2020). Taking into account the temperature, for this scenario and for the chosen period, the CMCC predicts in the Dolomite area of interest, an increase in temperature of 5 °C, this detail can be seen in the figure 2.18 (This figure can be found at the end of the paragraph 2.5). This increase of 5°C has been distributed in a linear way over all the twelve months of a year, without distinction between summer and winter; Adding this value to all the temperatures measured in the last 10 years does not account for the variability, that will likely change4 as wee. In fact the variability between summer and winter was not considered, but not having weather models available to be able to consider the variability of the months, it was decided to implement this simplification.

However, this scenario also predicts an increase of precipitation in the winter months and a decrease in the summer months; CMCC suggests an 80% increase in precipitation for the winter months (December-January-February) and a 40% decrease for the summer months (June-July-August) (See figure 2.19 and figure 2.20 at the end of the paragraph 2.5). In order to relate these variations to a monthly scale, a "factor" was counted by which each value of precipitation in Misurina must be multiplied (Table 2.4).

Table 2.4: Rainfall factors calculated to relate precipitation variations to a monthly scale.

Month	Rainfall Factor
January	1.9854
February	1.725933333
March	1.466466667
April	1.207
May	0.947533333
June	0.688066667
July	0.4286
August	0.688066667
September	0.947533333
October	1.207
November	1.466466667
December	1.725933333

Each precipitation value in January has to be multiplied by the January specific factor, the same for February, and so on, for all the years considered in our dataset. At this point the precipitation values obtained were used to calculate the Net Rainfall, as described in paragraph 2.4.3.

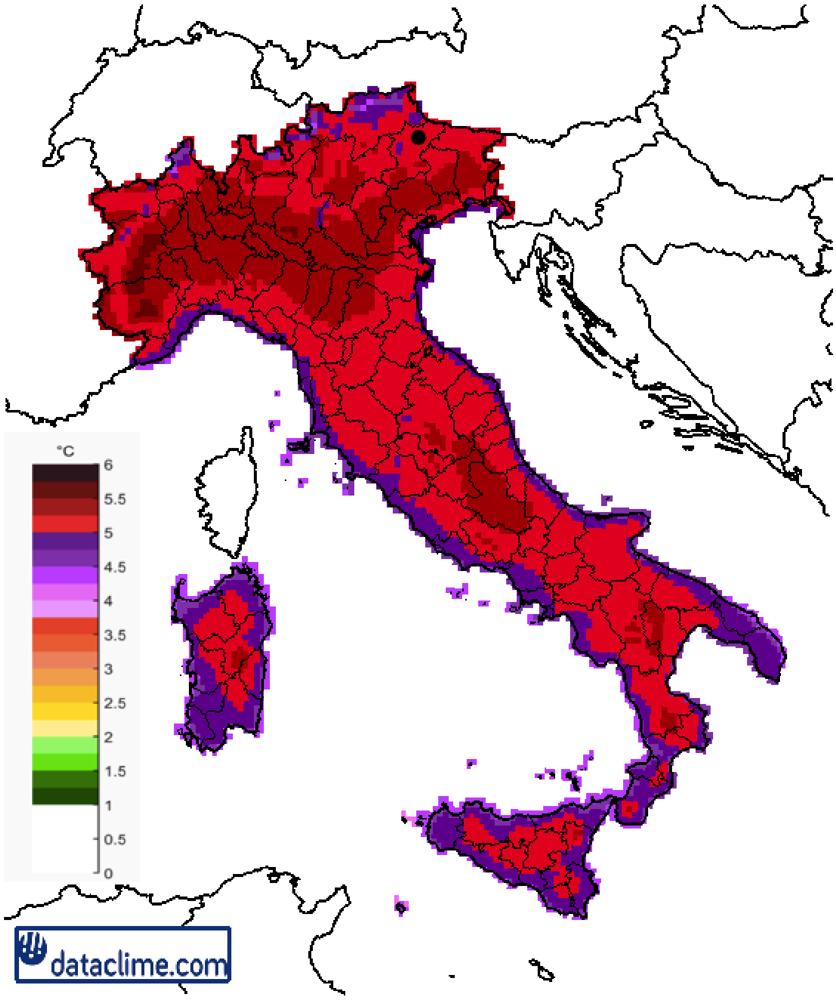


Figure 2.18: Map of the daily mean temperature over the period 2070-2100, with scenario RCP 8.5. In the map, the black dot identifies the zone of interest. DataClime elaboration.

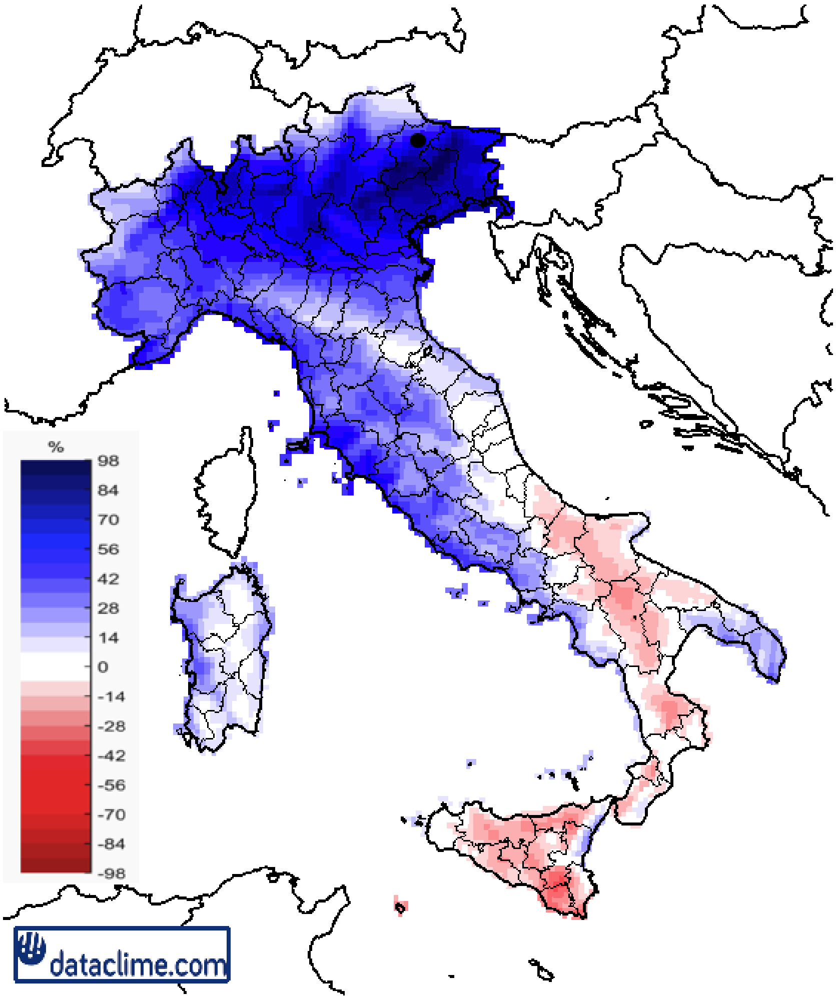


Figure 2.19: Map of winter precipitation over the period 2070-2100, with scenario RCP 8.5. In the map, the black dot identifies the zone of interest. DataClime elaboration.

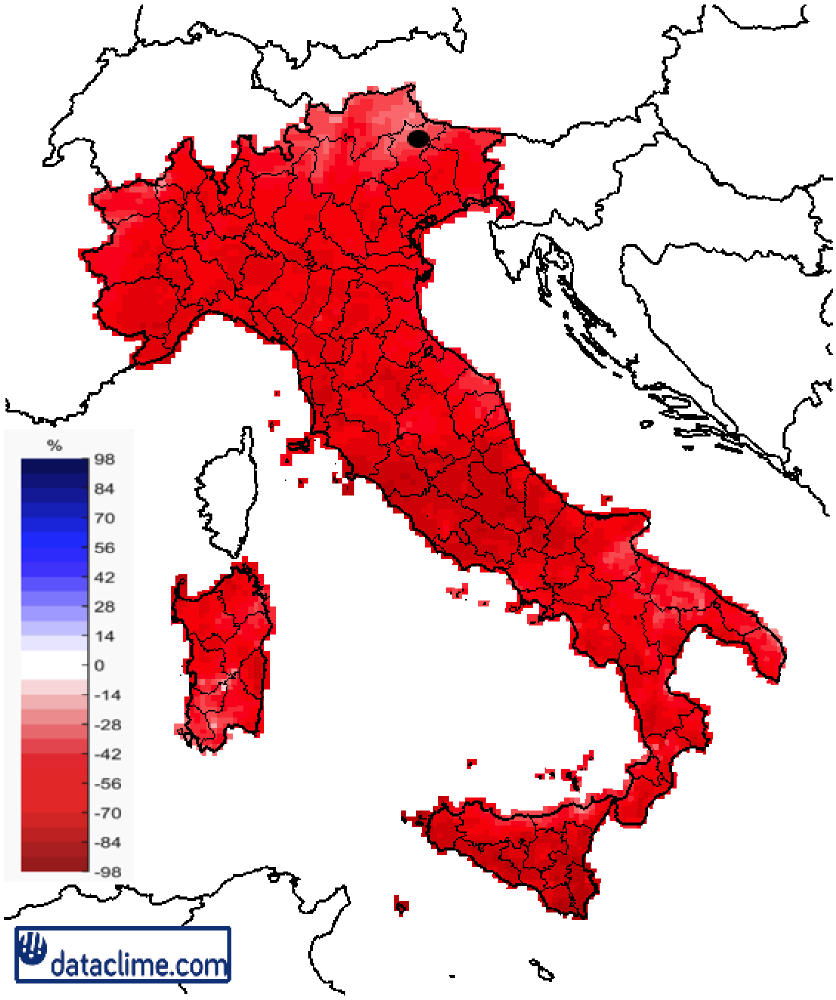


Figure 2.20: Map of summer precipitation over the period 2070-2100, with scenario RCP 8.5. In the map, the black dot identifies the zone of interest. DataClime elaboration.

Chapter 3

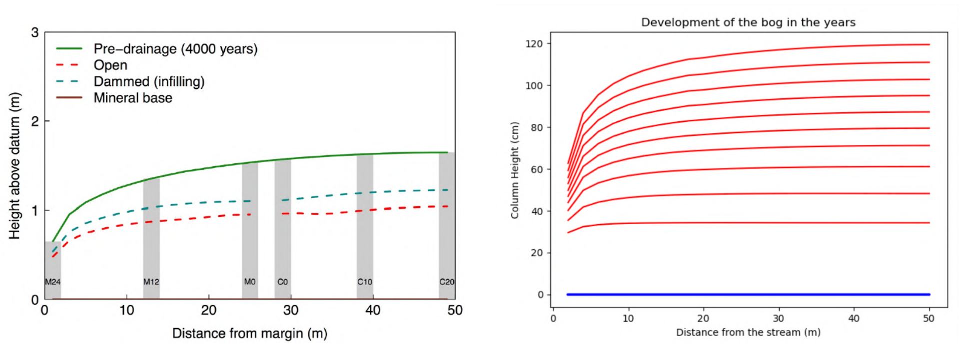
Results and Discussion

In this chapter the results and respective conclusions of the data processing described in the previous chapter (Chapter 2) will be discussed. Before using DigiBog with Misurina data, we decided to reproduce previously studied situation by D. M. Young et al., 2016, to understand if the model provided comparable results and if the created Python code could reproduce similar graphs. For the first elaborations it has been decided to use the default values of the model, making it run for 1000 years instead of 4000 like in the simulations performed by D. M. Young et al., 2016.

Table 3.1: Parameters used in the first simulations of the thesis.

Parameters	Values
Oxic Decay Base α_{an}	0.035
Anoxic Decay Base α_{ox}	0.001
Base Temperature C	6.2900
Bulk Density ρ	0.1
Porosity s	0.3
Temperature Sensitivity Q_{10}	3.0
Hydraulic conductivity parameter a	1586.8624
Hydraulic conductivity parameter b	8.0
Mean Annual Temperature C	11.35
Model Run Time y	1000
x Extent	27
y Extent	3

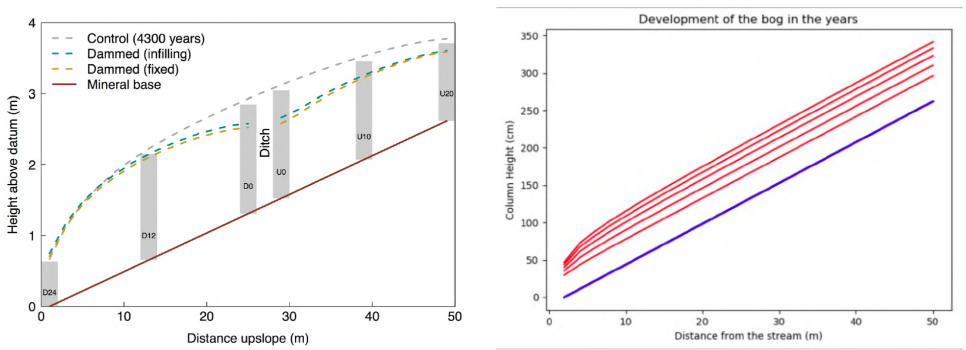
This because the model takes a long time to generate the output and and for issues of time and logistics it was decided to decrease the years of run, looking for a compromise between expected results and years of calculation. In figure 3.1 it is possible to see the comparison between the output coming from D. M. Young et al., 2016 (left) and the output resulting from this work (right), both with a flat bog bottom.



(a) (b)

Figure 3.1: Comparison of Young et al. (2016) output for 4000 years (left, a) and output obtained for thesis work for 1000 years (right, b).

From the first simulation, although the years were different, it can be seen that the model works well and that the Python code created for the plotting of the graphs succeeds to reflect the behaviour already created in the previous studies. Since the study site is located on a slope, we proceeded to vary the shape of the bottom to produce a simulation with an sloping bottom.



(a) (b)

Figure 3.2: Comparison of D. M. Young et al., 2016 output for 4000 years (left, a) and output obtained for thesis work for 1000 years (right, b); figures with slanted background.

Also in this simulation, the generated code was able to reproduce results fairly close to the simulations done by D. M. Young et al., 2016. It should always be kept in mind that the number of years of the simulations performed in this study is smaller to that of the simulations by D. M. Young et al., 2016.

As for the runs for the Misurina peatland, we performed using as input the values described in section 2.4.3 and 2.4.4. Also in this case the run was done for 1000 years.

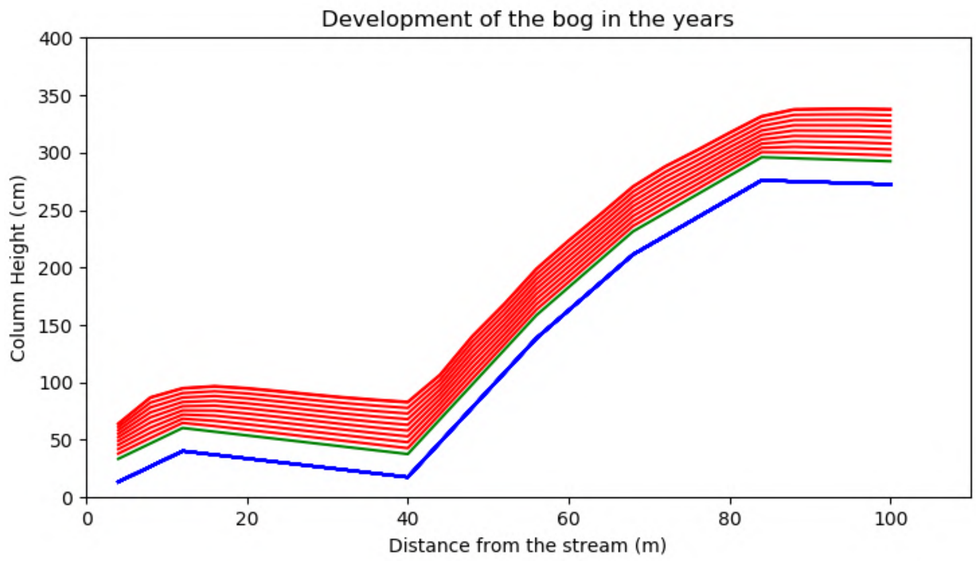


Figure 3.3: Reconstruction of the Misurina bog profile; in the x-axis there is the distance from the stream while in the y-axis there is the height in cm of the bog. The blue line represents the base of the peatland, reconstructed from field sampling data; the green line represent the first year of accumulation of peat over 20 cm of mineral soil, and the red lines represent the growth of the peatland over the course of a thousand years. Each red line represents 100 years of development.

From figure 3.3 it can be seen that there is greater accumulation of peat in the flatter areas of the peatland, while less accumulation where the ground is steeper. It is also possible to see that in 1000 years, the bog accumulates about 1 m of peat and this result is in line with the studies conducted by Segnana et al., 2020, in which it was found a growth of about 110 cm after 1000 years in a bog in the eastern Italian Alps.

After plotting the output profile of the Misurina bog with current climate conditions, we studied how the peat bog could grow under different climatic conditions. The temperature and precipitation data described in section 2.5 were used for this simulation. This simulation is not to be considered a real prediction starting from the current situation, this is because we are not simulating how the existing peatland evolves under the future climate, but we simulate the growth of the peatland as if it developed from the bottom with the climate predicted by the CMCC predictions for the period 2070-2100.

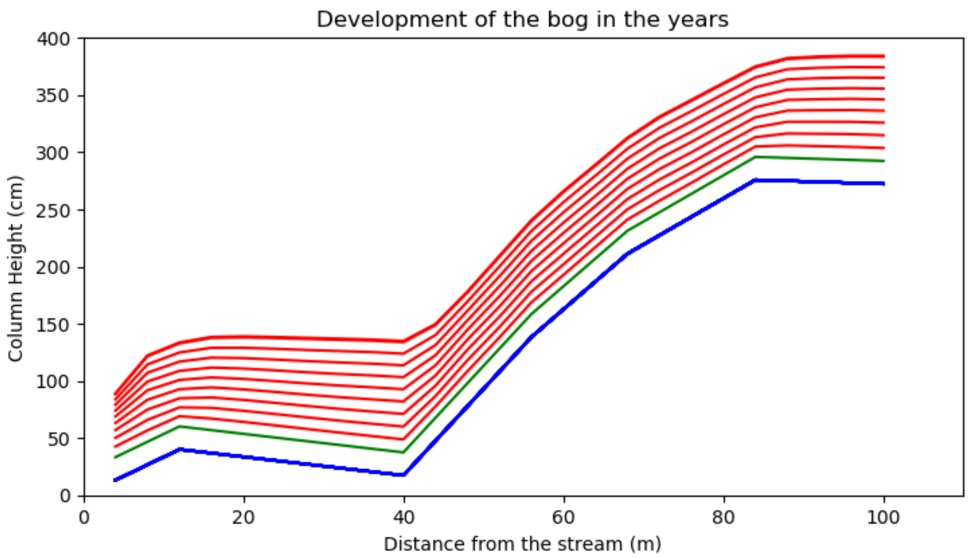


Figure 3.4: Reconstruction of the Misurina bog profile with IPCC predictions; in the x-axis there is the distance from the stream while in the y-axis there is the height in cm of the bog. The blue line represents the base of the peatland, reconstructed from field sampling data; the green line represent the first year of accumulation of peat over 20 cm of mineral soil, and the red lines represent the growth of the peatland over the course of a thousand years. Each red line represents 100 years of development.

The basic morphology of the land is very important and it can be seen that in both profiles (Figure 3.3 and figure 3.4) there is a larger accumulation of peat on the flatter areas (as observed in the previous simulations), while where the slope is present the accumulation is smaller.

In figure 3.4 an increased accumulation of peat with respect to the simulation with present climate conditions can be seen, reaching about 140 cm in thickness in the initial part to the left. During this simulation the temperatures were increased by 5°C throughout the year (as discussed in the paragraph 2.5), thus reaching an average temperature of about 100% higher than that used for the previous simulation and this has meant that the majoriry of temperature values exceeded the activation temperature of the degradation of organic matter, which in the model is 6.29°C, thus allowing a greater degradation but an even larger accumulation of peat. This increase in temperature affects a lot the net litter production, as can be seen from the formula 2.3. In the simulation with the scenario RCP8.5 the precipitation and the net rainfall were also increased, and having increased precipitation there is a greater amount of water and this corresponds to a lower thickness of the oxic zone, and it is for this reason that the peat degradation affects less than the increase in temperature. For this reasons it is possible to say that the RCP8.5 scenario allows the peat bog to grow more.

From figure 3.3 and figure 3.4, other observations can be made; as already discussed above, both graphs show a greater accumulation of peat in the flat areas. In fact, in the first graph (figure 3.3) the peatland grows up to 100 cm in 1000 years of development, while in the second graph (figure 3.4) it can be seen that peat (under different climatic conditions, with increasing temperatures and increasing precipitation) accumulates up to 140 cm in height. There is therefore about a 40 cm difference in peat accumulation between the two climate conditions; as commented earlier this difference could be due to the fact that the proposed climate conditions for the RCP8.5 scenario are more conducive to peat accumulation.

In addition, for both figures it can be seen that the model causes more peat to accumulate at first, then as the years pass the layers are thinner. This is because, as the peat accumulates, the water level in the stream at the low boundary does not change, hence constraining the growth of the water table. As a result, the oxic peat layer becomes thicker overtime and therefore the peat degradation increases while accumulation decreases. This thesis work could further expanded to study Alpine peatland growth, both under current and future climate conditions.

Conclusions

In this thesis we described the analysis of alpine peatlands, taking as a real case a bog near Misurina. The peatlands are very important environments from the climatic point of view because they are able to store giga tons of carbon dioxide below ground. These environments are present in many areas of the planet, but in this study we decided to make an in-depth study in the alpine peatlands, because they are a type of environment little studied.

We used a mathematical model (DigiBog) to analyze the growth of the peat bog of interest; a sampling was also performed to collect real data that could then be used in the model. Two main simulations were performed: one representing peatland growth under current climate conditions, and one representing peatland growth under extreme climate conditions, with data provided by CMCC forecasts.

From these simulations it can be deduced that the model is able to faithfully reproduce the growth of the bog, from the simulation with the scenario RCP8.5 it can be seen that the extreme climatic conditions (temperature increase of 5°C and increased precipitation especially in the winter months) favor the growth of peatland, increasing the production of peat, despite the increase of mean temperatures in the summer months.

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