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COMPARISON OF PEATLAND HYDROLOGICAL MODELS

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Peatlands have a vital role in carbon sequestration and mitigation of global climate change. Peatlands in the boreal and sub-arctic regions store around 15–30% of global soil carbon. In the European Union the move towards the climate neutrality policy includes activities specifically aimed at the reduction of negative greenhouse gas emissions from peatlands through nature conservation and renewal. In Latvia the total area of peatlands is 645 100 ha. Due to industrial peat extraction and other processes a considerable proportion of peatlands in Latvia are degraded, thus leaving negative impact on both the local wildlife environment and on the global effort to tame the climate change. Areas in Latvia where peat extraction has ended or has been suspended without revitalisation activities in place amount to 18 010 ha. Given the conditions the restoration of degraded peatland environments is important and most often take place in the raised bogs calling for evidence-based decision making through deployment of hydrological models that are applicable for restoration of raised bogs in conditions of Latvia. The analysis of available hydrological models indicate that mathematical deterministic physically based models are applicable for the restoration activities of peatlands. The raised bog model deployed in Männikjärve bog holds the potential to be integrated within a virtual reality environment after further improvements, thus potentially improving decision and environmental policy making process for raised bog area restoration activities. Further work on tailored model for bog restoration considering the data acquisition challenges with input data fed through remote sensing capabilities is proposed.

Keywords: wetlands, peatlands, hydrological models

INTRODUCTION

According to Xu et al. (2018), most of the world's *wetlands* are in Asia (38.4%) and North-America (31.6%), while wetlands in Europe cover only 12.5% of territory. Meanwhile subtype of wetlands - *peatlands*, cover only 3% of global Earth surface, while boreal and sub-arctic *peatland* regions while acting as carbon sinks sequester enormous amounts of carbon from atmospheric CO2, and in the form of *peat* stores around 15–30% of global soil carbon (Limpens et al., 2008). *Peatlands* are considered as some of the most endangered types of natural habitats in Europe (Kiely et al., 2018). The global significance of peatlands in terms of carbon sequestration and mitigation of global climate change has been considered since 2008. However, on 20 April 2012 resolution the European Parliament voiced concerns about the ongoing degradation trend of wetlands, which are considered a significant biotope, thus the need for a coordinated relief action based on the tools provided by the EU was stressed (European Commission, 2012).

On the one hand the climate change put biotopes and species under risk, on the other hand the environment protection is incredibly significant to mitigate and to adapt to the climate change. Taking into concern the fact that the global climate change cause more adverse weather conditions, the restoration of degraded peatland environments is ever more important. The European Union's move towards the climate neutrality policy, reduction of negative greenhouse gas emissions from peatlands and adaption to climate change, is based on ecosystem protection solutions - nature conservation and renewal (IPBES, 2019).

These actions can only be successfully performed with a given knowledge base, a process that until now has been delayed in Latvia by the following obstacles:

- Peatlands have different definitions and sub-type names;
- Classification of peatlands depends on the different national and regional typologies;
- Classification of peatlands is based on different criteria;
- Data collection can be obstructed due to available data sets;
- Data collection is time consuming and labour intensive and thus economically disadvantageous.

In Latvia areas having peat cover 10.7% of total land surface while functional peatlands cover only 4.9%. (Pakalne, et al., 2016). The total area of peatlands is 645 100 ha, whilst 70% of these territories are natural peatlands. There are 237

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areas where peatland has been or is actively extracted with the total area of 50 179 ha. Degraded peatland areas where peat extraction has ended or has been suspended and no revitalisation activities had been performed reach 18 010 ha (Petersons, et.al. 2018). Therefore, degraded peatland restoration to mitigate negative impact on global warming is a significant topic of research in Latvia. In the meantime, the degraded raised bogs are bogs which natural hydro-biological environment has been altered or they have been partially used for peat extraction, but in which it is possible to recreate the hydro-biological regime and further peat forming is expected to restart in 30 years' time (Aunins, et al., 2010). Peatland restoration most often take place in large-scale raised bogs. Based on the described reasons the aim of this article is to conduct a review of hydrological models that would be applicable in the case of raised bogs on a single local scale bog subject in conditions of Latvia, whilst considering the plausible obstacles in data collection, which serves the novelty of this study.

MATERIALS AND METHODS

The study includes analysis of different obstacles to deployment of hydrologic models. The study was carried out whilst using the method of scientific literature and document analysis, abstraction method, and systematic argumentation approach. There were eight conceptual models (MODFLOW, SWAT, WEAP, MIKE SHE, HecRAS, QUAL2K, Männikjärve model, SIMGRO) from Canada Estonia, Germany, India, Latvia, Lithuania, Netherlands, New Zealand, Sweden, UK, USA, that were further analysed along with a single sub-model, as well as the existing challenging factors were figured out. The comparison of different models reveals that there are variety of combinations of processes within the models.

RESULTS AND DISCUSSION

In the European countries classify their peatlands according to different terminologies – for instance, in the United Kingdom lowland wetlands are called 'mores'. Variation of the name is used to describe peatlands in the Netherlands "moreas" and Germany "morast". Meanwhile the term "moor" (in Latvian - "tirelis") is commonly used in the northern Scotland to define a top layered peatland. Also, the synonym of the term "bog" is "muskeg." This term which name originates from the North-American Indian "cree" tribe term "maskek", that defines a low-land swamp. This term is widely used in the Alaska and Western Canada (Roland, 2013). There are over 20 forms of bogs, 19 forms of fens, and 6 forms of swamps which would be considered peatlands (IPS, 2021).

The term *peatlands* are attributed to every type of ecosystem that has accumulated at least 30 to 40 centimetres of peat layer. Meanwhile the *peat* is classified as a partially degraded vegetation (incl. moss) remains – mostly *Sphagnum* moss. A bog is a wetland that accumulates peat, a deposit of dead plant material – often mosses, and in most cases, *Sphagnum* moss (Keddy, 2010).

There are two main types of peatlands – bogs (*mires*) and *fens:*

- ***Bogs*** are characterized by a vegetation that indicate the effect of a high-water table and a general lack of nutrients. The surface of a bog is often raised in the form of a mound and because it is isolated from mineralized waters, the main source of nutrients comes from precipitation and wind. Nutrient input is carried by precipitation (rain and snow) and wind, acidic water of pH lower than 4.5. The dominant vegetation includes the *Sphagnum* mosses accompanied by shrubs and trees (Frolking, et al, 2011).
- ***Mire*** is a peatland where peat is currently being formed. Mires arise because of incomplete decomposition of organic matter, usually litter from vegetation, due to water-logging and subsequent anoxia (Frolking, et al., 2011).
- ***Fens*** are characterized by a high-water table, but with a slow internal drainage by seepage along very low gradient slopes. The surface of a fen varies from flat to very gently sloping and it receives water that has been in contact with upslope mineral terrain that is enriched with dissolved mineral nutrients. Nutrient input from surrounding mineral terrain, acidic to slightly alkaline water of pH ranging from 4.5 to 7.5 and dominant vegetation are brown mosses and sedges (Frolking, et al, 2011).

The significant difference between bogs and fens lies in the source of water: while the former is fed by the precipitation and they lack minerals, the latter are fed by the minerals richer surface and groundwater sources as well as nutrients from precipitation waters. Peatlands can also be attributed to natural forests and open surfaces with moss and sedges vegetation and bushes. The allocation of peat is significantly affected by the climate conditions and terrain. In northern latitude, the relatively low temperatures can be sufficient for the growth of plants, but too low for a significant microbe growth response. In some cases, there the peat has been allocated several thousand years ago during more humid climate periods, while during more arid climate periods, the deposition of peat stalled (Parish, et al, 2008). The variety of the described synonyms and forms indicate towards problem that is linked to the problem of the international science community to come to a common classification of quite different terms that often describe intangible level of detail (International Review…, 1964).

Most of the wetlands classification has been defined and adapted according to the typology of the northern hemisphere types of wetlands in boreal and temperate climate zones, in which the dominant type of peat storing moss is the *Sphagnum* moss. Also, there are highly detailed wetland classification systems in Europe, Russia, also central Asian and Balkan countries, and North America (especially in Canada), that make up about 90% of peatland area worldwide. There are different classifications based on a single or multiple criteria that mirror the aims and goals of experts defining them. For instance, those of the nature conservation specialists, ecologists, peat industry lobby groups, forestry sector lobby groups. Unfortunately, these definitions are not standardised, which cause significant inconsistencies, although with some similarities. The main attributes used in definition of wetland and peatland classification and typology and include floristic, physiognomy, morphology, hydrology, stratigraphic, peat chemistry, and physical properties. In these terms, wetlands have been defined based on vegetation, chemistry, source of water, hydro morphology (Lindsay, 2018).

However, the most crucial factor affecting creation of wetlands is water. The length of flooding period and prolonged saturation of soil with ground waters determine the plausible vegetation. The long-term changes in the moisture conditions due to the climate change will determine whether the natural peatlands will continue to exist as a globally significant net carbon sink or will change into carbon releasing factor (Swindles et al., 2019; Gallego-Sala et al., 2018).

In case of reduced precipitation there is a high possibility of a rapid reduction in groundwater level thus causing expansion of more dry moss and undergrowth. Examples of such processes can be seen in different regions in northern hemisphere. This however would facilitate forest and shrub growth. As a result of the climate change in case of increased precipitation, in degraded, dried out peatlands the vegetation would turn to more hydrophilic species (Whitfield et al. 2009).

The carbon absorption potential of peatlands is dependent on the specific carbon reception balance of given species, and the microbiome decay ratio. The speed of both processes will increase with the warming of climate. There is a positive link between the accumulation of carbon and the cumulative photosynthetic active radiation during the growth season in the peatlands of mid to high latitude territories of both hemispheres. However, in the lower latitudes, this proportion is inversed and thus in such conditions the accumulation of carbon is less pronounced (Gallego-Sala et al., 2018). The cold season processes have a vital role in the peatlands of northern hemisphere During the winter season and spring thaw months it is difficult to conduct field studies in peatlands, thus affecting the number of available research finding in this field for northern regions (Whitfield et al. 2009). Consequently, on a variable timescale, the dynamic of peatlands differs due to complicated nonlinear interdependence with thermal and moisture conditions. These processes can be better understood whilst using different hydrologic models, which are used also in the case of bog/mire peatlands.

The analysis of scientific papers indicate that the use of simulation models is becoming ever more prevalent in problem solving and as a support tool for decision makers (Sarget, 2011). The data for models is collected through direct and indirect monitoring methods. Indirect methods can include the use of closed camera method, but due to frequent observation requirements, this method is expensive. One of the indirect observation methods is based on the analysis of the bog vegetation content is the GEST method (Schwill et al., 2010). The use of aero scanning MAMAP (Methane Airborn Mapper) and satellite data remote observation method helps determining gas concentration, however there is still an uncertainty in terms of data analysis in territorial units and division of types of overlaying topographic information. Additionally, these methods are expensive (Fehr, 2016). The drone technologies for use in geospatial analysis of remote and hard to reach areas are becoming ever more common. This holds a higher potential in terms of cost economy than other commonly used methods and technologies (Berman et al. 2012). Thus, the use of drones can serve as the technological approach for overcoming the data scarcity caused by the lack of proper data sets. Also, the use of drones reduces the practical entry barriers for data acquisition and is less expensive in terms of data collection.

Hydrological model classification

The purposes of using hydrologic models are: 1) to ensure simplified explanation of complicated systems and to describe the system from a quantitative and systematic perspective (Davie, 2008); 2) to forecast the reaction of the modelled system in conditions which are difficult to determine, and to use the forecast in decision making process of object modelling, resource management or research activities (Singh, 2010). The choice of available models (Fig. 1) depends on the aim of the research. The *Deterministic Physical model*, unlike the *Mathematical model*, reproduces the model system in a smaller scale (Nourani et al., 2007, 2014).

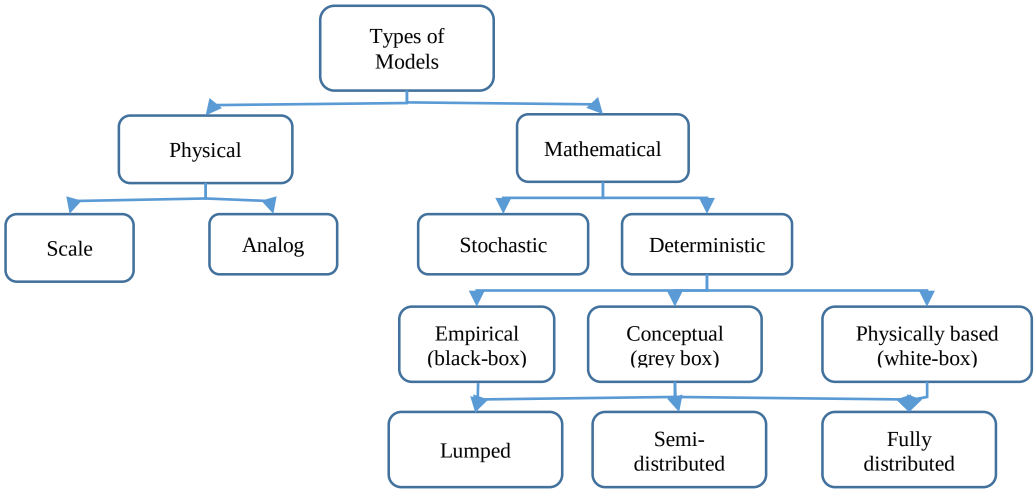

Figure 1. Classification of hydrological models (Duranel, 2015)

Meanwhile computers allow functional application of *Mathematical model* (Fig. 1) for information [one output] (*Deterministic model*), and for acquisition of set of multiple plausible results (*Stochastic models*), that is very useful for evaluation of flooding (Shaw et al. 2010). *Empirical models (black-box)* are only valid for the environmental conditions in which they were derived and therefore are not analysed in this paper. Meanwhile the *Conceptual models (grey-box)* describe different process relationships and can be used to determine and test the consequences of different presumptions, while *Physically based models* prescribe physical implementation of theoretical models in a given test environment where the relevant hydrological processes would take place. The *Conceptual models* differ also based on the used spatial discretisation. *Lumped model* represent the model domain as a single spatial unit, *Semi-distributed model* discretises the model domain in a series of sub-catchments or hydrological units of similar hydrological characteristics and *Fully distributed model* represent the model domain is discretised into a grid or triangular mesh of relatively small elements (McDonald, Harbaugh, 2003; Francés et al., 2014).

Historically the most well-known *Conceptual models* to be applied for use in the case of raised bogs are *Klymo, Ingram, Almquist-Jacobson* and *Foster integrated model, Kirkby and Vitt model* (Clymo, 1978; Clymo, et al., 1998; Ingram, 1982; Almquist-Jacobson, Foster, 1995; Kirkby et al., 1995; Vitt et al., 2000). *Ingram model* (*Hydrological/groundwater mound model*) which is based on peat hydrology and hydraulic properties allows determining the shape and size of a bog. This model is best applied to defining small raised bogs (Vitt et al., 2000). *Almquist-Jacobson* and *Foster model* (also *Integrated model*) based on variable data from both external and internal processes allowing to determine the peat shape, accretion, and expansion (Bromley, Robinson, 1995). *Kirkby model* and *Vitt model* (*Modified hydraulic model*) analyse the net rainfall and its variability determines the peatland height. The model determines the interrelations between the productivity and decomposition processes within the deeper peat layers. This model has been widely used in Europe for monitoring of peat quality and determination of peat accumulation (Thiéry, 1990). The *Wildi model* is designed for testing of a single location with a large amount of specific parameters (Hilbert at el., 2000). *Winston model* is rather general, oriented towards hydrology and dedicated for control of peatland form and coal formation (Winston, 1994). *Korhola model* includes a topography-driven 3-D peat initiation, growth and expansion, but this model lacks the ability to determine the impact of climate and groundwater (Korhola et al., 1996). Meanwhile the *Hilbert model* is able to simulate the interaction between the different components of peatland, while using a system dynamic approach (Hilbert et al., 2000). The *Clymo model* for simulation of raised peat bogs is based on the methodology from *Forrester* (1961), *Wildi* (1978), *Winston* (1994), *Korhola* (1996), *Hilbert* (2000) *models* and is dominantly aimed at fens that are located within continental climate conditions. Continental fens are characterised by convex pattern with relatively limited water availability and more pronounced seasonality on annual comparison. The basis for *Clymo model* is the dynamic balance of peat addition rate and proportional decay rate which determines the possible peat accumulation (Almquist-Jacobson, Foster, 1995; Kirkby et al., 1995). The use of the model is limited by the need of multiple parameters which are difficult to acquire and test (Korhola et al., 1996).

Physically based models, represent the relevant hydrological processes in the mass flow and momentum transfer (Thiéry, 1990; Bromley, Robinson, 1995). They require complex information about the hydrological system and, due to the large number of parameters and the fine-scale spatial discretisation, their parameterisation requires a very large amount of data (Graham, Butts, 2015). In practice, it is not possible to measure all required parameter values for every single spatial discretisation unit, and some parameters are generally specified for groups of units. The accuracy of models describing small-scale hydrological processes is questioned in case of when the grid size is relatively large and the difficulties related to obtaining the field measurements for all parameters as well as the need for calibration, therefore these models are prone to possible mistakes and over-fitting issues, and are calculation-intensive, requiring high computing performance (Rochester, 2010).

For instance, *MODFLOW* is an open source modular ground water flow model created by the U.S. Geological Survey which imitation elements are programmed using object-oriented design (Hughes, et al., 2017).

SWAT (Soil & Water Assessment Tool) soil and water assessment tool is a river basin scale model that was used to imitate the quality and quantity of above ground and underground water basins. The model is used to forecast the land use and management as well as the impact of climate change on the environment (SWAT, 2021).

WEAP (Water Evaluation And Planning) has been developed in the Stockholm Institute of Environment with the purpose of development and revision of management opportunities of water resources, but this model cannot be used for assessment of impact of forest stand on the water balance (Stockholm Environmental Institute, 2021). This model has been widely used to evaluate and forecast the circulation of water and substances within as well as the impact of chemical substances and irrigation systems on the agricultural yields (Wang, et al., 2019).

HecRAS (Hydrologic Engineering Center's River Analysis System) can be applied for assessment of water depth, flow and floodplains based on the surface angle and topography. It is useful for calculation of transfer of sediments and calculation of water temperature (NSRC, 2020). This model does not perform interception and transpiration calculations; thus it is not applicable for assessment of impact of forest stands on the bog water balance.

QUAL2K is a model developed by the Department of Civil and Environmental Engineering of the Tufts University, which is a one-dimensional water and creek water quality model. It is aimed at depicting the vertical and side flows of channel (Tufts University, 2020), and it does not take into consideration vegetation, and it is not suitable for bog renewal projects.

MIKE SHE model is an integrated hydrologic model, because it is based on all of components of hydrologic cycle (incl. precipitation, evaporation, surface flow, infiltration, groundwater flow). This model is a process-based system that allows depicting each hydrologic process according to the topical problematic in different spatial and time scales. This model can be used to analyse, plan and manage wide variety of water resources and environmental challenges, incl. the management and revival of water lands, as well as research on land use and climate change. The model focuses on processes of evaporation and snow melting, which makes this the most applicable model from the previously reviewed for assessment of forest stand impact on the bog water balance. The *MIKE SHE model* is well applicable for use with the raised bogs (NIH: Centre of Excellence…, 2021).

However, when applying the *MIKE SHE model* for purpose of determining the impact of afforestation on the hydro ecologic conditions in the river catchment area of Dauges National Nature Reserve, a valley mire in the French Massif Central, the researchers faced challenges with defining the model reference positions and error in water balance (Duranel, 2015). In the case of Latvia, there is an additional limitation to the use of certain type of data sources. The Copernicus climate change agency (C3S) created the Climate Data Storage (CDS). This historical data storage is applicable for hydrological modelling of large bog areas, but in the case of single point modelling of bogs with a limited size of couple of square kilometres in Latvia, the data array of 0.5 x 0.5 geographical degree array is not sufficient (ECMWF, 2020).

When performing overall analysis of *Deterministic Phisically based* models and types of processes included within the models (see Table 1) it is evident that almost all of the given models (except MODFLOW include the *above ground water* process. The *underground water* process has not been utilised in the HecRAS and QUAL2K. The *peatland vegation* has not been included in the *QUAL2K* and *MODFLOW* models, while the *Interception* has been utilised only by the SWAT model. Furthermore, the *Transpiration* process has been used in the *SWAT* and *MIKE SHE* models while the *Snow melt* has been included only in the MIKE SHE model.

Table 1. Comparison of hydrological models (by authors)

Hydrologic model	**Types of processes included within the model**						**Utilized in bog restoratio n**
	Overland water	**Groundwater**	**Vegetation**	**Interceptio n**	**Transpiration**	**Snow melt**	
MODFLOW	-	×	-	-	-	-	-
SWAT	×	×	×	×	×	-	-
WEAP	×	×	×	-	-	-	-
MIKE SHE	×	×	×	-	×	×	-
HecRAS	×	-	×	-	-	-	-
QUAL2K	×	-	-	-	-	-	-
SIMGRO	×	×	-	-	-	-	×
Männikjärve model	×	×	×	×	×	×	×

'-' – not in place; '×' – in place.

Examples from the adjacent countries, include the hydrological model for decision-making utilised in Lithuania a combined surface and groundwater flow regional hydrological SIMGRO (SIMulation of GROundwater and surface water levels) model has been used in Dovine river basin. The model is aimed at determining the required changes to the drainage regime in river basins that can impact the wetlands within and simulates the flow of water in a saturated zone, unsaturated zone and surface water. Significantly large area of the peatlands is covered by raised bogs. The model allows for determination of the possible influence of the changed land use cover (e.g.. removal of deciduous trees, renewing or blocking drainage ditches, removal of scrubs and trees in the wetlands surrounding, etc.). This model is aimed at determining the proper method for improving the hydrological conditions of a greater lake through improving the outflow and water level conditions in the Lake and wetland system within the water basin (Povilaitis,2010). This however limits the use of such model in the micro level for a specific environment of a raised bog.

In different settings in Estonia's north-east within a nature conservation area encompassing Selisoo bog, a model was created for an area of underground mine which has caused the continuous decline of groundwater in observation wells and nearby aquifers. The conceptual underground water model using the MODFLOW 2000 flow-engine was used, with boundaries set for an area including groundwater-level monitoring wells covering 95 % of the Estonia underground mine areas with a grid consisting of with 257 rows, 451 columns and 9 layers. The model is a mathematical deterministic conceptual model which' spatial discretisation is based on a fully distributed model discretising the model into a grid of relatively small elements. The model can be used for simulating scenarios for the vertical hydraulic conductivity of the subsurface, which is of critical importance to potential wetland dewatering as a result of mining (Marandi et al. 2013).

Meanwhile in the Männikjärve Bog the system dynamics simulation model for decision-making validated the deployment of a model able to calculate the right tree cutting intensity to reduce the impact of evaporation and interception of trees on the water balance of the bog, thereby contributing to the restoration of the bogs. The model is a mathematical deterministic conceptual model which' spatial discretisation is based on lumped model thus representing the model domain as a single spatial unit. The model aims at representing the movement of water in the bog hydrological system from water intake through the precipitation to the water output through interception, sublimation, evaporation, transpiration, lake outflow and overland flow (Java et-al., 2020). This two-dimensional (2-D) model offers the possibility to track the water movement in vegetation, water spatial overland movement as well as the water level in a geographical point. The use of such model with three-dimensional (3-D) perspective (possibility to join several geographical points thus giving a possibility to model whole area of a bog) would allow for integration of the model within a virtual reality environment. Such approach would enable decision makers, environmental policy implementers and researchers to make more comprehensive analysis of peatland environment condition, thus leading to a more evidence-based decision making process enabling bog restoration.

The review of models indicates that few of the reviewed models have been created with a specific purpose for bog restoration. It is evident that despite the multifactor scope and practical nature of many of reviewed models, such models as the SWAT model, the *MIKE SHE* model are not applicable for use in bog restoration, since they do not provide the full set of processes (see Table 1). With the exception of the SIMGRO model, they have not been used for modelling of bog restoration. In the meantime, the Männikjärve model includes all of the defined processes and can be utilised for bog restoration process forecasting. For these reasons these are the given advantages of the Männikjärve model that is applicable in the case of swamp restoration modelling of raised bogs on a single local-scale bog subject in conditions of Latvia and include all six of the plausible peatland processes. Further research is necessary focusing on the application and improvements to the Männikjärve model in virtual reality setting.

CONCLUSIONS

1. Peat has a significant role in climate change mitigation as it is one of the most important carbon accumulators in the world, containing approximately 30% of earth carbon, which is three times more compared with trees.
2. Analysis of scientific literature indicate a vast variety of definitions and forms of the term “peatland”; wide variety of classification difference between countries and regions depending on the interests of lobbying groups. However common attributes in the classification of peatlands and bogs were determined, which include floristic, vegetation physiognomy, morphology, hydrology, stratigraphic, peat chemistry, and physical properties.
3. Detailed wetland classification systems are available for Europe, Russia, also central Asian and Balkan countries, and North-America (especially Canada), that make up about 90% of peatlands areas worldwide. In the peatlands of northern hemisphere, the cold season processes (incl. spring thaw) have negative obstructive impact on the data acquisition activities. This can be averted by utilising indirect remote sensing methods.
4. In the case of raised bogs restoration modelling, the use of drones can serve as the technological approach for overcoming the data scarcity and reduces the limitations for data acquisition while being less expensive in terms of data collection.
5. The study indicates that when comparing models by their ability to include variety of hydrological processes, the MIKE SHE model and Männikjärve model provide the most versatile set of processes and thus could be applicable for use in bog restoration. The Männikjärve model however additionally offers the possibility to model the interception process. The Männikjärve model includes all of the defined processes and can be utilised for forecasting of the restoration process of raised bogs on a single limited-size bog subject scale in conditions of Latvia.
6. Männikjärve model is a 2D model that is a useful tool for studying the mutual impacts and causal relationships existing between the elements forming the hydrological system of a bog where a well is set up and the groundwater level measurements are available, but in order for it to be used in the bog restoration, the third dimension is required. After improving the dimensional perspective, it would hold the potential to be integrated in a virtual reality environment for an improved environmental policy making process.

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