VIDZEME UNIVERSITY OF APPLIED SCIENCES

ENGINEERING FACULTY

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APPLICATION OF SIMULATION MODELLING AND SENSOR SYSTEM IN ECOSYSTEM MANAGEMENT

SUMMARY OF PHD THESIS

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The PhD thesis has been developed:

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NB This is just a summary! In order to fully understand the subject, it is recommended to familiarize with the full version of the PhD thesis.

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INTRODUCTION

The concepts “simulation modelling”, “sensor system”, “ecosystem” and “management” included in the title of the PhD thesis are widely interpreted according to the field, interaction and context to be used. In the introduction of the work, the author gives an understanding, interaction and interpretation of these concepts in the context of the PhD thesis.

The first concept included is “simulation modelling”. Simulation modelling is a reproduction of a real system model, showing its characteristics and processes in mathematical form, in order to study the properties and performance of the system, draw conclusions and take decisions on the implementation or improvement of such systems (Ozoliņa, 2021). In this case there is a real system at the centre of the PhD thesis, expressed in mathematical equations and expressions, which makes it possible to play different management scenarios in order (in this case) to improve the system (to transform the degraded state back to the natural state). Information technologies are instruments used or created to deal with problems of interest to professionals in all sectors (Kuļikovskis, 2015) and simulation modelling is one of these instruments. Simulation modelling is a system management process with suitable input data and evaluation and analysis of output data (Yin & McKay, 2018). Suitable system data can be provided using environmental sensors.

The second concept is “sensor system”. The sensor system is a number of sensors combined into a single unit with a single appropriate signal processing hardware and access interface (van Zyl, Simons, & McFerren, 2009). The sensor system, through the use of computer and communication tools, ensures the storage, acquisition, processing and transmission of raw data for the management of simulated ecosystems. Sensor systems may be considered to be a subdivision of information and communication technologies, as it is a set of knowledge, methods, techniques and technical equipment which ensures the acquisition, storage and dissemination of information through computers and means of communication (Kuļikovskis, 2015). Input data for simulation models are often based on objective data which, for example, are collected from a system that is modelled (Yin & McKay, 2018). Without a sensor system that collects data directly from the system, creating its simulation model may be difficult because of the lack of qualitative *in situ* data models needed to function.

The third concept is “ecosystem”, a functional natural environment system consisting of plants, animals and microorganisms present in a given area, together with their environment of existence (Baldunčika, 2007). There is a balance in ecosystems, they are stable until humans or a natural disaster intervene (Bērziņa, 2008). Ecosystems have adaptability and self-regulation capacity (Bērziņa, 2008). In the context of the PhD thesis, it should be noted that the “real system” referred to in the interpretation of the first concept of “simulation modelling” is understood henceforth to be an ecosystem. The simulation model developed by the author simulates the hydrological system and processes of the bog ecosystem, since a directly appropriate groundwater level is a key prerequisite for the return of natural high bog-like flora and fauna, which are two key factors for a healthy bog ecosystem. A detailed description of this ecosystem, distinguishing it from other natural ecosystems and making it unique, unrepeatable and valuable, is available in the first chapter.

The fourth essential concept is “management”. Management is the supervision and steering of an object in line with the objectives and strategy of the owner, giving consideration to judiciousness, economy, etc. (Kvēle, 2005). Basically, it is decision-making in order to choose the best form of governance. More and more models are being used to solve problems and for decision-making (Sarget, 2011). Modelling and simulation include the development of a model of the real-world system, conducting experiments with models to gain an understanding of the operation of the system in different circumstances, evaluating alternative management strategies and decision-making processes (Yin & McKay, 2018). The purpose of the PhD thesis is to develop, by using modelling and simulation methods, a simulation model of a bog hydrological system for assessing the impact of forest cover on the ecosystem’s water balance and the methodology for its use. The extended subsection 3.3.4, which details the performance of a test of the simulation model and the conclusions reached on the functioning of the ecosystem, is a validation approach, with practical verification of its functioning and, with determination of the standard deviation of variable dispersion and forecasting error, demonstrating the high accuracy and appropriateness of its operation for the management of the ecosystem.

This is an interdisciplinary PhD thesis, the author of which at the time of its creation has applied not only his knowledge in electrical engineering, electronics and information and communication technologies, but also acquired additional knowledge in biology, geology, hydrology, hydraulics and meteorology. The PhD thesis describes the development of a sensor system for the extraction of raw data for the purpose of simulation modelling, processing of the data and the development of the BogSim simulation model of bog hydrology, which is the basis for the development of the sensor system, since the sensor system addresses the availability of high-quality input data for the needs of ecosystem simulation models. The modelled ecosystem in the PhD thesis is the hydrological system of the bog, since exactly an appropriate level of groundwater is a key prerequisite for restoring the ecosystem-specific sensitive flora and fauna in a degraded high bog.

The BogSim model simulating the hydrological system of the bog deals with issues of interest to specialists in other sectors by utilizing information technology. Characteristics of the dynamics of the bog hydrological processes are reflected in appropriate mathematical equations, which allow for accurate analytical calculations related to water flows in the bog ecosystem. A methodology is proposed on how to create a simulation model in a system dynamics environment for the purpose of performing calculations. The advantage of this approach is that it allows one to list all the processes that take place in each part of the ecosystem depending on the input data and the water deficit in each of the stocks, redirecting the flows as they would flow in nature. The simulation model proposed by the author can be used as an engineering tool to help understand the non-linear and complex hydrological processes of bog ecosystems, in decision-making on their proper management, in training and for other purposes. The functioning of the simulation model was verified using the raw data of the intact Männikjärve bog located in eastern part of Estonia but validated using the raw data of the degraded bog part of the Sommaa National Park, located in the south-west of Estonia.

The development of a sensor system includes a methodology for ensuring the acquisition, storage, processing and transmission of raw data, through the use of computer and communication tools, needed for simulation models of ecosystem management. In the thesis, the software and hardware, sensor system architecture and raw data processing and input data distribution script are described, which makes it possible to create a physical network of NB-IoT sensors.

Scientific innovation

A number of hydrological models are currently developed and available. As models, they are simplified reflections of reality that are useful and work sufficiently accurately in large-scale modelling, but are unable to accurately portray all hydrological systems as specific as bog ecosystem water flows that are vital in regional-level models.

The scientific innovation of this study includes the following aspects:

1. The author has studied and compared existing hydrological models that allowed the flaws to be identified and has focused on eliminating them in developing the new approach. The developed simulation model approach makes it possible to list the characteristics of the dynamic system. This methodology provides more accurate results than existing approaches, particularly focusing on parameters that are not displayed at such high levels of detail in other hydrological models or are not considered at all. These parameters are the vegetation-related properties of the ecosystem that affect the water balance, such as interception and transpiration, which are not included at all in most hydrological models. Existing hydrological models use one hydraulic conductivity proportionality constant for each of the soil types and, therefore, the introduction of dynamic hydraulic conductivity of acrotelm is also considered to be a innovation of the author's simulation model methodology. The dynamic hydraulic conductivity means that the rate of water infiltration in the peat layer decreases as the distance to the surface of the earth increases until the catotelm is reached, while hydraulic conductivity in the catotelm remains constant. The author developed a number of logical expressions and a simplified approach to water percolation in the Devonian sandstone layer, resulting in an improved precision of the model's performance. The developed simulation model has been tested in two system dynamics environments, *Stella Architect* and *Insight Maker*, which allowed the identification of significant differences between a commercial and an open-source product;
2. The methodology proposed by the author includes a developed NB-IoT sensor system and a clear outline of its functioning and structure, including software and hardware, enabling the acquisition of raw *in situ* data, their processing, storage in a cloud server and distribution, addressing the accessibility issue of high-quality data for simulation models of ecosystems and environments.

Practical significance

1. The methodology proposed by the author allows the water balance of the bog ecosystem to be restored more quickly and effectively, thereby increasing natural diversity, restoring the water cycle, improving the quality of life for local populations and promoting recreational facilities. The simulation model may be used as a learning tool for the teaching of environmental sciences;

2. The developed NB-IoT sensor system deals with the availability of raw *in situ* data for environment simulation models;
3. Both the simulation model of bog hydrology developed by the author and the sensor system for collecting high-quality data are repeatable and replicable; the concept applies to other models in similar ecosystems.

The scientific results have been tested experimentally using system dynamics modelling tools. The simulation model in the *Insight Maker* environment is available online at https://insightmaker.com/insight/201089/Bog-hydrology-model.

Object of the study

Managing the ecosystem through information and communication technologies.

Subject of the study

A simulation model and extraction of raw data, processing and use thereof, for the management of ecosystems.

Objective of the study

The aim of the study is to develop, on the basis of an analysis of the structure of a real ecosystem and of the ongoing processes therein, a bog hydrology simulation model for assessing the impact of the forest canopy cover on the water balance of the ecosystem and the methodology for its use by modelling and simulation methods.

Tasks

- Define the ecosystem and its characteristics which distinguish it from other ecosystems;
- Identify existing models that can be used for simulating hydrological regimes;
- Explore elements that create an ecosystem and interact with each other;
- Develop a mathematical model for simulating the hydrological regimes of the ecosystem and its application methodology;
- Assess the operation and performance of the developed simulation model in a system dynamics environment;
- Identify IoT and network technologies that could serve in *in situ* sensor system development;

- Develop an *in situ* sensor system that autonomously collects raw data, process and transmit them to a data cloud where they are transformed into the input data format needed for simulation models to manage the ecosystem.

Propositions

- The simulation model was designed specifically for the bog ecosystem and to accurately simulate regional-level hydrological processes in the bog ecosystem;
- The size of the forest stand affects the total ecosystem water balance, and an appropriately designed simulation model by adjusting the leaf area index (hereinafter referred to as LAI), represents changes in the amount of the forest stands due to felling of trees, and simulates changes in the groundwater level close to the readings of measurements carried out in the field;
- The new simulation modelling method and its application methodology, combined with the developed IoT sensor system for the acquisition of high quality *in situ* data and the methodology for its use, can be used to mimic the functioning of the bog ecosystem.

Methods

The following methods have been used in the PhD thesis:

1. Theoretical methods – a systematic research and analysis of scientific articles, books, administrative documents and electronic resources;
2. Data collection methods – meteorological, groundwater level and LIDAR data obtained from indirect observations with equipment located in the Mannikjarve and Soomaa bogs in Estonia;
3. Data analysis methods – use of primary mathematical statistical methods for determination of groundwater level measurements and simulation data distribution, mean values, standard deviation; use of secondary mathematical statistical methods to determine correlation, mean square error and independence;
4. Evaluation of the result – verification of the simulation model of the bog hydrological system by comparing its output data points with intact high bog groundwater data;
5. Experiments – development of an engineering solution to simulate the hydrological system of a bog, using system dynamics modelling techniques to capture all parameters and changing them one by one to monitor their effects on changes in groundwater

levels. Carrying out experiments using data from several degraded bog plots where manipulation by forest stand thinning and/or filling of drainage ditches has been carried out with the aim of restoring the natural hydrological regime of the bog.

Study period

The study was conducted from September 2017 to August 2021.

Approbation

Scientific results reported:

1. The specification of hydrological model requirements for bog restoration. 25.-26.04.2019. International Scientific Conference SOCIETY. TECHNOLOGY. SOLUTIONS. Valmiera, Latvia
2. Bog restoration for greenhouse gas emissions sequestration and climate change mitigation, 2.-5.10.2018, AgroEco 2018, Kaunas, Lithuania
3. Why should degraded high bogs be restored? 24.-26.08.2018, International Smithy of Ideas 2018, Plunge, Lithuania
4. Restoration of degraded bog hydrological regime using system dynamics modelling, 21.-23.03.2018, International Conference on Innovations in Science and Education, Prague, Czech Republic
5. Significance of thinning degraded swamps forest stands in sustainable ecosystem`s development, 23.-24.11.2017, Rural Development 2017, Kaunas, Lithuania
6. Degraded swamps hydrological regime restoration using system dynamics modelling. 13.14.10.2017. 58th International Scientific Conference SCEE`2017, Riga, Latvia
7. The forest stand`s crown cover impact on the water balance of swamp`s ecosystem, 17.-19.05.2017, Research for Rural Development 2017, Jelgava, Latvia

Publications:

1. Java, O., Kohv, M., Lõhmus, A. (2021). Performance of a Bog Hydrological System Dynamics Simulation Model in an Ecological Restoration Context: Soomaa Case Study, Estonia. *Water*, 13(16), 1-13, DOI: 10.3390/w13162217 (indexed in Scopus and Web of Science)
2. Java, O., Sigajevs, A., Binde, J., Kepka, M. (2021). NB-IoT Sensor Network for Obtaining the Input Data for Hydrological Simulation Model. *Agris On-line Papers in*

Economics and Informatics, 13(1), 59-69, DOI: 10.7160/aol.2021.130105 (indexed in Scopus)

3. Java, O., Kohv, M., Lõhmus, A. (2020). Hydrological model for decision-making: Mänikjärve bog case study, Estonia. *Baltic Journal of Modern Computing*. 8 (2020), No. 3, 379-390, DOI: 10.22364/bjmc.2020.8.3.01 (indexed in Scopus and Web of Science)
4. Java, O. (2020). The Specification of Hydrological Model Requirements for Bog Restoration. *Baltic Journal of Modern Computing.* 8 (2020), No. 2, 164-173, DOI: 10.22364/bjmc.2020.8.1.11 (indexed in Scopus and Web of Science)
5. Java, O. (2018). Restoration of a degraded bog hydrological regime using system dynamics modelling, *CBU International Conference on Innovations in Science and Education*, Prague, Czech Republic, DOI: 10.12955/cbup.v6.1301 (indexed in Web of Science)
6. Java, O. (2017). Significance of thinning degraded swamps forest stands in sustainable ecosystem`s development, *Proceedings of Rural Development 2017*, Kaunas, Lithuania, DOI: 10.15544/RD.2017.104 (indexed in Web of Science)

Research projects

The methodology developed during the PhD thesis was applied to the project "reSilienT fARminG by Adaptive microclymaTe managEment (STARGATE)" (project 818187, 01.10.2019 – 30.09.2023), one of the European Union's research and innovation support programme's "Horizon 2020" projects, evaluating the technologies developed and validating them. The project uses the methodology developed by the author for transforming sensor data into the format needed to automatically convert them into the relevant system dynamics simulation model input data, and the principle for calculating water flows in soil.

During the final stage of dissertation, together with the Virtual and Augmented Reality Laboratory of Vidzeme University of Applied Sciences, the research project for the Fundamental and Applied Research Program entitled "Visualisation of real-time bog hydrological regime and simulation data in virtual reality" was launched (project lzp-2020/2-0396, 01.12.2020 – 31.12.2021), as part of which the methodology developed by the author and tested by experimental methods was applied to create a simulation model in the Python script that will calculate water flows in the ecosystem no longer in one but in two dimensions. In order to enable users to interact with the simulation model and to familiarize themselves with its output data in an interactive and easily understandable way, it was combined with a virtual reality environment using the Unity cross-platform game design.

Thesis structure

The PhD thesis consists of an introduction, 5 chapters, conclusions and a bibliography. The main text of the thesis is 128 pages, including 8 tables and 27 images. The thesis has been supplemented by 6 annexes. The bibliography contains 220 sources of information.

The PhD thesis is designed to develop a simulation model for ecosystem management, to apply it practically to test its operation and offer an NB-IoT sensor system as a tool for obtaining high-quality raw data for simulation models.

The first chapter of thesis defines an ecosystem, pointing to its main unique characteristics which distinguish it from other natural ecosystems and makes it one that could be restored, thus providing a justification for the creation of a simulation model of its hydrological system.

The second chapter provides a feasibility study for the application of existing hydrological models and simulation models to the restoration of degraded bogs. The feasibility study makes it possible to identify what has been done in the past and to identify the conditions that need to be focused on when developing an appropriate hydrological model for simulating the bog ecosystem.

In the third chapter, the author focuses on the practical development of the simulation model, starting with the specification of requirements and the mathematical formulation of the model leading to the development of a model in the environment of system dynamics. Initially, the BogSim simulation model is created in both the *StellaArchitect* and *InsightMaker* environments, followed by an in-depth model performance test at five Soomaa bog plots in Estonia. In the chapter, all steps are described in detail as a methodology for recreating and operating the simulation model.

The fourth chapter is devoted to the development of a sensor system for the acquisition of input data for the needs for ecosystem management simulation models. The chapter describes the choice of appropriate network technology that provides sufficient coverage to allow the NB-IoT sensor system to be placed even in the most remote and difficult-to-reach corner of Latvia and the data to reach the cloud server. Thereafter, the chapter describes the components of the NB-IoT sensor system, the operating principle, architecture and the processing of raw data obtained to convert them into input data usable in the ecosystem simulation model.

In the fifth chapter, the author provides the economic and socio-technical justification for the work.

In order to make the information gathered in the chapters easier to perceive, it is structured as needed in up to three levels of subchapters.

1. PREMINARY STUDY OF HYDROLOGICAL MODELS AND PROCESSES

As Jørgensen mentioned in his publication, it is important to understand how these systems work and what to expect when we intervene or change them in order to properly manage bog ecosystems and optimize their role in the landscape (Jørgensen, Mitch, & Kells, 1988). It needs to be clearly understood how, by changing one part of the bog, we influence other parts of the ecosystem (Java, 2017). The groundwater level and its fluctuations are the main parameters of such awareness, so when the dissertation was developed, the author carried out an in-depth study to identify the world's practices in dealing with similar problems and to understand the hydrological structure of the bog.

There is an increasing need for reliable and applicable modelling tools to assess water supply and wetland status which can then be used as a basis for land use planning and management. The preferred feature of such modelling tools would be their resilience to specific land use changes in order to predict the consequences of new management regimes and the restoration of wetlands that have not been measured over time.

There are a number of available hydrological models which the author has studied and compared in Table 1. As models, they are simplified reflections of reality that are useful and work sufficiently accurately in large-scale modelling but are unable to accurately represent all such specific hydrological systems as bog ecosystem water flows that are vital in regional-level models. Understanding the bog's hydrological system is crucial for sustainable land development and efficient soil and nature conservation (Mioduskzewski, Povilaitis, Querner, & Ślesicka, 2010), but existing hydrological processes simulation models are unable to demonstrate the recovery scenarios applied to drained and forested bogs.

Table 1. Comparison of hydrological models

Hydro-logical model	Include overland water	Include ground-water	Include vegetation	Include inter-ception	Include trans-piration	Include snowmelt	Used in bog restoration project
MODFLOW	X	V	X	X	X	X	X
SWAT	V	V	V	V	V	X	X
WEAP	V	V	V	X	X	X	X
MIKE SHE	V	V	V	X	V	V	X
HecRAS	V	X	V	X	X	X	X
QUAL2K	V	X	X	X	X	X	X

Source: the author

Information is available on various degraded bog restoration projects where simulation models have been used to determine the exact extent of the intervention in the ecosystem, but none of them are readily available and constructed in a way that would allow them to be adapted and applied to other bog restoration projects. Bog restoration requires a simulation model that gives greater importance to the impact of vegetation on the water balance and provides accurate results at a regional level.

2. DEVELOPMENT OF A SIMULATION MODEL OF BOG HYDROLOGICAL SYSTEM

In order to be able to accurately predict the impact of human activities on an ecosystem, it is necessary to create a new hydrological model specifically designed for this ecosystem, with an increased focus on vegetation. The bog hydrological system is a complex system with many components, so that a conceptual model of the bog hydrological system was created before the simulation model was created (see Figure 1).

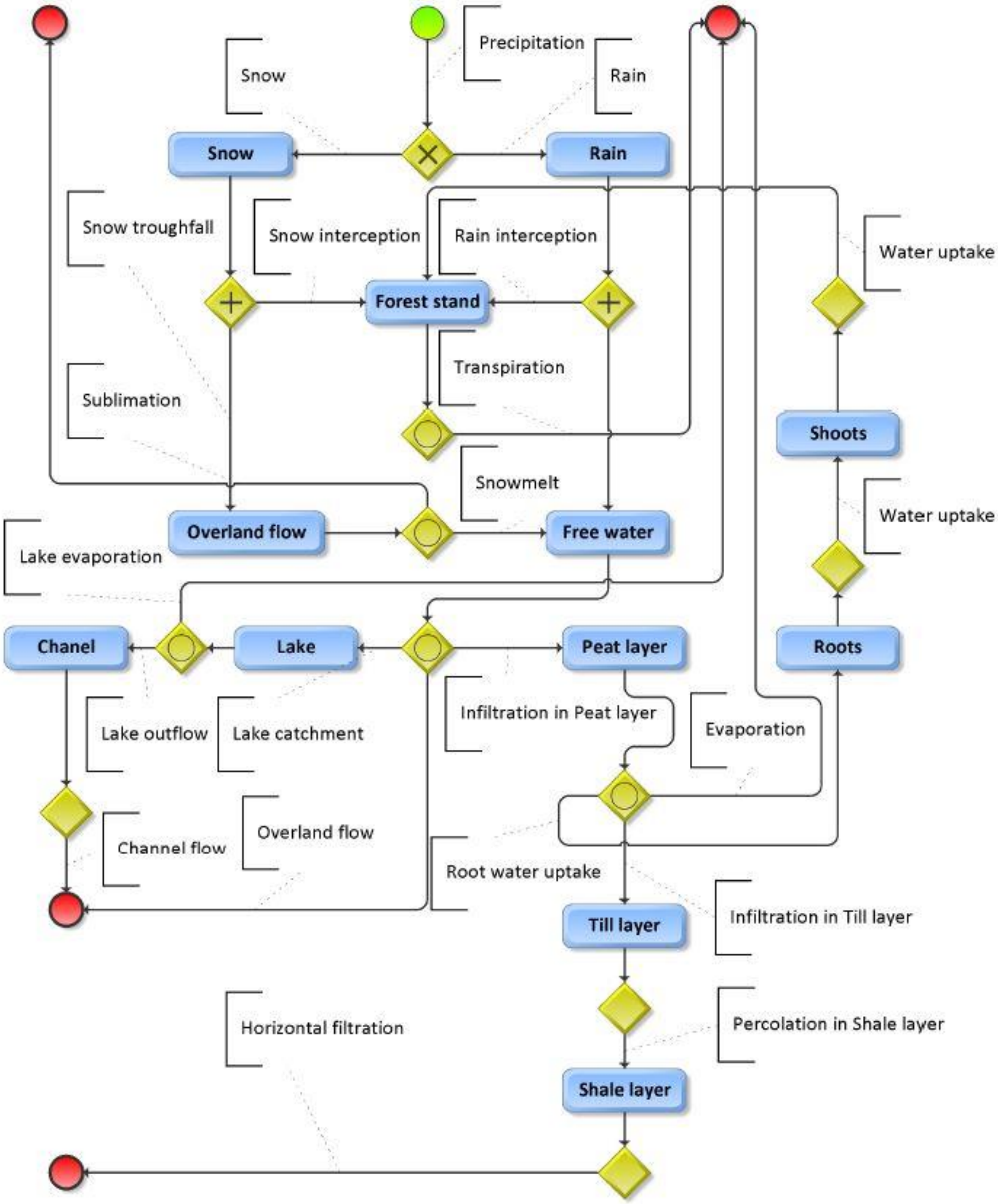

Figure 1. Conceptual model of the bog hydrological system

Source: the author

Using the requirement specification method, it was established that the following input data was required to operate the bog hydrology simulation model:

1. Meteorological data (Java, 2020):

- Precipitation (rain, snow);
- Wind speed;
- Sun radiation;
- Air temperature;
- Relative humidity.

The meteorological data for the model can be obtained in the form of indirect observations from the geographically closest weather station or collected from a weather station or a sensor system located in the bog if available (Java, 2020).

2. Geological data (Java, 2020):

- Bog slope;
- Lake area and depth;
- Channel width, depth and slope;
- Peat layer, till layer and shale layer depths;
- Peat layer, till layer and shale layer maximum water capacity.

The Baltic artesian region geological data for the model can be freely obtained from the modelling system of the University of Latvia using the mobile application “MOSYS mobile” (Latvijas Universitāte, 2018).

For higher accuracy, the author recommends using geological data collected by on-site measurements instead of the MOSYS model.

3. Soil hydraulic properties (Java, 2020):

- Peat layer wetting front suction head;
- Peat, till and shale total porosity;
- Peat, till and shale effective porosity;
- Peat residual saturation;
- Peat saturated hydraulic conductivity.

There are several scientific sources available that describe the hydraulic properties of various mineral and organic soils, for example “Estimation of Soil Water Properties” (Rawls, Brakensiek, & Saxtonn, 1982) and “Hydrological and Hydraulic Design of Peatland Drainage and Water Treatment Systems for Optimal Control of Diffuse Pollution" (Mojammadighavam, 2017). Using these studies, it is possible to choose data from the one with the most suitable climatic conditions and soil composition. However, in order to obtain the most accurate output data, the input data should also be accurate, so it is recommended to perform laboratory measurements of soil samples (Java, 2020).

4. Remote sensing data (Java, 2020):

- Reflectance in the near infrared band;
- Reflectance in the red band.

The most suitable data for leaf area index calculation are data obtained by remote sensing in the near red infrared and red bands, which can be obtained using a Light Detection and Ranging (LIDAR) sensor. If there is no available LIDAR data, it is appropriate to use Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Java, 2020), but in small regional-scale models where Baltic bogs can be included, their resolution will not be sufficient.

5. Values to be calibrated (Java, 2020):

- Leaf distribution angle;
- Specific leaf capacity;
- Snow interception coefficient;
- Maximum snow capacity of the forest canopy;
- Peat evaporation coefficient;
- Till infiltration coefficient;
- Shale infiltration coefficient.

The hydrological model of the bog is an important tool for obtaining output data that are difficult to measure in real life, such as (Java, 2020):

- Groundwater level;
- Interception;
- Evaporation;
- Transpiration;
- Overland flow;
- Infiltration in the peat layer.

The system dynamics environment is a closed dynamic system. This simulation model is designed to represent the movement of water in the bog hydrological system from the water entrance into the enclosed system in the form of precipitation up to its exit using interception, transpiration, evaporation, lateral flow, lake runoff and surface runoff.

Input data is intended to be loaded from a CSV database, but can also be manually loaded. The simulation model allows one to generate output data in the format of frequency tables and overview tables. How the user and modeller interact with the hydrological model of the bog and how the internal parts of the model interact with each other is shown in Figure 2.

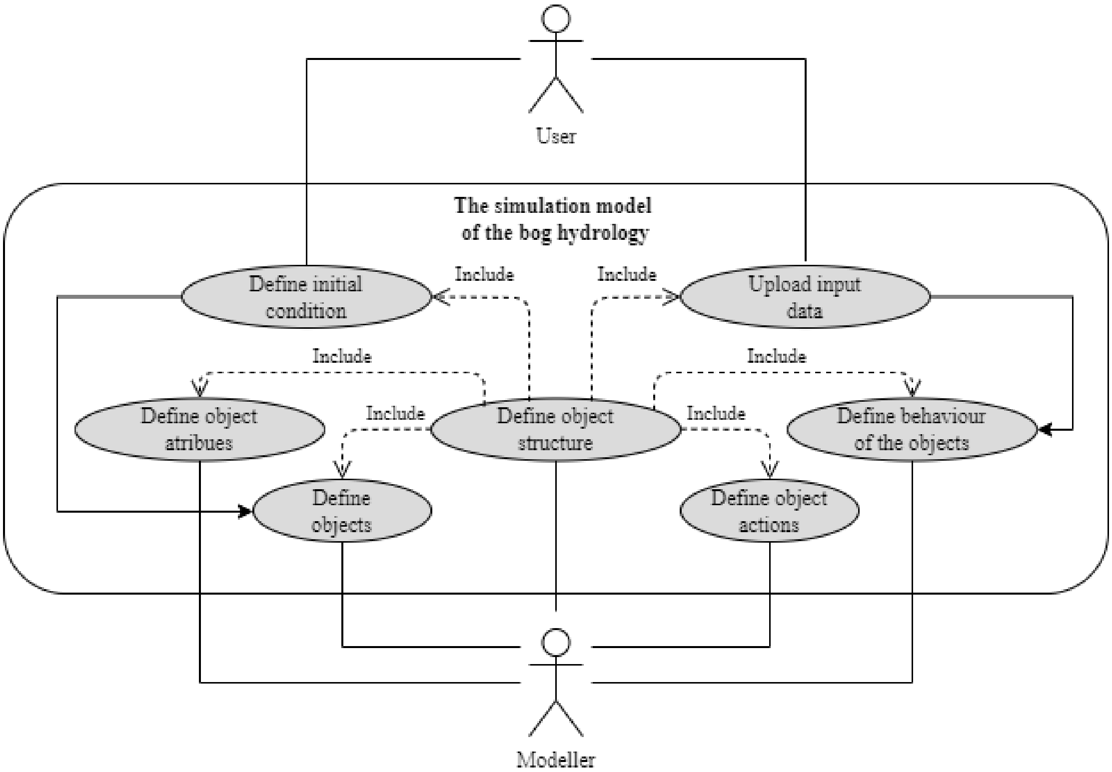

Figure 2. Internal steps of the bog hydrology simulation model, UML use case diagram

Source: the author

As in any dynamic system, in the bog hydrological system the water flow from one object to the next is based on mutual causation. Objects receiving, storing and transferring water further include forest stand, lake, canal and soil (peat layer, till layer and shale layer).

In Figure 3, all objects of the bog hydrology simulation model are visualized in classes. All input data are divided into classes based on affiliation with meteorological, geological, soil hydraulic data or coefficients. Each object class uses input data as values for the corresponding attributes. Water amount change processes are displayed as output data.

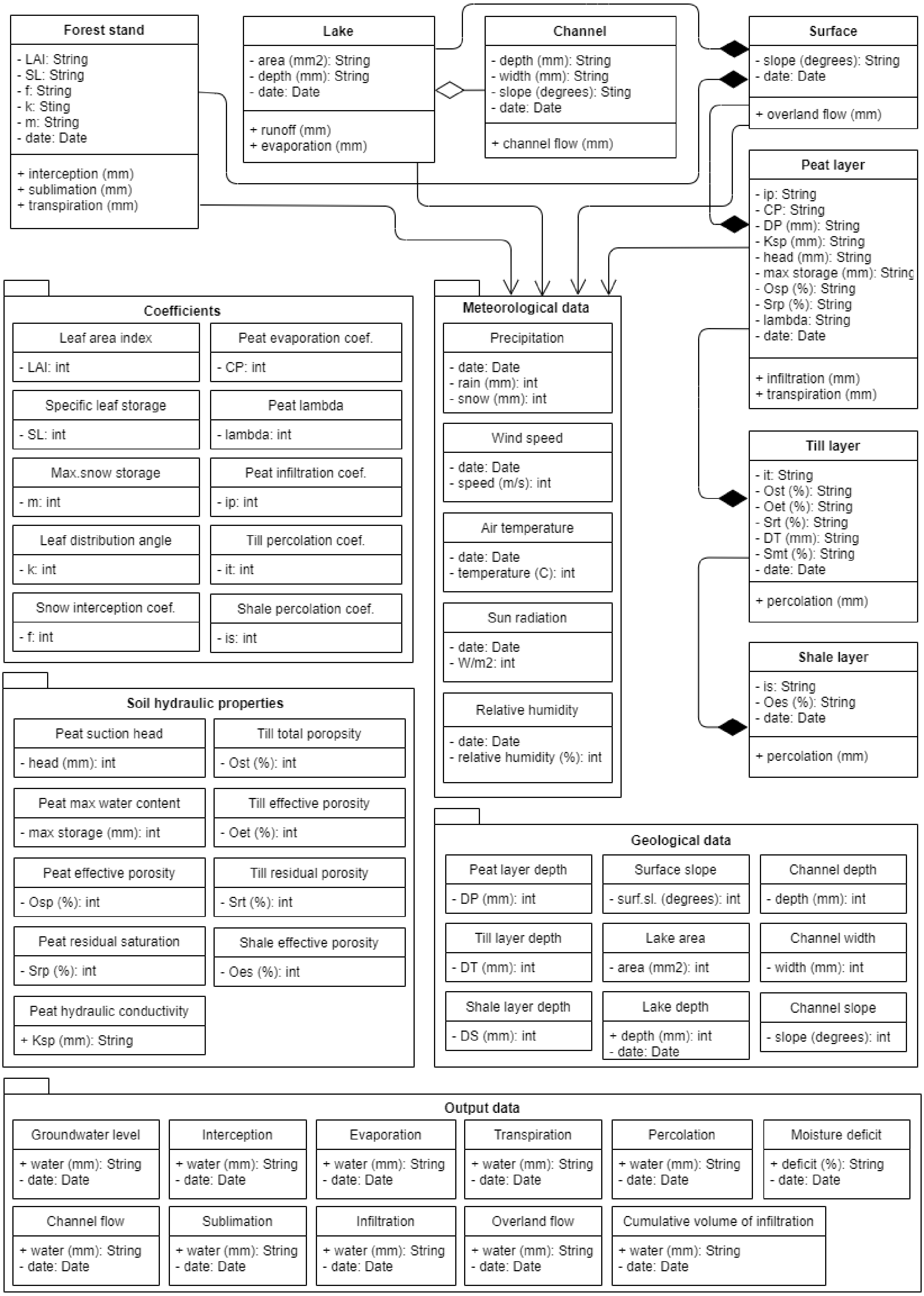

Figure 3. Bog hydrological model UML class diagram

Source: the author

In the formulation of the problem proposed by the author, the hydrological system of the bog is considered to be a dynamic system consisting of differential equations and logical expressions.

The model proposed by the author is not the first hydrological model to be developed in the environment of system dynamics. An SDW (System Dynamics Watershed) model was developed in 2005 (Elshorbagy, Julta, Barbour, & Kells, 2005). It did not include vegetation-related equations (Elshorbagy, Julta, Barbour, & Kells, 2005), so its improved version, GSDW (Generic System Dynamics Watershed Model), which includes interception and evaporation, was released in 2009 (Carey, Elshorbagy, & Kesha, 2009).

The simulation model proposed by the author is based on the GSDW model, for which several mathematical equations and logical expressions have been changed and adapted and new ones developed until the expected result was achieved – the simulated groundwater curve mimics the measured groundwater curve, indicating that the model includes and considers all parts of the ecosystem.

The simulation model is designed to represent the movement of water in the bog hydrological system from the water input in the form of precipitation to the water output from the system by interception, sublimation, transpiration, evaporation, infiltration into deeper soil layers, lake evaporation and lake and surface runoffs. As in a dynamic system, in the bog hydrological simulation model water flows from one reservoir to the next on the basis of mutual mathematical causality.

2.1. Mathematical model

The BogSim simulation model developed by the author consists of a total of 44 mathematical equations and logical expressions. Only those equations and logical expressions that have been developed or modified by the author to improve the precision of the model are discussed in the PhD thesis summary.

The author tested a number of equations for the calculation of snow interception found in scientific literature, but experimental testing pointed to errors in their functioning because of the difference between the simulated groundwater curve and the actual measured curve during the winter period, so the author adapted the rain interception equation by replacing the maximum rain interception capacity (S_{max}) with the maximum snow interception capacity (B) (Andreadis, Lettenmaier, & Storck, 2009), significantly improving the accuracy of the model:

$$I_{snow} = C_p B \left(1 - EXP\left(-f\frac{P_S}{B}\right)\right) \quad (1)$$

where I_{snow} is the water (mm/d) equivalent to snow precipitation, C_P is a function of tree crown water cover, P_S is total snow precipitation (mm/d) and f is the snow interception coefficient.

The infiltration capacity f_P is calculated on the basis of the cumulative volume of infiltration (Elshorbagy, Julta, Barbour, & Kells, 2005), based on the logical expression developed by the author (2):

IF $\theta_{iP}<\theta_{sP}$ AND $S_{SW}<K_{sP}$

THEN $S_{SW}*C_{tP}$

ELSE IF $\theta_{iP}\geq\theta_{sP}$

THEN 0

ELSE (3)*C_{tP} (2)

$$f_P = K_{sP}\left(1 - \frac{(20)\psi_P}{F_P}\right) \quad (3)$$

IF $\theta_{iP}\geq\theta_{sP}$

THEN S_{rP}

ELSE $\theta_{sP}-\theta_{iP}$ (4)

where S_{SW} is surface water (mm), K_{sP} is the saturated hydraulic conductivity of the peat layer (mm/d), θsP is the porosity of the peat layer or saturation level (mm), θiP is the initial humidity level (mm), ψ_P is the suction pressure head at the wetting front in the peat layer (mm), F_P is the cumulative volume of infiltration in the peat layer (mm) (Elshorbagy, Julta, Barbour, & Kells, 2005). S_{rP} is the residual peat layer capacity, in other words, the minimum moisture level that can be achieved in peat (mm) and the DP is the peat layer thickness (mm). The 4th mathematical expression describes the calculation of the initial moisture deficit (mm) developed by the author.

The amount (mm) of cumulative infiltration in peat layer (F_P) is calculated according to the author's approach, where:

IF Rt>0 OR S_{SW}>0

THEN S_{Fp}

ELSE 0 (5)

where S_{Fp} input is:

IF $\theta_{iP} \geq \theta_{sP}$ OR $S_{SW} > K_{sP}$

THEN f_p

ELSE 0 (6)

where S_{Fp} output is:

IF M_S=0 AND R_t=0

THEN S_{Fp}

ELSE 0 (7)

where R_t is rain throughfall (mm/d) and M_S is snow melt (mm/d). Considering that the peat layer is not homogenous, but it consists of acrotelm and catotelm, which have different hydraulic conductivity, and that the acrotelm is not homogenous in itself, as the upper part of it consists of live sphagnum moss, while at the lowest part the decomposition processes of dead moss are underway, with increased density and reduced hydraulic conductivity, the author looked for a new approach to accurately reflect water movement within it. Based on the extensive study of Custers and Graafstal (2005), "Characterization of the water flow in a pool-ridge microtope in a bog", an approach was developed in which the saturated hydraulic conductivity of the peat is not a constant value but is read from the curve (see Table 2). Upon reaching the catotelm, the hydraulic conductivity remains constant at 16 mm/d.

Table 2. Saturated hydraulic conductivity of peat layer, depending on the distance to the ground surface

Distance to the ground surface (cm)	**K_{sP} (mm/d)**
0	800
20	700
30	500
40	100
50	16

Source: the author

To simulate infiltration into frozen soil, infiltration is multiplied by the Li and Simovic (2002) coefficient C_{tP}, which takes into account thawing and re-freezing of the soil and is expressed using the logical expression, developed by the author, as:

IF $T_I < T_{Imax}$ THEN $(T_I / T_{Imax})^{ci}$

ELSE 1 (8)

where T_I

IF $N \geq N_n$ THEN 0

ELSE IF $T_a > 0$ AND $N < N_n$

THEN $\sum(T_a)$

ELSE 0 (9)

where N

IF $T_a > 0$

THEN 0

ELSE $\sum(N_o)$ (10)

where N_o

IF $T_a \leq 0$

THEN 1

ELSE 0

(11)

where T_a is the air temperature (°C), T_{Imax} (°C) is the maximum T_I point at which the surface of the ground is completely thawed, *ci* is an indicator that describes the impact of T_I on soil decay, N is the number of days in which the air temperature is repeatedly negative, N_n is the maximum number of days (N), after which soil thawing (T_I) will have ended and the soil will freeze again, and N_o is a logical variable to determine on which day the temperature is positive and on which the temperature is negative. The essence of the equation is to list the accumulated positive and negative air temperatures. Parameters *ci* and T_{Imax} are calculated during the calibration process (Li & Simonovic, 2002).

Percolation in the till layer can be represented by the logical expression (12) and equation (13), developed by the author, as follows:

IF $\theta_{iP} \leq S_{rP}$

THEN 0

ELSE IF $\theta_{iT} < \theta_{eT}$

THEN 0

ELSE IF $\theta_{iT} > \theta_{sT}$

THEN 0

ELSE (13) (12)

$$f_T = (S_{mP}/S_{mT})I_T \quad (13)$$

where I_T is the water infiltration coefficient in the till layer, S_{mP} is the water saturation of the peat layer, S_{mT} is the water saturation of the till layer, θ_{iT} is the saturation of the till layer (%), θ_{eT} is the effective porosity of the till (%) and θ_{sT} is the porosity of the till (%).

Considering that the shale layer in the Soomaa bog is located below the more than 1 m thick peat layer and below the 5 m thick till layer and that the water flow in it is almost constant and insignificant (less than 1 cm/d), the author has chosen to apply a simplified calculation approach to this layer. In this approach, the shale layer does not have a reservoir and the water flow within it can be represented by the approach developed by the author as:

IF $\theta_{iT} > \theta_{eT}$

THEN (15)

ELSE 0 (14)

$$f_M = (S_{mT}/\theta_{fS})I_S \quad (15)$$

where θ_{fS} is the capacity (%) and I_S is the coefficient of percolation in shale.

Although on the basis of the described mathematical model it is possible to develop a simulation model in different programming languages, the author chose to apply system dynamics. A fundamental feature of system dynamics as a visual programming language is that, although a model with graphically represented stocks, flows and converters resembles a conceptual model, it is a working model in which its components and flows are clearly visible. System dynamics are widely used to solve complex, dynamic problems and to understand systems with many aspects and components and to make the correct decisions on water and hydrological systems (Mashal & Fernald, 2020). Graphical representation of the system enables hydrology and biology experts to easily validate it and stakeholders and decision-makers to demonstrate the impact of the size of forest stand on the bog water balance and explain the importance and impact of the ecosystem restoration on the environment.

The simulation model of the bog hydrological system in both *Stella Architect* and *Insight Maker* environments (https://insightmaker.com/insight/201089/Bog-hydrology-model) has been established on the basis of a conceptual model (see Figure 1), maintaining the same logical structure as the bog hydrological system, which facilitates visual perception of the model and makes it easier to navigate within it. With the help of these system dynamics simulation models, system diagrams can be created that can be simulated over time. These diagrams allow one to better understand the behaviour of the system and to track the mutual relationships within it. The exposure of the modeller and the user of the model is designed according to the internal steps of the bog hydrological model described in the UML use case diagram (see Figure 2). The BogSim simulation model objects and their attributes, as well as required input data and model-generated output data are summarized in the UML class diagram (see Figure 3).

2.2. Performance verification of the simulation model

In order to validate the functioning of the model, it was necessary to verify its performance in a degraded bog where manipulation has been carried out with a view to restoring the hydrological regime of the bog and where the input data required to operate the simulation model are available. Suitable for such verification is the Soomaa bog, which in 2014-2015 underwent an experimental restoration of the bog ecosystem, including thinning of trees and/or backfilling of ditches, in various bog compartments which were separated from one another due to the commercial needs of the forest stands. Monitoring is still ongoing in the bog.

This chapter describes how the BogSim simulation model of a bog hydrological system, developed in the *Stella Architect* environment, is capable of simulating changes to the groundwater level when partial thinning of trees and/or amelioration ditch backfilling is carried out.

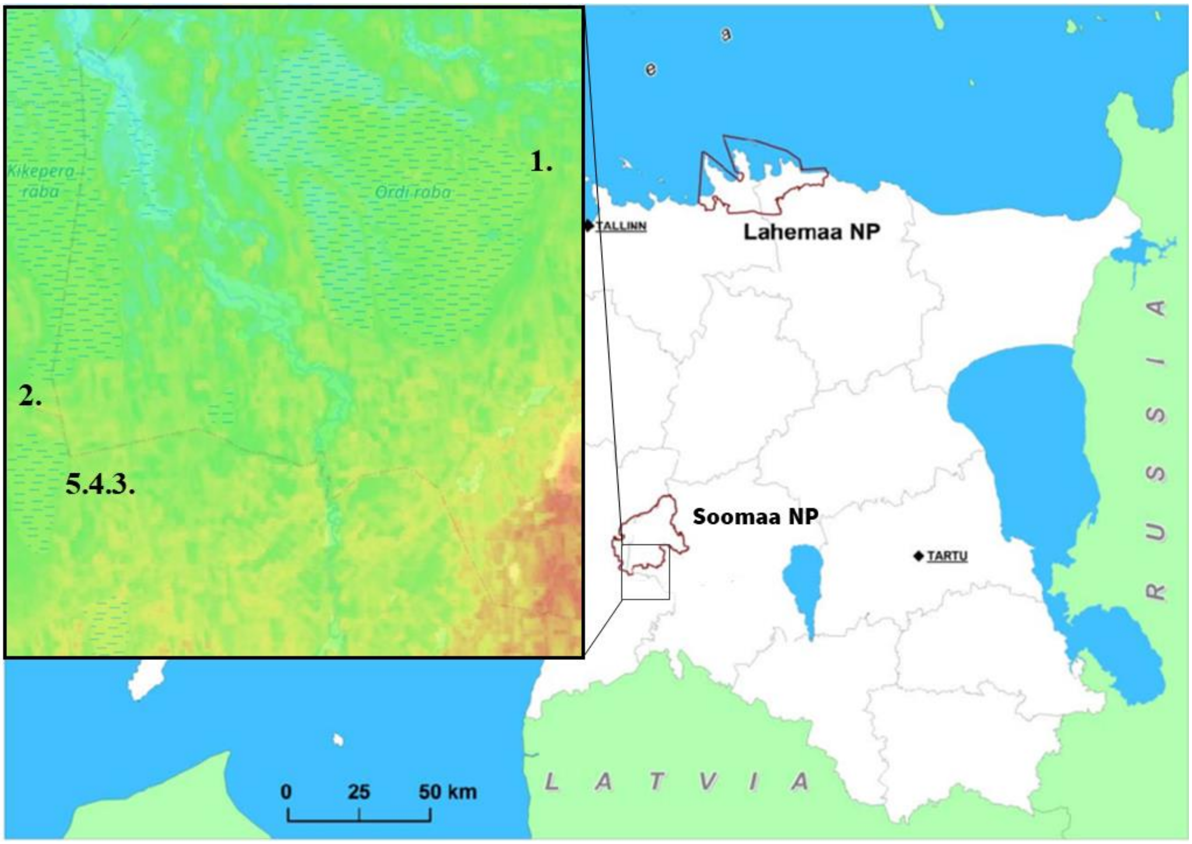

Figure 4. Soomaa National Park case study, Estonia

Source: (Järv, Kliimask, Ward, & Sepp, 2016), (topographic-map.com, 2020)

The study area was located in the Soomaa National Park and Kikepera Nature Reserve, in the southwest of Estonia, on the western slope of the Pärnu lowland and the Sakala highland (see Figure 4). The area is characterized by numerous mire systems that are divided by rivers and seasonally flooded meadows and forests. We used an ongoing experiment, which was designed in 2013 to restore peatland forest habitats for the Capercaillie (Tetrao urogallus), an iconic bird species in the Baltic States (Lõhmus, et al., 2017). The experiment combined ditch closure (backfilling where possible; damming elsewhere and in combination), partial harvest treatments in a block design and targeted draining of mixotrophic bog areas in the late 1960s. These treatments were similar to the ones used in Estonia and elsewhere for more general mire habitat restoration (Anderson, et al., 2016) (Laine, et al., 2011), but the intensity was adjusted for the specific objective of sustaining forest cover. The detailed forest inventory before and after the experimental operations and automatic groundwater-level sensors make this bog a good test site for performance validation of the simulation model.

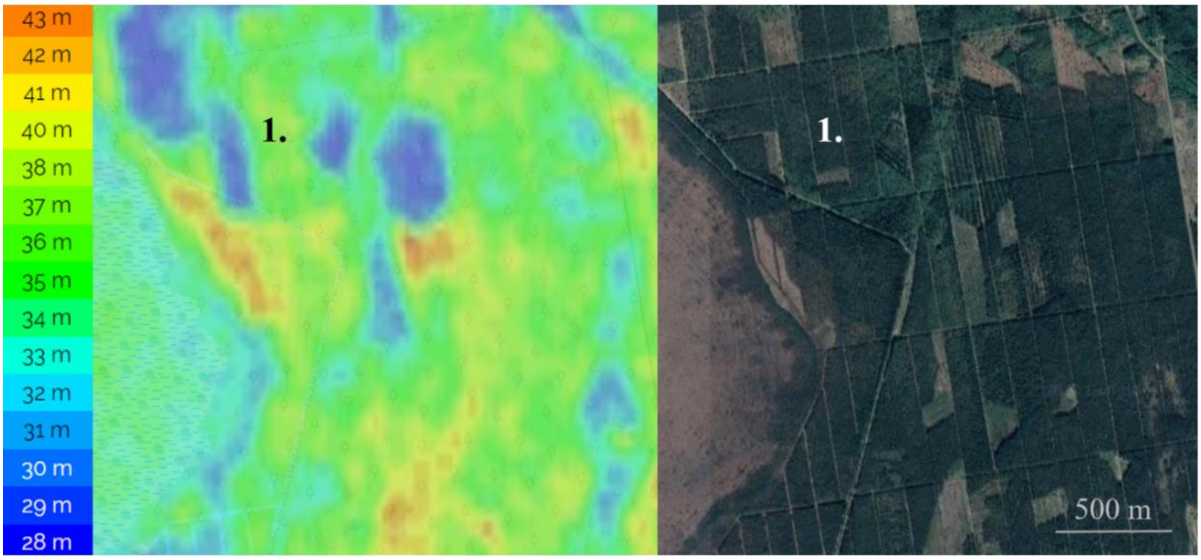

Figure 5. Topographic map and orthographic photograph of the eastern part of Soomaa National Park.

Source: (topographic-map.com, 2020), (Google, 2020)

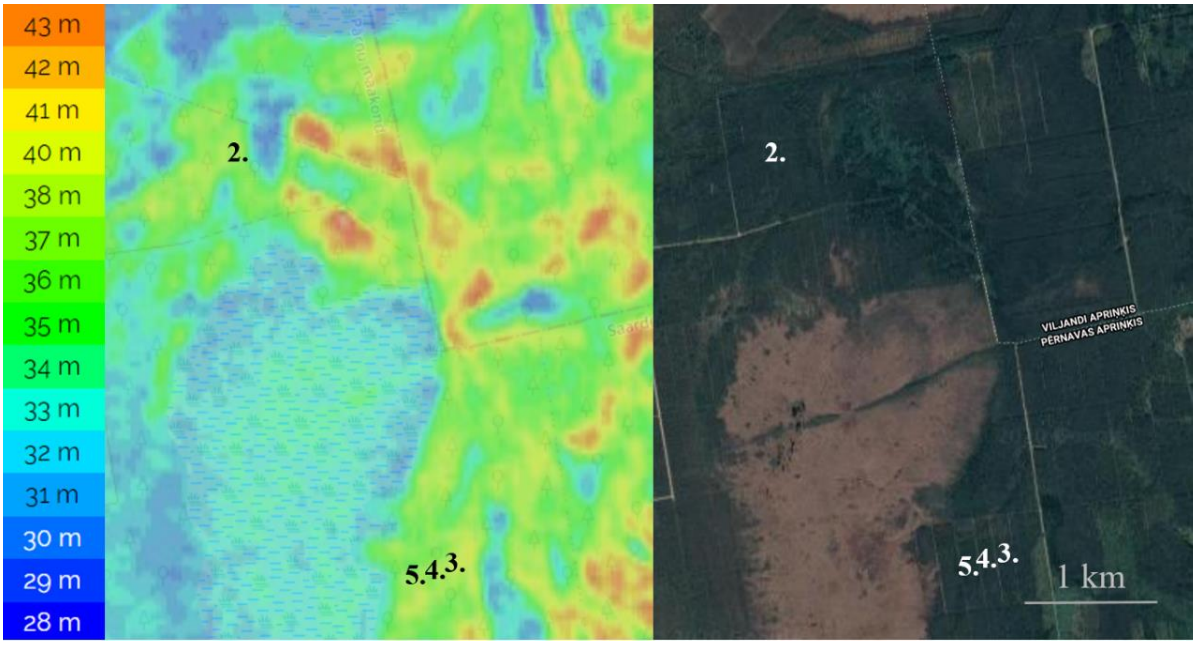

Figure 6. Topographic map and orthographic photograph of the southern part of Soomaa National Park.

Source: (topographic-map.com, 2020), (Google, 2020)

As shown in Figures 5 and 6, amelioration ditches set up in several parts of the Soomaa National Park form rectangular sections. Different plots have different peat layer thickness, altitude and forest density. Since the plots are separated by amelioration ditches, their effects on each other's hydrological regime are minimal, so they are suitable for experimenting with the thinning of forest stands.

Five plots with different manipulations were selected for the study in order to assess their impact on groundwater level fluctuations, which would serve as a basis for the development of a methodology for the restoration of degraded bogs in the future. Detailed plot information is summarized in Table 3.

Table 3. Characteristics of the plots covered in the chapter

No	Peat thickness (m)	Till thickness (m)	Date of Forest Thinning	Date of Closure of Drainage Ditches	Tree Removal at Thinning (%)	Hight Over the Sea Level (m)
1.	0.8	5	14.08.2014	Not performed	44	31
2.	1.2	5	15.10.2014	Not performed	31	31
3.	1.2	5	15.02.2015	Not performed	38	32
4.	1.3	5	Not performed	01.12.2015	0	31
5.	1.15	5	18.02.2015	01.12.2015	34	30

Source: the author

The simulation model was operated using historical data from November 1, 2013, to December 31, 2018. Each data point corresponded to the data for each day, for a total of 1836 data points. The input data set includes meteorological data (diurnal precipitation, average diurnal air temperature, average diurnal relative humidity, average diurnal wind speed, average diurnal sun radiation), remote sensing data (reflectance in the Red and the NIR light spectrum bands before and after tree thinning), geological data (peat and till layer thickness, surface slope), soil hydraulic properties (peat layer wetting front suction head; peat, till and shale total porosity; peat, till and shale effective porosity; peat residual saturation; peat saturated hydraulic conductivity) and values to be calibrated (leaf distribution angle, specific leaf capacity, snow interception coefficient, maximum snow capacity of the forest canopy, peat evaporation coefficient, till infiltration coefficient, shale infiltration coefficient).

The performance of the BogSim simulation model in the various test plots was different, with the average deviation between the simulated and measured groundwater level of 0,88 to 2,63 cm (see Table 4.). The lower mean offset and root mean square error (RMSE) value between the simulated and measured curves, indicating a higher accuracy within the model, was in the plots with a moderate range of groundwater level fluctuations. In contrast, the correlation coefficient and the coefficient of determination R^2 higher value and the closer relationship between the simulated and measured groundwater level curve was demonstrated in plots where more extensive ecosystem restoration works were carried out, followed by a sharp increase in groundwater levels.

Table 4. Parameters that indicate the accuracy of the simulation model by study plots.

No	Mean Difference (cm)	Correlation	R^2	RMSE (cm)
1	0.96	0.70	0.50	0.32
2	1.25	0.78	0.60	0.37
3	0.88	0.68	0.47	0.28
4	1.64	0.94	0.89	0.42
5	2.63	0.94	0.88	0.71

Source: the author

The BogSim simulation model of the bog hydrology in the system dynamics environment developed by the author of the thesis uses LAI as an indicator characterizing vegetation. By definition, LAI is the ratio on one-sided (in case of conifers, two-sided due to square leaves) green leaf area per unit ground surface area (Gong, Pu, Biginb, & Larrieu, 2003). LAI determines many ecological processes, such as transpiration, interception, and carbon flux (Zheng & Moskal, 2009). This is an indicator that reflects the growth status of forest vegetation (Yu, Wang, Liu, & Cheng, 2019), so this study uses a method based on reflectance in the red (Red) and near infrared (NIR) light spectrum bands to calculate LAI, based on the amount of energy consumed for biomass photosynthesis (Härkönen, Lehtonen, Manninen, Tuominen, & Peltoniemi, 2015).

Table 5. Characteristics of the forest stands in the study plots.

No	NIR before Forest Stand Thinning	Red before Forest Stand Thinning	LAI before Forest Stand Thinning	NIR after Forest Stand Thinning	Red after Forest Stand Thinning	LAI after Forest Stand Thinning	Forest Stand Thinning Intensity (%)	Changes in LAI (%)
1	85	29	2.36	97	53	1.76	44	-25
2	77	41	1.76	97	60	1.54	31	-13
3	52	30	1.65	56	41	1.28	38	-22
4	59	31	1.78	70	36	1.81	0	+2
5	37	21	1.67	44	26	1.61	34	-4

Source: the author

As can be seen in Table 5, the LAI was not directly proportional to the extent of tree removals at thinning. This can be explained by the compensatory responses of the undergrowth after opening up the canopies (Java, Kohv, & Lõhmus, 2021).

It should be noted that for test plot No 1., NIR and Red measurements were not performed after thinning of the forest stand, therefore they were selected by experimenting with them until the simulated groundwater curve approached the groundwater measurements as closely as possible. This operation can serve as an example of how to apply a calibrated simulation model to find an unknown parameter value.

2.3. Comparison of hydrological models

As described in Chapter 1, there are significant differences between existing hydrological models as well as between them and the BogSim simulation model, which prevents them from being objectively compared, i.e. replicating and operating them with, for example, the Soomaa bog input data and comparing their generated groundwater curves. However, it is worth looking into the case studies available in the scientific literature, where existing hydrological models have been used to give a limited comparative picture of the BogSim simulation model. The two most common values used to show the precision of hydrological models are RMSE and R^2. In most cases, one scientific publication uses either one or the other, but very rarely both, which makes comparison difficult.

Root mean square error (RMSE) is the standard deviation of prediction errors. Residuals are a measure of how far from the regression line data points are. In other words, it tells one how concentrated the data is around the line of best fit. RMSE is commonly used in climatology, forecasting and regression analysis to verify experimental results (Glen, 2021).

Multifactor correlation factor square R^2 illustrates how well simulation describes distributed variables (Abdulkareem, Pradhan, Sulaiman, & Jamil, 2018). Simulated values equal to 1 indicate a perfect match between the measured and simulated values of the model, but values equal to 0 indicate no correlation (Abdulkareem, Pradhan, Sulaiman, & Jamil, 2018).

Table 6. Comparison of RMSE and R^2 values of hydrological models

	BogSim	MODFLOW	SWAT	WEAP	MIKE SHE	HecRAS	QUAL2K
RMSE (cm)	0.28-0.71	20-81	1.83	-	50-1500	-	-
R^2	0.47-0.89	0.66-0.95	0.71	0.57-0.99	0.15-0.64	0.99	-

Source: the author

As can be seen in the comparison table between RMSE and R^2 of the hydrological models (see Table 6), the variation of the BogSim model groundwater RMSE varies from 0,28 to 0,71 cm in the test plots of the Soomaa bog, while the MODFLOW groundwater flow pattern in the case study on Birjand Plain in Iran amounts to 20-30 cm (Aghlmand & Abbasi, 2019). In the case study in the catchment area of Wadi Samail in Oman, the average RMSE value is 81 cm, but the conclusions show that the calibrated parameters were reliable because they provided a low value of RMSE (AL-Hasami, Gunawardhana, Sana, & Baawain, 2020). In the case study Al Buraimi in Oman, the RMSE value is even greater and amounts to 271 cm, but is considered to be proportionate to an area characterized by significant geological and hydrological diversity (Izady, Abdalla, Joodavi, & Chen, 2017). If the correlation factor R^2, which is 0,69 in the case study of Al Buraimi (Izady, Abdalla, Joodavi, & Chen, 2017), is considered, this statement can be accepted because, despite the large distribution of values, R^2 is closer to 1 than 0. When viewing other case studies with only R^2 values, they range from 0,66 (Jovanovic, et al., 2017) to 0,95 (Jiang, Xie, & Wang, 2020). Correlation factors vary across soil types, giving more accurate results for sediments (de Graaf, Sutanudjaja, van Beek, & Bierkens, 2015). Higher R^2 values are also found in cases where larger areas are modelled, such as the entire globe (de Graaf, Sutanudjaja, van Beek, & Bierkens, 2015), as opposed to regional-scale case studies.

Although, compared to other hydrological models, BogSim shows the smallest RMSE value (below 1 cm), which indicates a very close concentration of simulated groundwater level data around the trendline. At the same time MODFLOW, with a significantly higher RMSE value (20 cm), shows a much higher R^2, reaching 0,95, which is statistically very close to what is happening in nature. Given that existing hydrological models have been tested in river catchment basins, where (compared to a bog that receives water only in form of precipitation) huge water masses flow through, this is in line with that described in Chapter 2.2, which reveals that R^2 values are higher in the bog plots that have been a subject to more intensive bog restoration actions, promoting more rapid fluctuations in groundwater levels at greater amplitudes.

3. DEVELOPMENT OF A SENSOR SYSTEM FOR OBTAINING INPUT DATA NEEDED BY ECOSYSTEM MANAGEMENT SIMULATION MODELS

Access to real-time weather data helps to monitor the frequency and intensity of potential hazardous events such as drought, heavy rainfall, flooding and extreme air temperatures (Idbella, et al., 2020). These data are also useful for operating simulation models that allow one to understand causation to minimize the impact of human activity on the environment.

The IoT sensor system proposed by the author is expected to operate in the same way as an automatic meteorological station, but its main advantage will be that it does not require connection to the electrical and internet network and, therefore, it will be compact and relatively inexpensive.

3.1. NB-IoT sensor system architecture

The main objective of IoT technology is to capture, connect, collect, analyse and interpret data (Fogwing, 2021). Meteorological sensor networks are data-centric and process the meteorological data collected by the sensors (Yang, et al., 2019). In order to obtain the input data required specifically for the simulation model of the bog hydrological regime, the sensor system needs to obtain groundwater level measurements (mm) and meteorological data such as precipitation (rain, snow) (mm), solar radiation (W/m^2), air temperature (^{o}C) and relative humidity (%). If modelling was to be carried out in a geographically larger area than the average Latvian bog and were it to include a number of such sensor systems creating a sensor network, it would also be important to collect information on wind direction. Since the simulation model described in the thesis runs with historical data and does not require real-time input data, NB-IoT technologies, which read and transmit the data as needed, rather than continuously, are suitable for obtaining them (Java, Sigajevs, Binde, & Kepka, 2021).

The NB-IoT architecture (see Figure 7) consists of sensors described in section 2.2.1 of the PhD thesis: a controller, sensor interface, data format interface, a power-supply, radio modem and an antenna that together forms a sensor system (Java, Sigajevs, Binde, & Kepka, 2021).

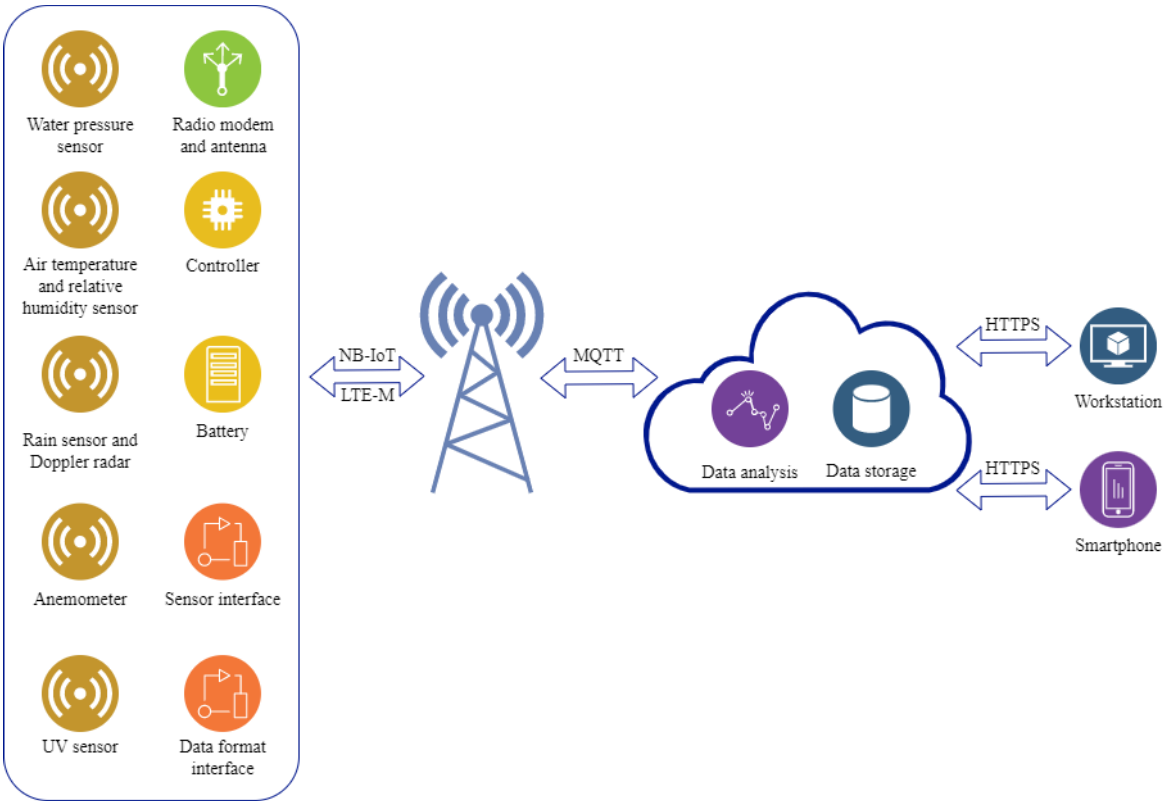

Figure 7. The NB-IoT sensor system architecture for obtaining bog hydrological simulation model input data

Source: the author

Sensors are integrated into a single system and placed in the selected remote location and are connected to a radio modem. The architecture uses NB-IoT network to transfer data from the device to a mobile cell tower. Using the MQTT protocol, data from a mobile cell tower is transferred to the data cloud where they can be stored and analysed. In the cloud, raw data is decoded into measurement data. The modem allows the modeller to interact with the devices attached to it. Once the communication mode is set up and the cloud server is configured, communication takes place between sensors and the cloud server. The architecture provides the modeller with access to data stored in the cloud by use of an Internet browser and, if necessary, the ability to remotely change the interface between the sensors and the data format (Java, Sigajevs, Binde, & Kepka, 2021).

The proposed architecture of the NB-IoT sensor system includes a number of new approaches for the acquisition of meteorological data. One of these is the use of the Doppler effect to measure precipitation. The Doppler effect is a change of frequency and wavelength when there is relative motion between a source, which generates a wave phenomenon with determinate frequency and wavelength, and an observer who notices a change in those physical quantities because of motion (Sasso, 2020). Doppler effect microwave radar allows one to detect movement, speed, and direction (Infineon Technologies AG, 2020) that can be converted to the amount of precipitation received.

A new approach to solar radiation measurements is the use of the IoT UV sensor proposed the author, which is based on measurements that state that 6% of the total solar radiation reaching the Earth's surface is UV radiation (Gharehpetian & Mohammad Mousavi Agah, 2017), (Jacobsen & Dangles, 2017).

The low cost of IoT sensors and the NB-IoT network data technology, small size and long battery life open up opportunities for wider acquisition of high-quality in-situ data that can be used for simulation models. While, based on cloud computing algorithms, it is not possible to create a single global meteorological data repository with sufficient resolution to make the data available and usable to operate high precision local simulation models, IoT sensor networks are suitable for obtaining these data and could become part of a global sensor network in the future. A sensor system that collects input data for the hydrological system dynamics model has the potential to use machine learning techniques to calibrate sensors, to look for faulty sensors, to know in advance that maintenance is required and to predict future weather forecasts if needed (Java, Sigajevs, Binde, & Kepka, 2021).

Other IoT sensors and microprocessor development boards similar to ones offered by the authors can be used to collect in-situ data to support hydrological models with input data taking into account the proposed architecture and working principles. The exception is the microwave doppler radar for which no alternative was available on the market during the development of the sensor network (Java, Sigajevs, Binde, & Kepka, 2021).

4. ECONOMIC AND SOCIO-TECHNICAL JUSTIFICATION OF THE THESIS

Although it is possible to calculate monetary the economic benefits that can be achieved by draining bogs to grow wood or to produce peat, since it is possible, on the basis of empirical equations, to calculate the growth rate of wood in cubic metres and it is possible to measure the volume of peat to be extracted in cubic metres, it is not possible to calculate the economic benefits of a natural raised bog because most of the lost bog functions are not sold on the market and are not priced.

The main functions of a natural raised bog are the capture of GHG emissions and various ecosystem services (water self-purification, water cycle and climate regulation, recreation, source of natural resources (food, tea, medicine), archaeological and research potential).

The theoretical findings developed by the author and the simulation model with its practical application can be used throughout the Baltic Sea region. When changing the parameters of the model, the range of its application can be geographically expanded. The main application of the simulation model is for restoration projects of degraded bogs - the determination of forest stand thinning intensity on the basis of changes in LAI in order to restore a natural raised bog-specific groundwater level, which is a prerequisite for the return of its characteristic flora and fauna to the bog. Because the model uses LAI, a number of expensive vegetation-related measurements are not required.

Figure 8 shows how the simulated groundwater level of the simulation model responds to changes in LAI. The LAI value of 2.37 reflects the situation that would exist if the forest stand had not been thinned in the area. The LAI value of 1.76 reflects the situation that corresponds to the thinning manipulations performed. The LAI value of 1.37 shows what the situation would be if even more trees were cut down. Looking at all three curves at the same time, the main conclusion that can be reached is that the thicker the forest stand, the greater the groundwater level fluctuations. During the winter, when the biological processes in conifers have almost stopped and the water in the soil is consumed to a negligible extent, the groundwater curve, regardless of the size of the forest stand, always reaches a level corresponding to the level of soil saturation, since the excess water, regardless of the size of the forest stand, leaves the plot in the form of surface run-off.

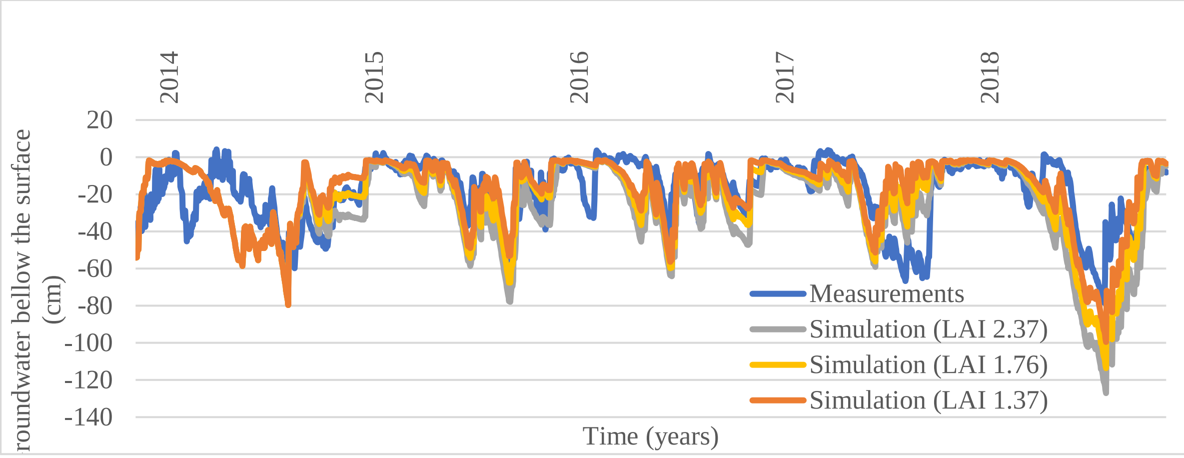

Figure 8. Groundwater level in test plot No 1 under the influence of LAI manipulation

Source: the author

During the simulated period of the simulation model, the amount of precipitation was 3319 mm. With the help of the model, it was possible to calculate that if thinning of the forest stand were not carried out in the plot, interception and transpiration would be 1655 mm or 50% of the precipitation received. In the current situation it is reduced to 1433 mm or 43% of the precipitation, but by reducing LAI to 1.37, the impact of transpiration and interception on the ecosystem water balance would be reduced to 1253 mm or 38% of the precipitation over the simulation period.

Since *Stella Architect* is not open code software and requires the purchase of a licence to run it, the author has created a web browser user interface within which anyone can experiment with changes to LAI in the plot No 1 (see Figure 9).

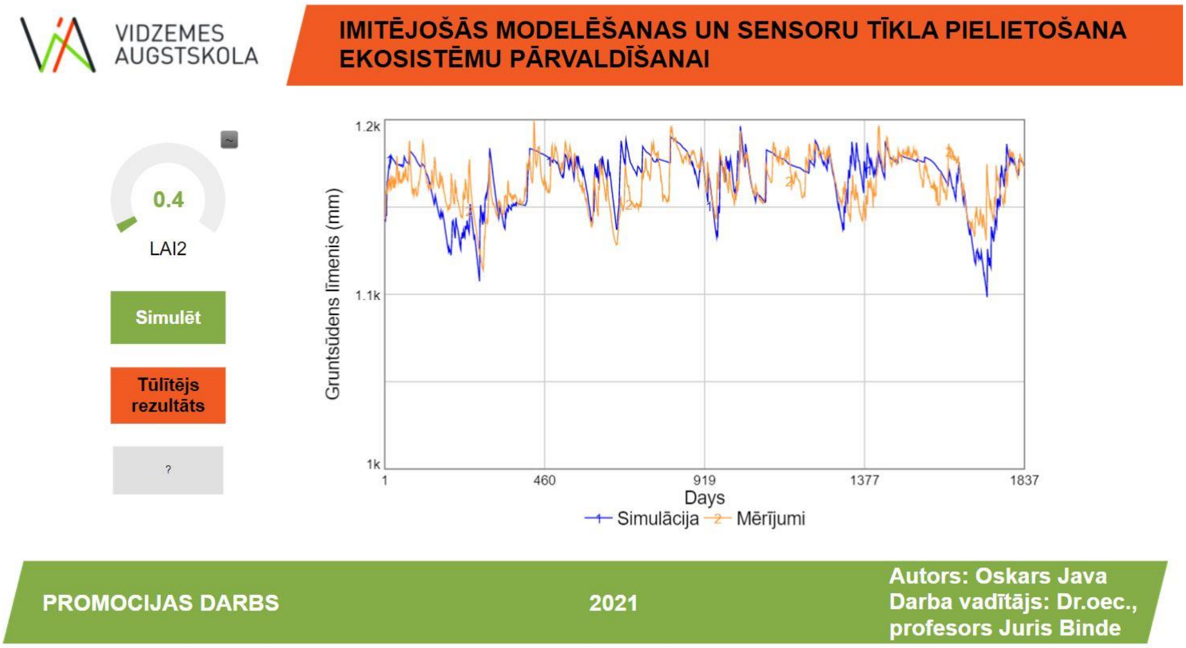

Figure 9. Screenshot of the user interface of the bog hydrological model https://exchange.iseesystems.com/public/oskarsjavapromocijasdarbs/bog-hydrologial-model

Source: the author

In the user interface (see Figure 9), it is possible to simulate a change in groundwater level from 0.1, corresponding to the surface in principle without any vegetation, to 8, corresponding to the average pine forest (Sumida, Watanabe, & Miyaura, 2018) and allow one to observe the effects of LAI on the groundwater level at a wider range.

The fully functional BogSim hydrological model is available at *InsightMaker* by opening this link in a web browser https://insightmaker.com/insight/201089/Bog-hydrology-model. The *Insight Maker* simulation model uses Männikjärve bog measurements as input data and allows one to study the architecture and mathematical formulation of the model in detail.

The simulation model of the bog hydrological regime shows that system dynamics is suitable for the modelling of hydrological processes, since its structure allows the understanding of the system and provides information on its functioning. System dynamics also provides insight into the interaction between the various hydrological processes, thus demonstrating that this is an effective modelling tool that allows structuring and integrating information from existing hydrological processes.

The direct economic impact of the NB-IoT sensor system described in the thesis on the information technology and communication sector cannot be assessed, since the construction of the system essentially consists of costs only. However, the practical importance of this approach should be emphasized, since it could contribute to the use of sensor systems for gathering meteorological and hydrological data, due to several times lower costs compared to standard meteorological stations. This, in turn, would expand the geographical range of application of these and other environmental and ecological models, providing researchers with a more general insight into the interaction between factors affecting the ecosystem and impacts on processes. Researchers' findings would contribute to building a sustainable and safe environment and to reducing the effects of human impacts on the environment.

CONCLUSIONS

The aim of the study was, based on an analysis of a real ecosystem structure and processes, to develop a bog hydrology simulation model for assessing the impact of forest crown cover on the ecosystem water balance and a methodology for its use, as well as to develop an IoT sensor system prototype for *in situ* meteorological and groundwater level raw data collection, processing thereof and a methodology for its use.

In the course of the research, the proposed theses were confirmed:

- A simulation model designed specifically for the bog ecosystem which accurately simulates regional-level hydrological processes in the bog ecosystem;
- The size of the forest stand affects the water balance of the ecosystem and this can be observed in the simulation model, according to LIDAR data, adjusting the LAI, as a result of which changes in the groundwater level close to the reading taken in nature are simulated;
- As part of the research project for the Fundamental and Applied Research Program entitled "Visualisation of real-time bog hydrological regime and simulation data in virtual reality" the new simulation modelling method developed by the author and a methodology for its use, combined with the developed IoT sensor system for obtaining high quality *in situ* raw data and a methodology for its use, was used in practice to simulate the functioning of the bog ecosystem.

The results of the study are straightforward and can be widely applied throughout the Baltic region.

Theoretical value of the PhD thesis – the simulation model approach developed allows the characteristics of the dynamic system to be listed. This methodology provides more accurate results than current approaches, as special attention is paid to parameters that are not featured in such hydrological models with as a high a level of detail, or are not included at all. These parameters are the vegetation-related characteristics of the ecosystem affecting the water balance, such as interception ant transpiration, which are not included at all in most hydrological models.

Scientific innovation of the PhD thesis – a methodology for the use of simulation modelling and sensor system for ecosystem management has been developed. The methodology differs from existing hydrological models' methodologies, as the model is used to simulate hydrological systems of "slow "ecosystems. Existing hydrological models use one hydraulic conductivity proportionality constant for each of the soil types and, therefore, the introduction of dynamic hydraulic conductivity of actrotelm is considered to be the innovation of the author's simulation model methodology. Dynamic hydraulic conductivity of acrotelm means that the rate of water infiltration in the peat layer decreases as the distance to the surface of the earth rises until catotelm is reached, whereas hydraulic conductivity in the catotelm remains constant. The author developed a number of logical expressions and a simplified approach to percolation in the shale layer, resulting in improved precision of the model. The scientific innovation also includes the NB-IoT sensor system architecture proposed by the author, which includes a number of new approaches to the collecting of the meteorological data, such as the use of a Doppler microwave sensor for precipitation measurement and the use of a UV sensor for solar radiation calculation.

Practical relevance of the PhD thesis – the methods proposed by the author enable the water balance of the bog ecosystem to be restored more quickly and effectively, thereby increasing natural diversity, restoring the water cycle, improving the quality of life of local people and promoting recreational opportunities; it can also be used as a training tool in environmental sciences. The developed NB-IoT sensor system deals with the availability of *in situ* raw data for environmental simulation models. The developed simulation model was tested in two system dynamics environments, *Stella Architect* and *Insight Maker*, which allowed the identification of significant differences between the commercial and free product. Both the simulation model of a bog hydrological system and the sensor system for collecting high-quality *in situ* data developed by the author are repeatable and replicable and the concept can be used in other models in similar ecosystems.

In the development of the PhD thesis, the following main conclusion have been reached:

1. The bog ecosystem is one of the most valuable and least valued natural ecosystems providing a number of valuable ecosystem services, such as providing clean groundwater, reducing the risk of wildfire, etc., thus it is worth protecting and restoring previously degraded bogs.
2. The simulated groundwater curves of the BogSim simulation model developed by the author in a system dynamics environment simulate the trajectory and fluctuations of the measured groundwater level curve in different test plots, including changes in LAI. The author performed statistical tests to determine how accurate the simulation model works. Statistical tests confirm that the simulation model works accurately and can be used not only to observe the causal relationship of the components of the hydrological

regime of the bog, but also to determine the intensity of forest stand thinning required for bog restoration projects.

3. Experiments with the BogSim simulation model developed by the author showed that LAI is not directly proportional to the forest stand thinning intensity, which could be due to different tree age, health status and the fact that cutting down trees reduces the shading of the undercover which promotes biological processes in the undergrowth.
4. The BogSim simulation model developed by the author not only graphically shows the impact of changes in LAI on the changes in the bog groundwater level, but it also allows expressing the impact of forest stand on the total water balance of the ecosystem in numbers and percentages. For example, in test plot No 1, prior to thinning, the forest stand blocked 50% of precipitation from reaching the ground and consumed it for biological processes, but by reducing the forest stand by 44% its impact on the water balance was reduced to 43%. Measuring interception and transpiration with gauges would be difficult, time-consuming and expensive, while the empirical equations integrated into the simulation model allow these values to be determined with a few computer mouse clicks based on LAI, meteorological conditions and soil saturation.
5. A system dynamics approach helps to mimic processes at a specific point and to understand causation, which makes it an appropriate tool to make sure that the system includes all components before large-scale process modelling in another environment. At the same time, this approach, which allows one to study each of the components of the system individually and all together, makes it a great simulation learning method.
6. The results of the PhD thesis are practically applicable and are further used in research projects such as the European Union research and innovation support programme Horizon Europe research project “reSilienT fARminG by Adaptive microclimaTe managEment (STARGATE)” (project No. 818187, 01.10.2019 - 30.09.2023); the fundamental and applied research project programme project “Visualisation of real-time bog hydrological regime and simulation data in virtual reality (BogSim-VR)” (project No. lzp-2020/2-0396, 01.12.2020 – 31.12.2021); the European Union Erasmus+ European University project “Engaged and Entrepreneurial European University as Driver for European Smart and Sustainable Regions (E^3UDRES^2)” (project No. 101004069, 01.10.2020 – 30.09.2023); the internal call project “Multi-Sensor Monitoring for Smart and Sustainable Farming in Europe ($MULTISENS^2E$)” (01.10.2021 – 30.09.2023).

7. The graphical representation of the system dynamics simulation model provides an opportunity for hydrology and biology experts to easily validate it, while demonstrating to stakeholders and decision-makers the impact of the size of the forest on the bog water balance and explaining the importance and impact of restoration of the ecosystem and the environment.
8. The large reduction in the number of aircraft flights due to the Corona virus SARS-CoV-2 pandemic has created problems for weather forecasting due to a significant decrease in available weather data (Guardian News & Media Limited, 2020). The NB-IoT sensor system proposed by the author not only collects the data needed to operate hydrological simulation models, but, for example, during a similar crisis, could provide the data needed to forecast weather conditions, particularly if the architecture of this sensor system, due to its low cost, were to be widely applied around the globe, creating a unified global sensor network. As a part of the PhD thesis, a sensor system for *in situ* input data collection and processing for simulation models as well as a widely applicable simulation model were developed, which in wider practical usage would have a major economic multiplier effect and a positive impact on the climate, bringing benefits to society as a whole, thereby justifying the use and necessity of the IoT sensor system. When evaluating the performance of the IoT sensor system and the simulation model the following conclusion was drawn: the low cost, small size and long battery life of NB-IoT sensors allow for more extensive acquisition of high-quality input data for simulation models.
9. While, based on cloud computing algorithms, it is not possible to create unified global meteorological data storage with sufficiently high resolution, in order that data be made available and usable to operate regional-scale simulation models that require high precision, IoT sensor systems are suitable for obtaining these data and could become a part of a global sensor network in the future.

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