Eesti Maaülikool
Estonian University of Life Sciences

# THE EFFECTS OF LAND USE AND CLIMATE CHANGE ON THE HYDROPOWER POTENTIAL IN ESTONIAN RIVERS

## MAAKASUTUSE JA KLIIMAMUUTUSE MÕJU EESTI JÕGEDE HÜDROENERGEETILISELE POTENTSIAALILE

**OTTAR TAMM**

A Thesis
for applying for the degree of Doctor of Philosophy
in Engineering Sciences

Väitekiri
filosoofiadoktori kraadi taotlemiseks tehnikateaduse erialal

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# CONTENTS

# LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following three publications, which are referred to by Roman numerals (**I-III**) in the text. The papers are reproduced with the permission of the publishers.

I **Tamm, O.**, Luhamaa, A., Tamm, T. 2016. Modeling future changes in the North-Estonian hydropower production by using SWAT. Hydrology Research, 47 (4): 835-846.

II **Tamm, O.**, Maasikamäe, S., Padari, A., Tamm, T. 2018. Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. Catena, 167, 78–89.

III **Tamm, O.**, Tamm, T. 2020. Verification of a robust method for sizing and siting the small hydropower run-of-river plant potential by using GIS. Renewable Energy, 155, 153-159.

The contributions of the authors to the papers are as follows:

| | I | II | III |
|---|---|---|---|
| Original idea | TT | TT | OT |
| Study design | OT, TT | OT, TT | OT |
| Data collection | OT, AL | OT, AP, SM | OT |
| Data analysis | OT, TT | OT, TT | OT |
| Manuscript preparation | OT, TT | OT, AP, TT | OT, TT |

**OT – Ottar Tamm**, AL – Andres Luhamaa, AP – Allar Padari, SM – Siim Maasikamäe, TT – Toomas Tamm.

# ABBREVIATIONS

| | |
|---|---|
| CVI | Complex Value Index |
| DEM | Digital elevation model |
| DMI | Danish Meteorological Institute |
| EU | European Union |
| HBV | Hydrologiska Byråns Vattenbalansavdelning |
| IDW | Inverse distance weighting |
| IPCC | Intergovernmental Panel on Climate Change |
| GCM | General Circulation Model |
| GIS | Geographical information systems |
| HIRHAM | high-resolution limited-area model |
| HRU | hydrological response unit |
| HSPF | Hydrological Simulation Program FORTRAN |
| HYPE | hydrological predictions for the environment |
| KGE | Kling–Gupta efficiency |
| KNMI | Royal Netherlands Meteorological Institute |
| LOCI | Local Intensity Scaling Method |
| NSE | Nash–Sutcliffe model efficiency coefficient |
| PBIAS | Percent bias |
| RBD | River Basin District |
| RACMO | Regional Atmospheric Climate Model |
| RCM | Regional Climate Model |
| RCP | Representative Concentration Pathway |
| RE | Renewable energy |
| RES | Renewable energy sources |
| R2 | Coefficient of determination |
| RoR | Run-of-river |
| SCS | Soil Conversion Service |
| SDM | Specific discharge map |
| SHP | Small hydropower |
| SQL | Structured Query Language |
| SRTM | Shuttle Radar Topography Mission |

| | |
|---|---|
| SWAT | Soil and Water Assessment Tool |
| VHA | Virtual Hydropower Assessment |
| VHPS | Virtual hydropower station |

# 1. INTRODUCTION

According to estimations, the global demand for energy is expected to increase by more than 25% by 2040. Renewable energy sources (RES), including biomass, hydro, solar, geothermal, and wind resources, are expected to accommodate approximately two-thirds of this need (World Energy Outlook 2018). This is mainly due to their considerably reduced greenhouse gases and a low environmental impact (IPCC, 2014a). The renewable energy (RE) share in Europe's electricity production increased to 20.1% and 34.2% in 2005 and 2015, respectively (World Energy Council, 2016).

The current RE directive in the European Union (EU) aims to achieve a minimum renewable energy contribution to total energy consumption of 32%, by 2030. Furthermore, through the use of RE, the EU aims to become climate-neutral (an economy with net-zero greenhouses gas emissions) by 2050. To achieve this target, a customized national action plan is being developed for each country, according to its available resources potential. Up-to-date assessments of the RE resource of countries are required to evaluate the national RE potential, acknowledging possible changes in the climate and land-use in the process. Water resources are highly susceptible to these changes.

Water-related environmental changes are currently being scrutinized in the context of climate change around the world. Water resources have already been redistributed in different regions of the world due to climate change (IPCC, 2014b, 2007), and this phenomenon is expected to continue in the future (Arnell and Lloyd-Hughes, 2014; KUNDZEWICZ et al., 2008; Op de Hipt et al., 2018). Besides climate change, anthropogenic land-use and land-cover changes significantly impact hydrology, and thus, water resources. Regarding RE assessment, especially for hydropower potential, variations in the availability of water resources can either be positive or negative, depending on the region of interest (Shu et al., 2018).

The overall impact of climate change on existing global hydropower generation is expected to be small, or even slightly positive (Edenhofer et al., 2011). Notable variations across regions and countries are projected; for instance, the largest increases are expected in Asia, whereas the largest negative changes are expected in Europe (Hamududu and Killingtveit, 2012). Hydropower potential in Southern, Eastern, and

Western Europe is estimated to decrease, whereas hydropower generation in the North is expected to increase, as suggested by an older comprehensive study on the impact of climate change on hydropower potential in Europe, where an overall increase by the end of 21st century was predicted (Lehner et al., 2005). The modelling results from the same study indicated a 19% increase in hydropower potential in Sweden and Finland, with an even more notable increase, of 30%, in Estonia. Although beneficial, these findings are country averages with a coarse computational resolution, thus requiring further detailed national assessments.

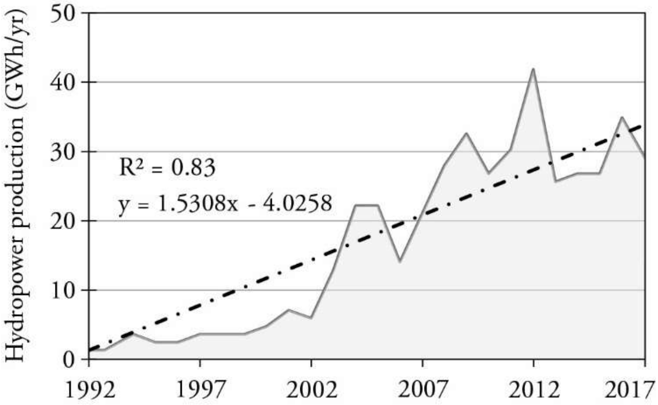

**Figure 1**. Annual hydropower production and trend (dash-dotted line) in Estonia from 1992–2017 (III).

Estonia's energy policy is currently transitioning from environmentally burdening oil shale-based energy production to clean renewable energy sources. Electricity production from renewable sources has been annually increasing, with a 13% reported growth from 2016 to 2017. However, oil shale persists as a prominent energy source in the country. Since joining the EU, the annual hydropower output in Estonia has increased from 14 GWh in 2006, to 42 GWh in 2012. Hydropower energy generated in Estonia is used for providing electricity in off-grid systems or is transferred to the electrical grid. Despite the strict environmental policies regarding the expansion of hydropower, hydropower energy generation in Estonia has increased almost three-fold since joining the EU (Figure 1). The average annual increase in hydropower production over the last 25 years is approximately 1.6 GWh.

This trend will presumably decline in the near-future due to the ever-strengthening environmental regulations and hydropower production requirements in Estonia. Possible increases in future water resources, however, may necessitate the renovation of existing hydropower plants in Estonia. Siting and sizing the new potential small hydropower (SHP) plants requires an automated systematical approach, with sufficient accuracy to provide credible results. The generated information would be useful to guide relevant policies pertaining to better management of Estonian water resources in the future.

The present thesis provides a comprehensive assessment of the current technical hydropower potential in Estonian rivers by methodically using automated geographic information systems (GIS), followed by the assessment of the effect of climate-related changes on hydropower production and potential. For this, the SWAT (Soil & Water Assessment Tool) hydrological model was used, after being parametrized, calibrated and validated, to assess the individual and combined effects of land use and climate change on water resources in Estonian rivers.

# 2. REVIEW OF LITERATURE

## 2.1. Climate change

The statistical distribution of weather patterns is subject to change, with factors like air temperature and precipitation influencing the hydrologic cycle, and thereby, water resources. Climate change is caused by a combination of natural processes and human activity, although the extent of anthropogenic influence is still uncertain. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the global linear trend (1906–2005) for the annual near-surface mean temperature has been increasing by 0.74 °C per decade (IPCC, 2007). Furthermore, according to Tietäväinen et al. (2010) the rate of warming has tripled during the last 50 year (up to 0.30 °C per decade) in the northern part of the Baltic Sea (Finland).

Jaagus (2006) analyzed the time series trends of air temperature and precipitation in Estonia during the period 1951–2000. There was a statistically significant increase in the air temperature trend during the cold period. Increases were also present in the precipitation trend from October to March, and in June. Furthermore, he determined that the snow cover duration in Estonia has decreased to 17–20 and 21–36 days on the inland and coast, respectively. An increase in winter flow has been detected in the Baltic Sea sub-basins, attributed to the earlier snowmelt caused by higher temperatures (BACC Author Team, 2008). From the above, it can be concluded that the climate in the eastern Baltic Sea region is evidently changing. As changes in climate are expected to continue in the current century, the future impact of climate change on hydrology (**I**, **II**) is of great interest to both scientists and policy makers.

Combining the current understanding of the climate system with advanced computer simulations, it is possible to analyze projected future climate effects on hydrology, and accordingly, on water resources in general. General Circulation Models (GCMs) are a fundamental basis of future climate studies; however, they possess a coarse resolution (Flato et al., 2013). Stone (2003) determined that in climate change impact studies, the resolution of the climate model plays an important role in estimating water yields in a basin. To overcome this limitation, one solution is to employ finer scale regional climate models (RCMs) which are constrained by GCM-generated boundary and initial conditions (Giorgi et al., 1990; Wang et al., 2004). Prein et al. (2016) demonstrated that a higher resolution climate model considerably improves the representation of spatial precipitation patterns. A study by Di Luca et al. (2013), however, suggested that RCMs represented surface temperature only slightly better than coarser resolution models. Furthermore, they found that the largest added value of RCMs appeared in coastline regions due to the different warming rates of land and water surfaces. As Estonia lies in the transition zone between maritime and continental climates, the RCM added value could be noticeable.

The typical analysis for climate change impacts on hydrology generally involves bias correction of RCM/GCM precipitation and temperature outputs, which are applied to hydrological models to simulate river flows (Piniewski et al., 2017b; Teutschbein and Seibert, 2012). A climate model bias is defined as the systematic difference between the simulated (e.g., precipitation) and real-world climate statistics (Maraun, 2016). Bias correction is needed as climate models often exhibit systematic deviations from the reference period (Kotlarski et al., 2014; Maraun, 2016). Various statistical methods have been developed for removing biases between observations and models (Ehret et al., 2012; Maraun et al., 2010). Despite the bias correction method employed, the underlying assumption of bias correction is that the climatic bias during the reference period of the climate model will remain the same in the future, assuming temporal stationarity; however, this cannot be guaranteed in climate modeling, thus introducing uncertainty in the investigation of the effect of climate change on water resources by hydrological modeling (Teutschbein and Seibert, 2012).

Climate model performance is tested via hind-casting, where the past climate is modeled. The model results are then compared with the observed climate to check the accuracy of the climate model. Typically, a 30-year (1961–1990) control period is used; however, the weather data quality in the second part of the 20th century can be defined as medium (Hartmann et al., 2013). This additional uncertainty is inevitably carried to future climate projections, since this data is used as a base for climate models. Despite these complications, climate models are useful tools for estimating possible changes in future rainfall and temperature.

## 2.2. Land-use change

In addition to climate change, changes in land use have a significant effect on hydrology (Wang et al., 2006), and thus, on water resources. At least one-third of the Earth's land surface has been modified by humans (Ellis, 2011). This tendency is likely to increase in the future to accommodate the growing demand for resources (MEA, 2005). The global forested area has reduced over 3 percent in the period from 1990 to 2015. The conversion of forest land for agricultural use has been the most significant factor of this change (Smith et al., 2016). In the Baltic countries, however, the trend of land use has been the opposite: after the Baltic States regained independence from the Soviet Union in 1991, a decrease in the agricultural land use was observed. This trend is attributed to the natural expansion of forests on abandoned agricultural lands, along with afforestation, where less fertile lands were planted with trees (Palang et al., 1998). According to the food and agriculture organization (FAO, 2010), 52% of the total surface area of Estonia is covered by forests, and approximately 23% is agricultural land. In addition to changes in the forest and agricultural land in Estonia, urban land use has increased significantly (Roose et al., 2013). Concludingly, the main drivers of land use changes in the Baltic countries have been both political and economic.

Anthropogenic land-use and land-cover change affect the hydrologic cycle through evapotranspiration and the interception of water. Climate- and land use-induced changes in precipitation and evaporation directly affect the amount of available water which can theoretically be used for hydropower production along with other uses of water resources. Due to the complexity of the hydrological cycle, changes in land use do not always linearly correspond to hydrological responses changes. A study conducted in Iran showed that land use directly influence the ratio of interception and transpiration in a catchment, and that different land-use types generate different amounts of flow (Ghaffari et al., 2010). The same study detected a threshold effect on the hydrological response to land cover change, where surface flow rapidly increased after a certain threshold was crossed. Therefore, it is important to consider possible trends in land use, along with climate change impacts (I, II), when modeling regional changes in water resources (II). The generated information from climate and land use change scenarios can provide practical guidance for policies related to adaption and mitigation measures. Furthermore, the combined effects of climate change and land use on the Estonian regional water resources, have not been explored to date.

## 2.3. Hydropower

Historically, the primary purpose of moving water was for irrigation and for the operation of various mechanical machines, such as watermills and sawmills. In the late 19th century, rapid progress in technology and electrical engineering was witnessed. The world's first hydroelectric power station was installed in 1870 in Cragside, England. The first hydroelectric plant in Kunda, Estonia, was constructed 23 years later with an installed capacity of approximately 200 kW. By the end of 1930, hydroelectricity accounted for almost 30% (installed capacity of 9.3 MW) of the total electricity generation in Estonia.

The basic principle for generating hydropower from falling water has remained the same. During hydroelectricity generation process, water flows through penstocks, which are controlled by valves to adjust the flow rate for an optimal load. Through the penstock, water enters turbines that run the electricity generators. Finally, water is discharged through the tailrace into the river. Hydropower is the combination of head and flow, where both must be present to produce energy:

$$P = \Delta \mathrm{h} \mathrm{Q} \eta \mathrm{g}, \tag{1}$$

where $\Delta h$ is the water pressure created by the elevation difference between the water intake and the turbine i.e. net head (m), $Q$ is the flow rate (volume of water which passes per unit time) ($m^3s^{-1}$), $\eta$ is the turbine efficiency, and $g$ is the acceleration due to gravity (9.81 $ms^{-2}$), and $P$ is power (kW).

Hydropower projects can be classified according to their size, head, and facility type. This research addresses small-scale hydropower plants with a capacity of up to 10 MW. This approach of classifying small and large-scale hydropower plants is common in Europe (Kaunda et al., 2012). Small hydropower plants (SHPs) can be further classified into mini (< 1 MW), micro (< 100 kW), and pico (< 5 kW) plants. The most common types of SHPs are pumped storage, reservoir storage, and run-of-river (RoR) hydropower (Edenhofer et al., 2011). This thesis focuses on RoR-type plants, which are typical for the study area, Estonia. RoR-type plants exhibit significant fluctuations in energy production, they are directly affected by weather conditions and their limited ability to store water.

## 2.4. Estimation of hydropower potential

Various types of potentials can be defined when assessing hydropower potential. The theoretical potential is the total natural energy. Much of this theoretical potential remains undeveloped due to technological, environmental, and economic constraints. The technical potential is the energy that can be utilized through existing technology, whereas the exploitable potential also considers non-technical factors, such as environmental restrictions (particularly the possible negative environmental impacts and the availability of land). The economic potential is the exploitable potential that is financially beneficial if utilized, and depends on the cost of the facility and the energy price. The exploitable and economic potentials are highly location-dependent; therefore, they require in-depth analysis at each potential site. This is the primary reason why the majority of RE assessment studies focus on the theoretical potential.

In this decade, four separate studies have estimated the theoretical global hydropower potential to be between 31 and 128 petawatt hours per year (Fekete et al., 2010; Hoes et al., 2017; van Vliet et al., 2016; Zhou et al., 2015). These estimates are dependent on the methods applied and the quality of the input data used. It is estimated that the globally available economical hydropower potential (available at a cost below US$0.10 kWh$^{-1}$) is 5.7 petawatt hours per year, located primarily in the Asia Pacific region (37%), South America (28%), and Africa (25%) (Gernaat et al., 2017). Many studies have focused on assessing the hydropower potential at regional and (sub-)national scales (Coskun et al., 2010; Kusre et al., 2010; Mosier et al., 2016; Nguyen-Tien et al., 2018; Reichl and Hack, 2017; Rojanamon et al., 2009). Most of these studies have focused on synthesizing the streamflow of ungauged rivers, through hydrological modeling (Kusre et al., 2010; Mosier et al., 2016; Nguyen-Tien et al., 2018), flow-duration curves (Reichl and Hack, 2017; Rojanamon et al., 2009), or some other methods (Coskun et al., 2010; Yi et al., 2009). Depending on the method, an extensive amount of input data may have been required.

The above hydropower potential estimations are based on the observed data of current climatic conditions. However, the two primary factors affecting the hydrological cycle, namely climate and land-use, are constantly subject to change. Changes in these factors can alter the future hydropower production potential, which is directly related to changes in river flow, as the head (Equation 1) is not affected. Changes in precipitation and temperature in the catchment area may lead to changes in flow volume, variability and seasonality, directly affecting water resource availability for hydropower production. The global impacts of climate change on hydropower resource potential are expected to be relatively small, but regional changes can be significant (Hamududu and Killingtveit, 2012). Global assessments are based on the annual average flow, disregarding the changes in variability and seasonal distribution of flow. In order to make more accurate predictions of hydropower potential changes on a national scale, it is necessary to analyze changes in the temporal distribution of flow.

Hydrological models are one of the tools used to assess the possible changes in future hydrology and water resources on a regional scale. Specific tools that are widely used in the Baltic Sea region are the Soil and Water Assessment Tool (SWAT)(Arnold et al., 1998; Neitsch et al., 2005), the Hydrologiska Byråns Vattenbalansavdelning (HBV) (Bergström and Forsman, 1973; Lindström et al., 1997), hydrological predictions for the environment (HYPE)(Lindström et al., 2010), and the Hydrological Simulation Program Fortran (HSPF)(Bicknell et al., 1997). The hydrological models employed in these studies factor in the impact of climate change on water quantity (Kjellström and Lind, 2009;

Latkovska et al., 2012; Øygarden et al., 2014; Tamm et al., 2015) and quality (Arheimer et al., 2012; Donnelly et al., 2011; Rankinen et al., 2016). There are no regional studies on the impact of land-use change, nor on the combined impact of climate and land-use change on future water resources in the eastern Baltic Sea region.

The total theoretical hydropower potential of Estonian rivers has been estimated at 300 MW (Raesaar, 2005). Approximately 10% (30 MW) of this is considered a technically feasible potential. As these estimations were conducted during the Soviet era, no description of the method applied is available. Furthermore, the land-use and climate trends have changed since then. Advances in computational tools, such as GIS, have advanced the efficiency of the data processing and analysis, thus providing more accurate results. However, despite the availability of tools, no studies covering the entire country have been carried out to date.

# 3. AIM AND TASKS OF THE THESIS

Following the renewable energy pathway to achieve climate neutrality by 2050 in Europe, accurate and up-to-date information about the current natural resources and their possible future changes are needed. Among the various natural resources available, hydropower the most cost-friendly. Information regarding the future magnitude and distribution of hydropower potential in Estonia benefits the planning and formulation of policies to help achieve the renewable energy target set by the EU.

The main aims of this study are as follows:

- to assess the usability and performance of the SWAT hydrological model in Estonia.
- to assess the current technical hydropower potential in Estonian rivers.
- to analyze the individual and combined effects of climate and land-use change in Estonian water resources by the end of the 21st century, using the SWAT hydrological model.
- to provide accurate and up-to-date information regarding the current and potential future changes in hydropower potential in Estonia, for policy makers.

The following tasks were conducted to achieve these aims:

- the SWAT hydrological model was employed in various Estonian river watersheds, where hydropower is or has been harvested.
- regional parameters were obtained for the SWAT models by calibrating and validating against the observed flow.
- SWAT model performance was estimated using qualitative and quantitative techniques.
- a reliable method for sizing and siting small hydropower run-of-river hydroelectricity plants was developed.
- the accuracy of the proposed method was verified through data from twenty small SHP plants currently operating, or abandoned, in thirteen Estonian rivers.
- two regional climate models were applied and bias-corrected against the observed climate.
- land-use change scenarios were generated and projected for the end of the 21st century.
- future scenarios were generated based on the combinations of changing climate and land-use.
- SWAT was used to model future scenarios in selected Estonian rivers, and the modeling results were analyzed to provide information about the possible future changes in water resources in Estonian rivers.

# 4. MATERIALS AND METHODS

This study provides a comprehensive analysis of hydropower potential in Estonia. A reliable technical hydropower potential estimation method was developed and verified in Estonia (III). The suggested method was applied on Estonian rivers to assess their technical hydropower potential. The effects of future climate change (I, II) and land-use change (II) on hydropower potential was assessed using the SWAT hydrological model.

The procedure for estimating the impacts of possible future climate and land-use changes on hydrological behavior, was as follows: (1) parametrization and calibration of the SWAT hydrological model by using current climatic inputs, land-use map and observed river flow; (2) two regional climate models (RCMs) were applied and bias corrected against the observed climate; (3) land-use change scenarios were generated for the end of the 21st century; (4) future scenarios were generated based on the combinations of estimated changes in climate and land-use; and (5) the modeling results of the current and future periods were compared with the interquartile range.

## 4.1. Study area (I, II, III)

This study was conducted in the northeastern Baltic Sea region. The Baltic Sea drainage basin has an area of approximately 1745000 km$^2$, and is divided into multiple sub-basins. The Baltic Sea is almost completely enclosed by land, with the only connection to the North Sea being through the narrow Straits of Denmark. Estonia is situated between 57.5° and 59.5° N on the eastern coast of the Baltic Sea (Figure 2). The climatic region of the study area can be described as semi-continental (coastal) and continental (inland). The weather is typically breezy and humid due to the proximity of the Baltic Sea. The average annual precipitation and actual evaporation in the study area are approximately 700 and 400 mm, respectively. Around 20% of the precipitation is snowfall, and the melting of the snowpack typically results in annual peak flows in Estonian rivers during the spring months. Despite the autumn peak usually not being as high as the spring peak flow, it is still distinguishable in the river hydrograph. The higher flow in autumn months is caused by rainfall.

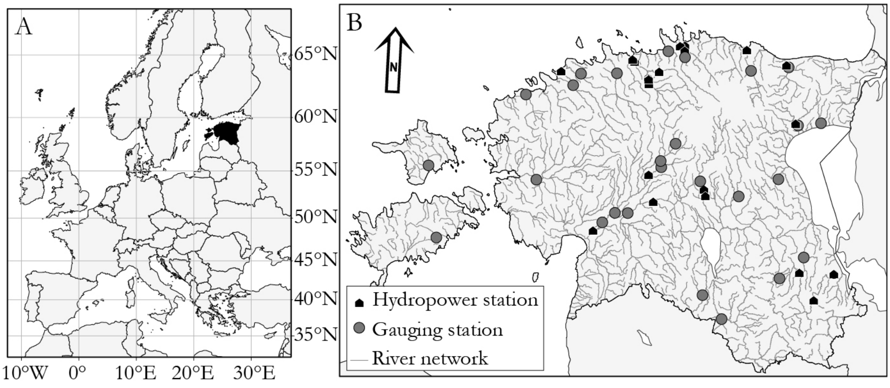

**Figure 2.** (A) Location of the study area in Europe (marked in black); (B) map of Estonia with rivers, and flow gauging and hydropower stations (I, II, III).

With an average elevation of approximately 50 m above sea level, the major part of the hydropower potential in Estonia originates from the river flow rate, instead of the net head. Although there are over 7000 streams and rivers in Estonia, most of them are short and have a relatively small annual flow rate. Approximately 60 rivers have an annual flow rate exceeding 2 $m^3/s$, which is considered to be the minimum to produce hydropower. Among these rivers, average annual flow of 26 rivers exceeds 5 $m^3/s$, and that of 14 rivers exceeds 10 $m^3/s$. Consequently, as the hydro energy potential is proportional to the head and the flow rate of the river, hydropower plants equipped with high dams and large reservoirs for flow regulation, cannot be utilized in Estonia; however, numerous rivers are suitable for SHP production. Estonia currently has over 40 SHP plants with a total installed capacity of approximately 8 MW.

Estonian hydrological regimes are characterized by large seasonal variations in river flows. A low winter flow is followed by a snowmelt-driven spring flood peak, followed by low flow during summer and higher precipitation-induced flow in the fall. The uneven seasonal water availability, particularly the water shortages during summer, impact the water supply for hydropower production. Seasonal fluctuations and small river flows primarily enable SHP generation through RoR-type hydropower plants. A summary of the twenty largest currently operating, or abandoned, SHPs in thirteen Estonian rivers are provided in Table 1.

**Table 1.** Summary of the largest SHP stations in Estonia (H - net head, Q - design flow, P - capacity) (III).

| River (SHP) | H (m) | Q ($m^3/s$) | P (kW) |
|---|---|---|---|
| Ahja (Saesaare) | 8.0 | 3.0 | 194 |
| Jägala (Linnamäe) | 10.0 | 13.5 | 1152 |
| Jägala (Jägala-Joa) | 17.0 | 13.5 | 2000 |
| Jägala (Kaunissaare) | 3.5 | 9.2 | 246 |
| Jägala (Tammiku) | 2.5 | 10.0 | 220 |
| Keila (Keila-Joa) | 8.7 | 5.5 | 365 |
| Kunda (Kunda-Vana) | 9.0 | 7.0 | 400 |
| Kunda (Kunda-Silla) | 6.4 | 7.0 | 336 |
| Loobu (Joaveski) | 11.0 | 3.0 | 300 |
| Navesti (Tamme) | 2.8 | 6.8 | 158 |
| Purtse (Sillaoru) | 7.8 | 8.0 | 300 |
| Põltsamaa (Kamari II) | 5.0 | 7.2 | 311 |
| Põltsamaa (Silla) | 2.5 | 8.0 | 185 |
| Pärnu (Jändja) | 2.5 | 4.0 | 190 |
| Pärnu (Sindi) | 3.2 | 50.0 | 1290 |
| Rannapungerja (Tudulinna) | 6.0 | 2.5 | 150 |
| Soodla (Soodla) | 12.0 | 1.6 | 155 |
| Valgejõgi (Kotka) | 6.5 | 4.5 | 160 |
| Valgejõgi (Nõmmeveski) | 8.0 | 4.3 | 200 |
| Võhandu (Leevaku) | 3.0 | 7.9 | 184 |
| Võhandu (Räpina) | 5.0 | 9.0 | 350 |

The largest SHP station in Estonia is present on the Jägala River, namely the Jägala-Joa SHP, and possesses a design capacity of 2000 kW. This exceptional design capacity results from the combination of a relatively high net head and design flow. Sindi SHP is the second largest station with a design capacity of 1290 kW. With a low net head of only 3.2 m, the power mainly originates from a high design flow of 50 m3/s. This could be considered as paradigm of Estonian SHPs: where the net head is high, design flow is low, and vice-versa. There are many rivers in Estonia, which are suitable for small, mini, and micro hydropower production. Furthermore, RoR-type SHPs are increasingly gaining popularity due to their relatively low cost per kWh, short implementation time, and low environmental impact (Kumar and Katoch, 2015).

### 4.2. Virtual hydropower assessment method (III)

Searching for new and appropriate locations to produce hydropower can be a resource-intensive task, requiring expensive field studies and extensive hydrological analysis. This study attempts to minimize the amount of input data necessary for assessing the technical hydropower potential. The flowchart of the proposed virtual hydropower assessment (VHA) method for sizing and siting SHP sites along a river, is presented in Figure 3. The necessary topographic attributes of the river watershed are derived from the digital elevation model (DEM). To calculate the hydropower capacity, historical river flow data were used to generate the mean annual specific discharge map (SDM) using GIS. VHA is a reliable, straightforward method that does not rely on site-specific parameters, such as penstock length and turbine type.

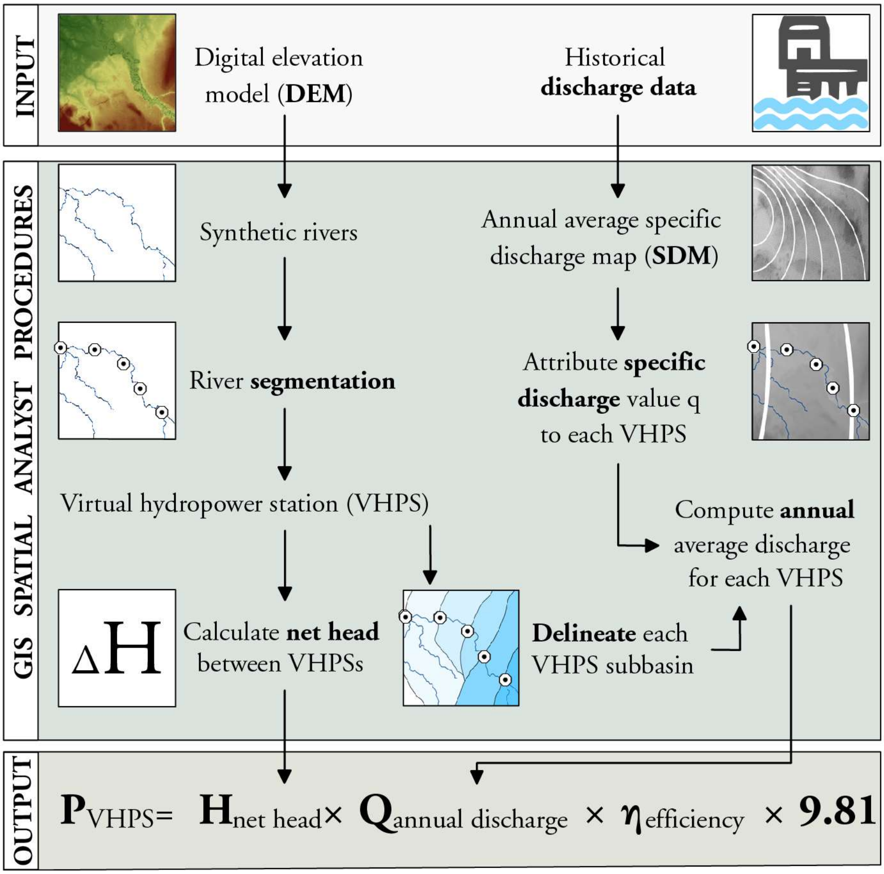

Figure 3. Virtual hydropower assessment framework (III).

As shown in the methodological framework, a synthetic river network is directly derived from the DEM using the built-in flow routing algorithms of ArcGIS. The generated rivers are divided into equal segments with a user-defined distance moving upstream to the end of each segment, where a virtual hydropower station (VHPS) is located. In this study, a distance of 500 m was used. The calculated elevation difference between the VHPSs was specified as the net head for power calculation. The DEM was also used for delineating the subbasin areas for each VHPS moving downstream; indexing began upstream. Historical flow data from nearby gauging stations were used to generate the SDM. The inverse distance weighting (IDW) interpolation technique was applied in the GIS to generate the SDM, and the average specific discharge value from the SDM was applied to each VHPS.

The magnitude of the hydropower production potential is directly dependent on the flow rate, specific weight of water, and hydraulic net head. The virtual hydropower plant capacity at any given location can be calculated as follows:

$$P_{VHPS} = \Delta \mathrm{h} \mathrm{Q} \eta \mathrm{g}, \tag{2}$$

where $P_{VHPS}$ is the computed virtual hydropower plant capacity (kW), $\Delta\mathrm{h}$ is the net head (m) computed from the elevation differences between the VHPSs, $\mathrm{Q}$ is the flow rate ($m^3s^{-1}$), $\eta$ is the overall system efficiency (unitless), which was assumed to be 75% (0.75), and $\mathrm{g}$ is the acceleration due to gravity (9.81 $ms^{-2}$). The VHA method uses the annual average flow as the hydrological component for each VHPS, which is derived from the SDM as follows:

$$\forall_i : i = 1 \ldots n-1 \quad \mathrm{Q}_i = A_i q_i + Q_{i+1} \text{ and } \mathrm{Q}_n = A_n q_n$$

$$Q = Q_1 = A_1 q_1 + Q_2 = A_1 q_1 + A_2 q_2 + Q_3 =$$

$$= A_1 q_1 + A_2 q_2 + \ldots + Q_n =$$

$$= A_1 q_1 + A_2 q_2 + \ldots + A_n q_n =$$

$$= \sum_{i=1}^{n} A_i q_i. \tag{3}$$

The flow rate Q ($m^3s^{-1}$) for the first VHPS was obtained by multiplying the annual average specific discharge value q ($m^3s^{-1}km^{-2}$) of the first VHPS with the subbasin area A ($km^2$). Moving downstream to the next VHPS, its subbasin was delineated. The area gained for the given river segment was multiplied by the specific discharge value of the corresponding VHPS. The multiplication result was added to the previous flow rate to obtain the flow rate of the VHPS. The same procedure was repeated to obtain the flow rate for every VHPS until the river mouth (Equation 3).

The performance of the proposed VHA method should be investigated to ensure its suitability. The capacities and locations of historically installed and currently operating hydropower plants can be verified. Numerous hydropower-siting studies in the past have omitted verifying the accuracy of their proposed methods, thus reducing the credibility of their results. Typically, a combination of qualitative and quantitative criteria is applied to determine the representativeness of a proposed method or model. These include statistical methods, such as the coefficient of determination ($R^2$), or even simple graphical XY plots for visual comparison, which are used in the current study:

$$R^2 = \left( \frac{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)}{\sqrt{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2} \sqrt{\sum_{i=1}^{n} \left(P_i - \bar{P}\right)^2}} \right)^2, \tag{4}$$

where O and P are the installed and computed values, respectively, and n is the number of hydropower stations used for assessment. The $R^2$ statistic ranges from 0 to 1, where 0 indicates no correlation and 1 indicates a perfect correlation between the proposed model and reality.

### 4.3. Climate change scenarios (I and II)

Regional future climate scenarios are needed to assess the impacts of future climate change on water resources, using a hydrological model. Modeling results from the EURO-CORDEX project (Jacob et al., 2014) were used as a SWAT model input for future climate. EUROCORDEX is an international climate downscaling initiative that aims to provide high-resolution climate scenarios for Europe. In the EURO-CORDEX project, models are run with two resolutions: 50 and 12 km, and both cover the Baltic Sea region. For the current study, two different RCMs from EURO-CORDEX high-resolution simulations were used: (a)

Regional Atmospheric Climate Model (RACMO) with boundaries from EC-EARTH r1i1p1 developed by the Royal Netherlands Meteorological Institute (KNMI) (Meijgaard et al., 2008); and (b) high-resolution limited-area model (HIRHAM5) with boundaries from ECEARTH r3i1p1 run by the Danish Meteorological Institute (DMI) (Christensen et al., 2007). The RCMs applied in this study were generated from the analysis conducted by the Estonian Environment Agency (Luhamaa et al., 2014). Both RCMs contained projections for the historical period (1971–2000) and for the future period (2071–2100), which were used in the current study. To improve accuracy of the comparison with the historical data, the RCM data were applied only to existing meteorological stations.

Both future projections were forced by RCP4.5 (Representative Concentration Pathway 4.5), which can be considered as a stabilization scenario in which total radiative forcing is almost stabilized by the end of the 21st century (Clarke et al., 2007; Smith and Wigley, 2006). RCP4.5 assumes relatively ambitious emission reductions and is considered "optimistic". It should be kept in mind that climate change scenarios can be interpreted as plausible descriptions of possible future climatic conditions. Although RCMs provide added value over the coarser GCMs, dynamical downscaling may fail to notably improve the simulation of climatic parameters (Rockel et al., 2008). Therefore, a dynamically downscaled climate may still produce GCM-derived biases in the downscaled climate, which are carried to future impact predictions. Despite this finding, RCMs still provide a better simulation of local climatic conditions.

In order to use RCMs in impact studies, however, bias-correction is typically necessary. The air temperature (daily minimum and maximum) is modified with the established delta method by monthly additive correction. For precipitation, the local intensity scaling method (LOCI) is applied (Schmidli et al., 2006; Widmann et al., 2003).

### 4.4. Land use change scenarios (II)

Land-use changes are affected by various factors (e.g., population change and economic development). It is accepted worldwide that the arable land area per capita will decrease in the following decades (FAO, 2002, 2009). Concurrently, the abandonment of agricultural land has occurred (Leal Filho et al., 2016). The leading trends in Estonian land-use change during the 20th century have been the decrease in agricultural land from 65% in 1918 to 30% in 1994, and the increase in forest cover from 21% to 43% (Mander and Palang, 1999); therefore, the primary contributors of land-use change were forest and agricultural land. In the current study, three land-use scenarios were implemented for the compilation of land-use maps for SWAT modeling. The main focus of the scenarios was the balance between agricultural and forested land. The procedures for generating the land-use change maps are summarized in a flow chart (Figure 4).

During the land-use scenario compilation, specific conditions were set. It was assumed that wetlands and protected areas will not change, because of their natural character. These areas were temporarily excluded from the analysis (from the map). The land cover changes were modeled to the remaining part of the study area. Future urbanization was related to the local master plans, particularly, areas reserved for staged urban development were used for urban growth modeling. To simulate changes in forest coverage, a straightforward forest growth model was applied. First, a stand diameter criterion of 6 cm was applied for the division of forest areas into young and old. Second, maturity age was defined according to the national law (Forest Act, Rules of Forest Management) to determine the harvesting time, namely, when the forests transitioned from old to young. Storylines for the three land-use scenarios were generated.

The first land-use scenario was the baseline scenario (L0), which assumed that land-use would remain constant during the 21st century and is the basis for the remaining two scenarios. The deforestation scenario (L1) assumed a high demand for food and biofuel (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). According to this scenario, the area of agricultural land in Estonia would increase up to 13 000 km$^2$ by 2100. The main sources for the arable land increase were forest land (deforestation scenario) along with grassland and bushy areas. The third scenario (L2), the afforestation scenario, hypothesized that the agriculture sector would produce food solely for the Estonian internal needs. The total Estonian arable land area according to this scenario was set to 5000 km$^2$, projecting a decrease in agricultural land of approximately 50% (compared with the baseline scenario), and predicting a more forested Estonia.

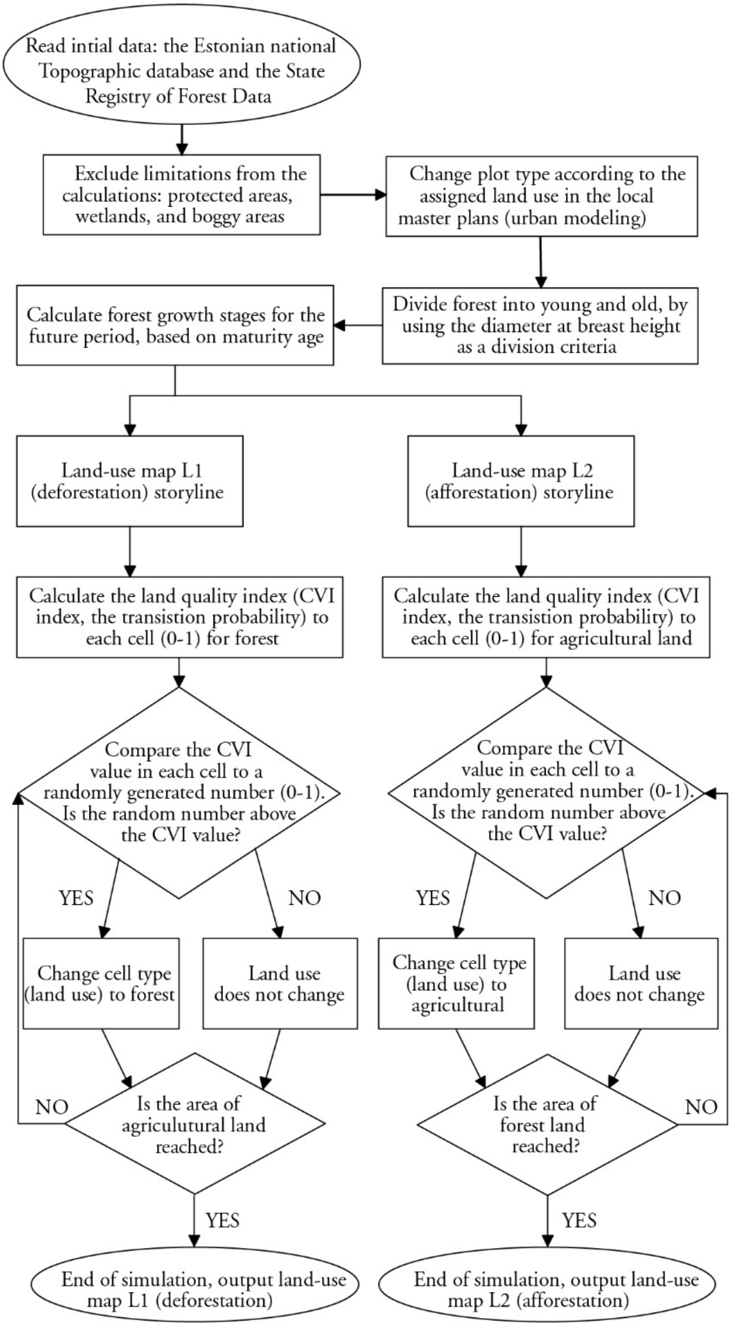

**Figure 4.** Flow chart for the implementation of the land use change model (II).

The entire Estonian maps was divided into grid cells with a spatial resolution of 100 m. The Complex Value Index (CVI) was chosen as a quality measure, to determine the land use transformation (Maasikamäe et al., 2014). The higher the CVI value in the cell, the less susceptible it is to change. Random cells from the grid were selected for evaluation and possible transformations. The CVI value was compared to a random number from 0 to 1 to evaluate the transition probability. If the CVI of a cell was lower than the random number and the change was logical according to the storyline, the transition was accepted. This procedure was looped until a set target value corresponding to the storyline was achieved. The outcome of the land-use modeling was three static maps, according to the storyline.

## 4.5. Climate and land use scenario combinations (II)

To assess the individual and combined impacts of climate and land-use changes on river flow, eight different scenario combinations (Table 2) were established.

**Table 2.** Summary of generated model scenarios (C0 represents the baseline climate; C1 represents the KNMI RCM; C2 represents the DMI RCM; L0 represents the baseline land use; L1 represents the deforestation scenario; L2 represents the afforestation scenario) (II).

| Scenario | Climate | Land use |
|---|---|---|
| 1 | C0 1971–2000 | L1 2071–2100 |
| 2 | | L2 2071–2100 |
| 3 | C1 2071–2100 | L0 1971–2000 |
| 4 | | L1 2071–2100 |
| 5 | | L2 2071–2100 |
| 6 | C2 2071–2100 | L0 1971–2000 |
| 7 | | L1 2071–2100 |
| 8 | | L2 2071–2100 |

The scenarios were modeled with the calibrated SWAT model as follows: Scenarios 1 and 2 only take into account the change in land-use and can be considered as deforestation and afforestation scenarios, respectively. In Scenarios 3 and Scenario 6, the land use remained constant (baseline), while the regional climate models KNMI (C1) and DMI (C2) were applied for the period 2071–2100, respectively. The remaining four scenarios used a combination of both future climate and land use. Linking climate change models and land use can result in a more realistic scenario for future impact studies.

## 4.6. SWAT hydrological model (I and II)

River hydrology interrelates the subjects of climate, geology, topography and, anthropological activities (such as land and water use). Understanding these interactions in water cycle processes is critical to the assessment of changes in water quantity and quality over time. One of the methods to assess the impact of climate and land-use change on river flow, and thus on hydropower potential, is hydrological modeling. A hydrologic model is a simplification of a part of the hydrologic or water cycle. The interaction between model processes is described using series of mathematical equations. These relations are either empirically or physically based.

The SWAT hydrological model is a widely used semi-physically based and semi-distributed model that can simulate long-term flow rate and water quality. SWAT has been used in various water quality and quantity studies (Easton et al., 2010; Gassman et al., 2007; Piniewski et al., 2017b). SWAT is process based, where water, sediments, and nutrients are routed from individual sub-watersheds along the main stream towards its outlet. The SWAT model simulates the water balance (Neitsch et al., 2005) as follows :

$$SW_t = SW_o + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (4),$$

where $SW_t$ is the final soil water content (mm), $SW_o$ is the initial soil water content on day i (mm), t is the time (days), $R_{day}$ is the precipitation amount on day i (mm), $Q_{surf}$ is the surface runoff on day i (mm), $E_a$ is the amount of evapotranspiration on day i (mm), $W_{seep}$ is the water entering the vadose zone from the soil on day i (mm), and $Q_{gw}$ is the groundwater discharge on day i (mm).

In SWAT, sub watersheds are partitioned into combinations of unique soil, land use, and management characteristics, also known as hydrological response units (HRUs), which are linked to the river network. It is assumed that HRUs are non-spatially distributed. Rainfall and evaporation are calculated separately for each HRU. This study defined HRU thresholds as 10% for soil and 10% for land use. Potential evapotranspiration was estimated using the Hargreaves method (Hargreaves and Samani, 1982). For surface flow calculation, the modified USDA Soil Conversion Service (SCS) curve number method was applied.

SWAT requires a significant amount of data and parameters for development and calibration. These include a DEM, land use-map, soil map and weather data. Climate inputs comprise precipitation, solar radiation, maximum and minimum temperature, wind speed, and relative humidity. In this study, the daily maximum and minimum temperature, wind speed, humidity and solar radiation data were available for all study basins. Daily precipitation data was used from surrounding meteorological stations. Daily discharge data were available from the river hydrological stations. A high-resolution DEM with a 10 m grid derived from light detection and ranging was used.

## 4.7. SWAT model calibration and validation (I and II)

SWAT model performance was evaluated for calibration and validation with various approaches. The goodness of fit was qualitatively (visually) and quantitatively evaluated with the Nash–Sutcliffe coefficient of efficiency (NSE, Nash and Sutcliffe, 1970), percent bias (PBIAS), and Kling–Gupta Efficiency (KGE, Gupta et al., 2009):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}, \tag{5}$$

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}, \tag{6}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} 100\%. \tag{7}$$

In equations 5–7, O and P are measured and modeled flow, respectively, n is the length of the time series, $\bar{O}$ is the average measured flow, $r$ is the Pearson correlation, $\alpha$ is the ratio of the standard deviation of the modeled to the measured flow, and $\beta$ is the ratio of the mean of the modeled and measured flow.

The NSE (Equation 5) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"), and constitutes the optimal objective function for reflecting the overall fit of a hydrograph (Servat and Dezetter, 1991). NSE ranges from a value of 1, indicating a perfect agreement between the model and measurement to, of minus infinity. A value of zero or lower indicates that the model output is no better than that obtained by using the averaged observed flow. NSE performs better under low-flow conditions, at the expense of high sensitivity to peaks flows. To alleviate this hindrance, the KGE (Equation 6) was selected to investigate the hydrological model performance.

KGE accounts for multiple hydrological responses for a more consistent assessment of model performance. These include the evaluation of the bias in the mean, bias in the variability, and cross-correlation with measured flow (differences in the hydrograph shape and timing). As can be derived from Equation 6, the higher the combined value of hydrological responses, the higher the KGE value. A KGE value of 1 indicates a perfect agreement between the modeled and measured flow. A value of -0.41 indicates that the model performance is equivalent to that obtained by using the averaged observed flow (Knoben et al., 2019).

PBIAS (Equation 7) measures the average tendency of the simulated data to be smaller or larger than their observed data counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0, indicating no bias. Positive values indicate underestimation bias, and negative values indicate model overestimation. Simulation results can be considered unsatisfactory when the absolute PBIAS value is higher than 25%. Values below 10% are considered to be “very good”, while values ranging from 10% to 25% are rated from “good” to “satisfactory” during calibration and validation (Moriasi et al., 2007).

# 5. RESULTS

This thesis conducted a comprehensive assessment of the energy production potential of the Estonian water resources. For the assessment of hydropower potential in Estonian rivers, two different approaches were followed. For the estimation of current technical hydropower potential, a novel VHA method was proposed (III). Data from twenty currently operating or abandoned SHPs in thirteen rivers were used to estimate the sizing and siting accuracy of the VHA method. The VHA method demonstrated sufficient accuracy in producing a realistic output for SHP location siting and capacity sizing. After successful verification, the current hydropower potential in Estonia was assessed.

The effects of changing climate (I, II) and land use (II) were investigated using the SWAT hydrological model. To assess the effect of land-use change on water resources, two RCMs (KNMI and DMI projections) were selected and bias corrected against the observed data. The bias-corrected climate model outputs were inserted into the SWAT. The SWAT models were calibrated and validated for a continuous period of over 40 years. The calibrated SWAT models were applied to estimate changes in future river flow rates, which is fundamental for assessing the changes in hydropower potential in Estonia. **Paper I** evaluated the effects of climate change on three North-Estonian SHPs. In order to assess the individual and combined impacts of climate and land-use changes on water resources, eight combination scenarios (Table 2) were introduced and evaluated in **Paper II**. For this purpose, two hypothetical (but plausible) land-use change maps were generated. Scenarios 1 and 2 accounted solely for changes in land use and could be considered as deforestation and afforestation scenarios, respectively. In scenarios 3 and 6, the land use was considered to remain constant (baseline), and the regional climate model projections KNMI (C1) and DMI (C2) were applied for the period 2071–2100, respectively. The remaining four scenarios used a combination of both future climate and land-use changes.

## 5.1. Verification of VHA method (III)

The proposed hydropower sizing and siting VHA method was applied to Estonia to evaluate its suitability for RoR-type SHP plants, through various built-in ArcGIS spatial analysis procedures. To evaluate the performance of the developed method, the results were compared with the designed and installed capacity of larger Estonian hydropower plants. Data from twenty currently operating or abandoned SHPs in thirteen rivers were used for sizing verification (Table 1).

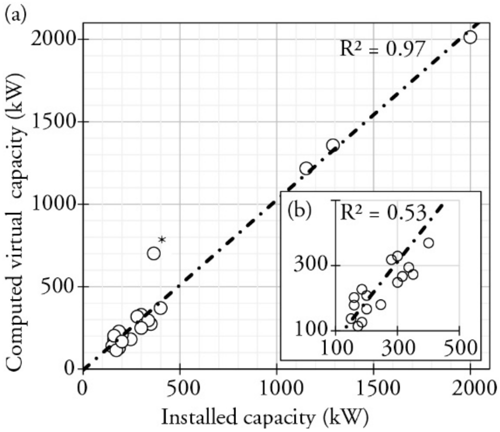

**Figure 5**. Goodness-of-fit plot for the virtual and installed SHP capacities for larger Estonian hydropower plants, outlier Keila River is marked with an asterisk (III).

The goodness-of-fit of the proposed model is shown in Figure 5a. The fitted linear regression with an $R^2$ value of 0.97 and slope of 1 demonstrated no overall significant difference between the installed and computed virtual capacities. Furthermore, visual inspection revealed no systematic over- or underestimation, excluding one outlier (marked with an asterisk) in the Keila River.

Figure 5b shows a weaker correlation of 0.53 between the computed virtual capacities and the installed capacities of the mini SHPs with a range narrower than 0.5 MW. This result was expected, as social, environmental, and other location specific limitations have a greater effect on the design, than they would on larger hydropower schemes. Additionally, the proposed model does not directly consider the hydropower turbine type, generator efficiency, and penstock head losses.

In-depth analysis was conducted to estimate the sizing and siting accuracy. The results of applying the proposed VHA method on the Jägala, Keila, and Valgejõe Rivers are shown in Figure 6. The dash-dotted bar corresponds to the installed capacity (kW) of the plants, while the solid bars indicate the computed virtual capacity of the river. These North-Estonian rivers flow to the Baltic Sea. The hydropower potential was relatively small in the upper reaches of the rivers, owing to the low flow rate, and thus, figure 6 presents the results only for the first 35 km from the river mouth.

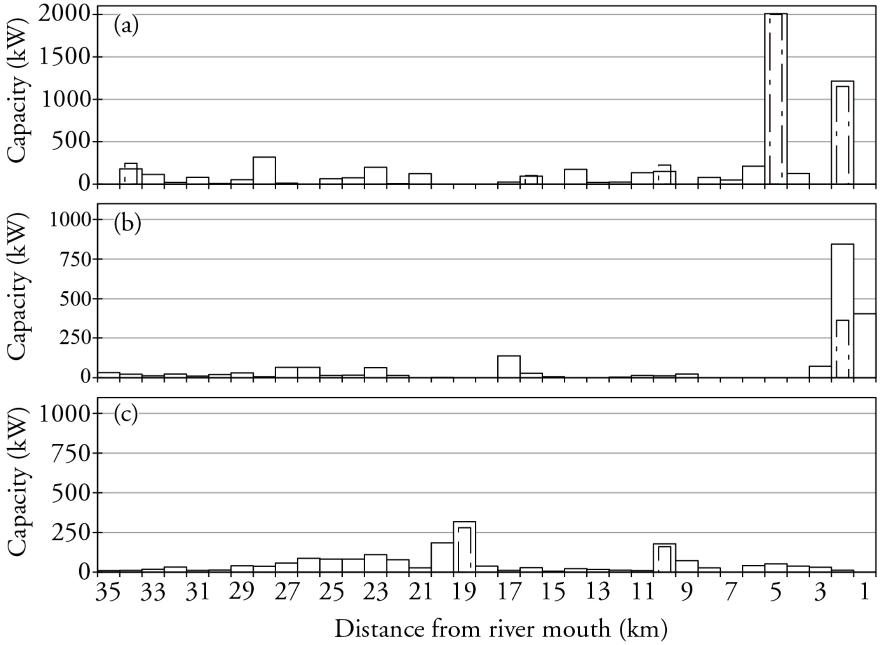

**Figure 6**. Results of the VHA method, including the computed virtual hydropower station locations and capacities compared to installed plants (dash-dotted line) in three Estonian rivers: a) Jägala, b) Keila, and c) Valgejõe (**III**).

Five SHPs have been installed along the Jägala River (Figure 6a), which were used to assess the sizing and siting accuracy. Approximately half of the river segments have a relatively low hydropower potential, only allowing the generation of micro- or pico-hydropower with low economic feasibility. The computed virtual capacities corresponded well with the installed capacities in all cases, and the siting was consistent with the SHP locations. The unutilized hydropower locations with capacities above 100 kW were identified.

The major hydropower potential of the Keila River is located near the river's mouth (Figure 6b). This was significantly different from the other rivers, where most of the suitable locations for hydropower production have already been occupied. The only currently operating SHP in the Keila River has an installed capacity of 365 kW, which is over twofold lower than the computed virtual capacity. Additionally, the VHA method identified unutilized potential hydropower sites at the river mouth that possessed a similar capacity as the operating station. Close to the mouths of the Jägala and Keila Rivers, the river valleys cut into the Baltic Klint, yielding a higher net head. More suitable locations for hydropower production were found in the middle reaches of the Valgejõe River. The optimal locations for hydropower production identified by the VHA method were in good accordance with the already installed SHP locations (Figure 6c). The sizing of the virtual capacities was also efficient, as the differences between the virtual and installed capacities were negligible.

### 5.2. Estimation of the current technical hydropower potential in Estonia with the VHA method

The verified VHA method was applied to Estonia to evaluate the technical hydropower potential in Estonian river basin districts (RBD). Estonia is divided into three river basin districts: West Estonian, East Estonian and, Koiva RBD (Figure 7). Two of these RBDs, East Estonia and Koiva, share borders with Russia and Latvia, respectively. The VHA method for estimating hydropower potential included rivers in Estonia, with a length exceeding 25 km (excluding the Narva River). The rivers were divided into equal segments with a user-defined distance of 500 m, where a VHPS was located. The locations of the generated VPHSs are shown in Figure 7.

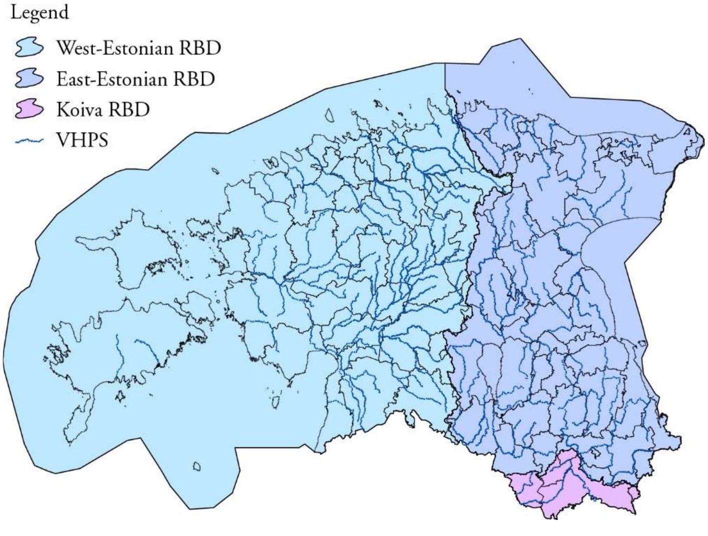

**Figure 7**. River basin districts in Estonia and the location of the generated VHPS.

According to the VHA methodology applied to Estonian rivers, the total technical hydropower potential in Estonia is approximately 80 MW (Table 3). The majority of this potential is derived from micro hydropower, with a total estimated capacity of 46.6 MW (when fully exploited). Approximately one-third of the total hydropower potential derives from mini hydropower, with a capacity of slightly less than 26 MW. The remaining potential is divided between pico (4.3 MW) and small (5.8 MW) hydropower. As can be seen from the results, the technical hydropower potential can significantly vary depending on the RBD investigated.

Among all Estonian RBDs, most of the technical hydropower potential (65%) is located in the West-Estonian RBD, where a significant portion of the currently installed hydropower stations are located. The combined micro and mini hydropower potential in the West-Estonian RBD amount to over 50% of Estonia's hydropower potential. According to the results, small hydropower (capacities exceeding 1000 kW) can only be harvested in the West-Estonian RBD. The VHA identified four potential locations for small hydropower production, of which three locations are already being utilized for hydropower generation. A potential new small hydropower plant can be installed in the Pärnu River, where no hydropower has been produced to date. Over 80 potential mini hydropower sites were identified, from which sixteen VHPSs had a computed capacity exceeding 250 kW.

**Table 3.** Estimated technical hydropower potential in Estonian RBDs.

| Type | Capacity | West-Estonian | East-Estonian | Koiva | Total (MW) |
|---|---|---|---|---|---|
| Pico | <5 kW | 2.1 | 2.1 | 0.1 | 4.3 |
| Micro | 5-100 kW | 26.9 | 17.8 | 1.7 | 46.6 |
| Mini | 100-1000 kW | 17.6 | 6.4 | 0.0 | 25.9 |
| Small | >1000 kW | 5.8 | 0.0 | 0.0 | 5.8 |
| Total (MW) | | 52.3 | 26.3 | 1.7 | 80.3 |

One-third of the total hydropower potential in Estonia could be technically generated in the East-Estonian RDB. Most of this potential derives from micro hydro (17.8 MW). The remaining East-Estonian RDB potential lies in mini and pico hydropower, with technical potentials of 6.4 MW and 2.1 MW, respectively. The largest VHPS in the East-Estonian RDB was identified on the Võhandu River, with a computed capacity of 435 kW. The VHA method detected 32 potential mini hydro locations, of which only four VHPSs had a computed capacity exceeding 250 kW.

No notable hydropower potential was detected in the Koiva RDB, with a total micro hydropower capacity of 1.7 MW. The largest VHPS was located on the Pärlijõgi River, with a potential capacity of approximately 80 kW. According to the results, only five potential micro hydro sites, with a computed capacity of over 50 kW, were found. This study did not assess hydropower potential in the Narva River, as it is influenced by Lake Peipus. This trans-boundary lake has a catchment area of 47 800 km$^2$, of which two thirds lies in Russia. Most of the hydropower resources in the Narva River are utilized by the Narva Hydropower Station (125 MW), operated by the Russian Federation.

### 5.3. SWAT model in Estonia (I and II)

The initial SWAT model consisted of default parameter values, which do not represent the hydrogeological processes in Estonia. Therefore, in order to obtain a more accurate hydrological simulation using the SWAT hydrological model, default parameters need to be calibrated and validated against measured flow data. For this, eighteen parameters were selected based on various research papers concerning sensitivity analysis and calibration studies. The selected initial and fitted parameter ranges for all the study basins are reported in Table 4.

The observed flow data were used to calibrate the SWAT model by the software SWAT-CUP, using the SUFI-2 (Sequential Uncertainty Fitting Procedure Version 2) algorithm (Abbaspour, 2008). River flow from every study basin was calibrated and validated against daily measured data from 1972 to 2010 (I) and 1970 to 2010 (II), thus using a continuous period of over 30 years. Calibration was performed using measured data from 1970/1972 to 1997, and validated with measured data from 1998 to 2010. Two-year flow data was set as the warm-up period.

**Table 4.** Summary of the parameters used for calibration and the fitted ranges over all the study basins (II).

| | Parameter [1] | Description and units | Initial parameter range | Fitted parameter range |
|---|---|---|---|---|
| Groundwater | v_GW_DELAY.gw | Groundwater delay time (days) | 0.5 … 4.0 | 1.31 ... 2.19 |
| | v_ALPHA_BF.gw | Base flow alpha factor (days) | 0.05 … 0.25 | 0.10 ... 0.18 |
| | v_GWQMN.gw | Threshold depth of water required in the shallow aquifer for return flow to occur (mm) | 0.01 … 15.0 | 2.38 ... 7.75 |
| | v_GW_REVAP.gw | Groundwater 'revap' coefficient | 0.02 … 0.20 | 0.07 ... 0.10 |
| | v__REVAPMN.gw | Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm) | 0.1 … 15 | 9.05 ... 14.55 |
| Surface | r_CN2.mgt | Initial SCS runoff curve number for moisture condition II | -0.15 … 0.15 | -0.05 … 0.18 |
| | v__SURLAG.bsn | Surface runoff lag coefficient | 0.05 … 0.15 | 0.06 ... 0.13 |
| | v_OV_N.hru | Manning's "n" value for overland flow | 0.1 … 0.4 | 0.14 ... 0.32 |
| | v_CH_N2.rte | Manning's 'n' value for the main channel | 0.02 … 0.1 | 0.03 ... 0.05 |
| | v_EPCO.hru | Plant uptake compensation factor | 0.5 … 1.0 | 0.37 … 0.72 |
| | v_ESCO.hru | Soil evaporation compensation factor | 0.5 … 1.0 | 0.74 … 0.98 |
| Soil | r_SOL_AWC.sol | Available water capacity of the soil layer (mm $H_2O$/mm) soil) | -0.2 … 0.2 | -0.32 … 0.42 |
| | r_SOL_K.sol | Saturated hydraulic conductivity (mm/h) | -0.2 … 0.2 | -0.05 ... 0.38 |
| | r_SOL_BD.sol | Moist bulk density (mg/$m^3$) | -0.2 … 0.2 | -0.19 … 0.16 |
| Snow | v_SFTMP.bsn | Snowfall temperature (°C) | -1.5 … 1.5 | -1.4 … -0.50 |
| | v__SMTMP.bsn | Snowmelt temperature (°C) | 0.0 … 2.0 | 0.11 … 0.85 |
| | v__SNOCOVMX.bsn | Minimum snow water content that corresponds to 100% snow cover (mm H2O) | 40 … 80 | 43.9 … 76.5 |
| | v__SNO50COV.bsn | Fraction of SNOCOVMX that corresponds to 50% snow cover | 0.4 … 0.7 | 0.44 … 0.64 |

Notes: [1] r_: parameter value is multiplied by (1 + a given value) or relative change; v_: parameter value is replaced by given value or absolute change.

The quantitative "goodness" of fit of the SWAT model between the daily measured and simulated flow during the calibration and validation periods, is presented in Table 5. The objective functions used with the SUFI2 algorithm for automatic calibration were the NSE (I) and KGE (I, II). The measured and simulated flows of all study basins corresponded well, and the average PBIAS for calibration was approximately 0.8%, presenting a marginal bias towards underestimation. Validation presented a similar magnitude of underestimation. Admittedly, no notable model over- or underestimation was detected, with all values being within the proposed acceptable range of 10%. The highest bias was detected in Kunda River basin (I), with an 8.5% underestimation during the validation. The amount of uncertainty involved in the modeling of Kunda was higher due to the unexpected behavior of the karst aquifer physical groundwater system. Relatively small fluctuations in PBIAS values implied that the water balance was adequately modeled, which is one of the prerequisites for a future impact evaluation.

**Table 5.** Calibration and validation results for the study region (II).

| River - *Station* | Calibration (1970-1997) | | | Validation (1998-2010) | | |
|---|---|---|---|---|---|---|
| | NSE | KGE | PBIAS | NSE | KGE | PBIAS |
| Kasari - *Kasari* | 0.73 | 0.79 | 5.4% | 0.70 | 0.81 | -2.3% |
| Pärnu - *Oore* | 0.80 | 0.90 | -0.7% | 0.75 | 0.87 | 2.6% |
| Pärnu - *Tahkuse* | 0.76 | 0.86 | 2.9% | 0.71 | 0.80 | 8.7% |
| Vihterpalu - *Vihterpalu* | 0.77 | 0.86 | 2.4% | 0.74 | 0.86 | -3.6% |
| Keila - *Keila* | 0.74 | 0.86 | 1.5% | 0.73 | 0.85 | -2.7% |
| Jägala - *Kehra* | 0.79 | 0.89 | -4.4% | 0.74 | 0.86 | 1.8% |
| Valgejõgi - *Vanaküla* | 0.77 | 0.89 | -1.5% | 0.71 | 0.85 | 4.3% |
| Average | 0.77 | 0.86 | 0.8% | 0.73 | 0.84 | 1.2% |

As can be seen in Figure 8, the SWAT model underestimated certain peak flows during the calibration and validation periods. This can be partly explained by the spatial variability of precipitation, particularly, rainfall may fluctuate in intensity at the locations of the rain gauges, introducing uncertainty in the total estimate of precipitation, and thus, in the model calibration. This is expected, however, as SWAT is not designed to simulate a single extreme event, and the model usually underestimates the largest flow events (Tolson and Shoemaker, 2004). A similar tendency was observed in this study. This underestimation, nevertheless, does not significantly affect hydropower harvesting in the current study because peak flows exceed the maximum flowrate of the turbines in the study basins.

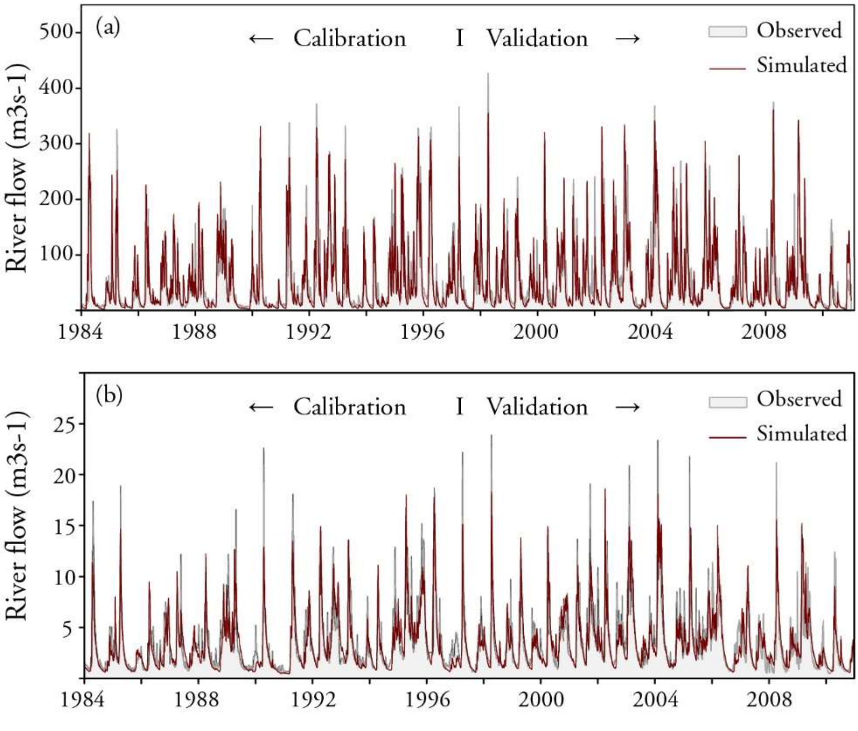

**Figure 8**. Observed and simulated daily flow hydrograph at (a) Pärnu river [Oore], (b) Valgejõgi [Vanaküla] in the period 1984–2010 (**II**).

The calibrated parameter set was transferred to ArcSWAT by updating the .mdb databases with Structured Query Language (SQL) sentences. HRU analysis was performed, after which the SWAT input files were rewritten and the model was re-executed. Meticulous attention was paid to snow processes during model creation, owing to the importance of snowmelt extent and its timing in achieving a representative hydrological model of the study basins.

## 5.4. Bias correction of climate model projections (I and II)

Regional scenarios for future climate were applied using the SWAT model to assess the impacts of future climate change on Estonian water resources. This study used two modeling studies from the EURO-CORDEX high-resolution simulations: the RACMO model with boundaries from EC-EARTH r1i1p1 ensemble member from the Netherlands (Meijgaard et al., 2008) and the HIRHAM5 model with boundaries from the EC-EARTH r3i1p1 ensemble member from Denmark (Christensen et al., 2007). The RCP 4.5 scenario was applied for both.

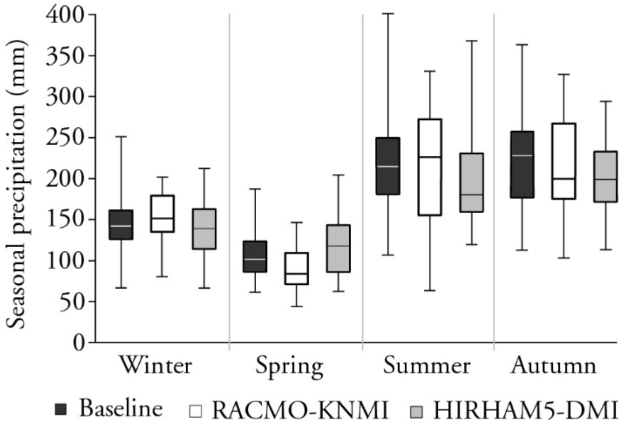

**Figure 9**. Box plot showing the ability of the bias-corrected RCMs (RACMO-KNMI and HIRHAM5-DMI) to simulate the seasonal precipitation of the (1971–2000) baseline period (**I**).

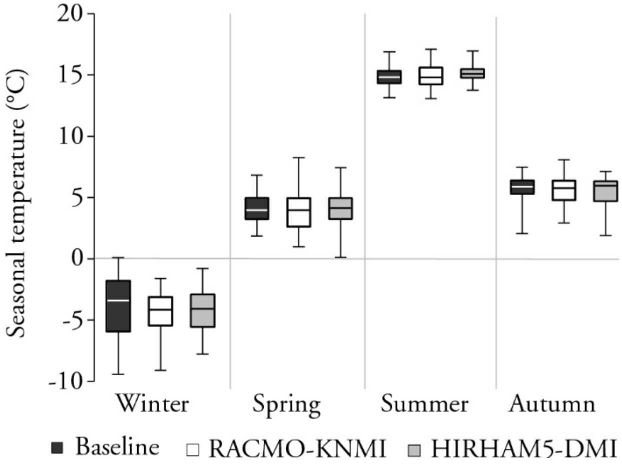

**Figure 10**. Box plot showing the ability of the bias-corrected RCMs (RACMO-KNMI and HIRHAM5-DMI) to simulate the seasonal temperature of the (1971–2000) baseline period (**I**).

Both selected initial climate projections presented cold biases on a year-round basis. A larger bias was detected during the spring and summer periods; approximately -2 °C according to the RACMO-KNMI model and -3 °C according to the HIRLAM5-DMI. For the rest of the period, the cold biases were less than -1 °C. Bias correction was also necessary for daily precipitation data. The precipitation amounts in RACMO-KNMI were overestimated in winter and spring, whereas in HIRLAM5-DMI, the precipitation was overestimated during winter months and underestimated during summer months. In terms of average annual precipitation, a clear overestimation of approximately 100 mm was present in the RACMO-DMI model. A tendency to overestimate the frequency of low-intensity rain events was encountered in both RCMs.

Bias correction was performed to provide a more accurate representation of the climate. Near-surface air temperature was modified via monthly additive correction, and the LOCI method was applied for precipitation. The LOCI method improved the possible positive bias towards wet-day frequencies, thus reducing excessive drizzly days and improving the overall hydrological representativeness of the model. Both bias correction methods were used for their simplicity, as no "superior" bias correction method is available. Bias-corrected precipitation and temperature projections for the baseline period 1971–2000 are shown in Figure 9 and Figure 10, respectively. The modeled climate bias behavior was assumed to remain unchanged with time. The abovementioned bias correction methods were applied for future climate, which served as input data for the SWAT model to assess possible changes in future water resources.

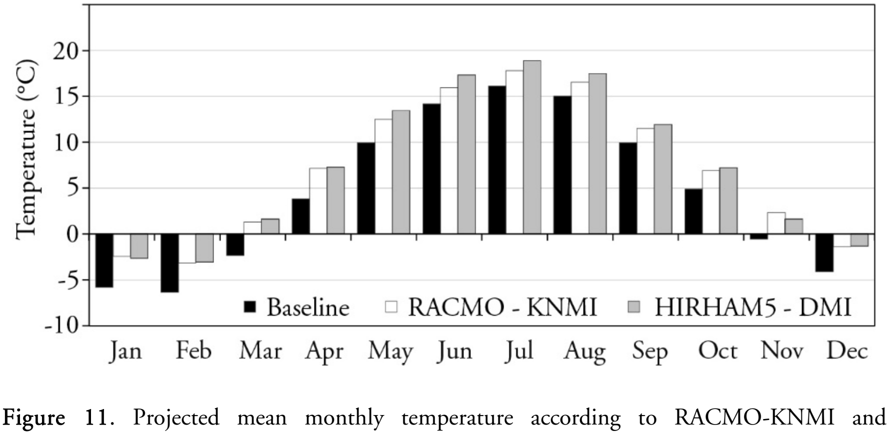

**Figure 11.** Projected mean monthly temperature according to RACMO-KNMI and HIRHAM5-DMI climate models for the 2071–2100 period, compared with the baseline period 1971–2000 (I).

According to the output of the climate model projections, it was estimated that the average temperature will increase by 1.9 °C (KNMI) and 2.5 °C (DMI) by 2100, compared with the baseline period. The projected mean monthly temperature for Estonia is summarized in Figure 11. The most notable increase in temperature is likely to occur during the winter months, where monthly average temperatures of approximately 5 °C higher were projected. No relevant changes in the average temperatures were projected during summer months, according to both climate projections.

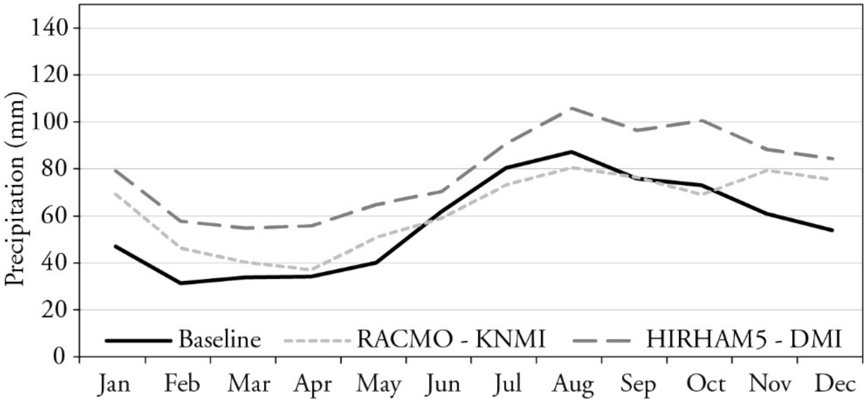

**Figure 12**. Projected mean monthly precipitation according to the RACMO-KNMI and HIRHAM5-DMI climate models for the 2071–2100 compared with the baseline period 1971–2000 (**I**).

The DMI model predicted an overall 30% increase in precipitation (Figure 12), which potentially implies higher flows throughout the year. The KNMI model predicted an overall 10% increase in precipitation, except for the summer months, where a slight reduction in monthly precipitation is expected, suggesting a reduction in summer flows.

## 5.5. Impact of climate change on water resources (I and II)

A comprehensive climate change impact analysis on hydropower potential was estimated in **Paper I** for three rivers in North-Estonia: Keila, Kunda, and Valgejõe, where SHPs are installed. Physical and technical parameters of the studied hydropower plants and water permits limitations were considered (Table 6). Hydropower plants in Estonia are required to guarantee a minimal residual flow (e.g., through the spillway), namely, water cannot be extracted while river the flow is lower than the minimal residual flow. The upper threshold for energy generation is limited by the maximum flow rate of the turbine, and thus, the available water for energy generation ranges between the maximum flow rate of the turbine and the available water for consumption.

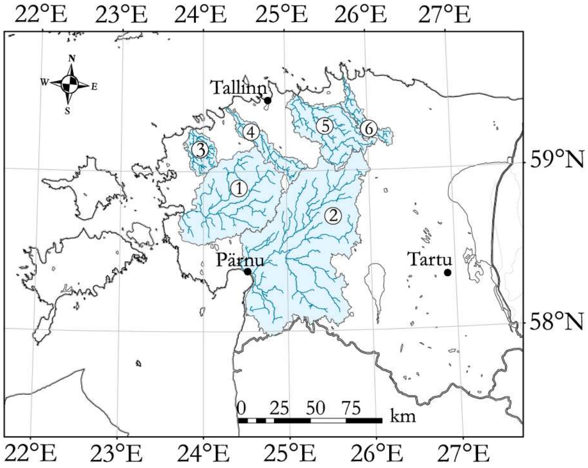

**Figure 13**. Geographical location of the West-Estonian basin district in Estonia (1-Kasari, 2-Pärnu, 3- Vihterpalu, 4-Keila, 5-Jägala and 6-Valgejõgi) (**II**).

Regarding the efficiency reasons of the Kaplan turbine peculiarity, flow rates exceeding 30% of the turbine's maximum flow rate is extracted by the turbine for energy generation.

**Table 6**. Physical and technical characteristics of the studied hydropower plants (**I**).

| Basin | SHP name | Area ($km^2$) | Capacity (kW) | H (m) | Hydrometrical station | Residual flow ($m^3/s$) |
|---|---|---|---|---|---|---|
| Keila | Keila Joa | 678 | 365 | 6.2 | Keila | 0.64 |
| Valgejõe | Nõmmeveski | 405 | 370 | 8.6 | Vanaküla | 0.76 |
| Kunda | Kunda | 492 | 336 | 6.4 | Sämi | 1.44 |

The simulation results of the SWAT hydrological model indicated a positive change in river flow according to both climate scenarios. Increases in the mean annual flow of 15% and 55% were predicted by the climate projections KNMI and DMI, respectively (Table 7). The spring peak in the study basins tended to occur earlier, and was smaller compared to the baseline period. This pattern was more pronounced in the DMI climate projection, resulting from an increase in precipitation

(Figure 12) and less winter-snow accumulation. A notable increase in autumn discharge was indicated by the same model.

**Table 7**. Projected changes in flow and hydropower (I).

| Hydroclimate | Baseline | Change (%) | |
|---|---|---|---|
| | | KNMI | DMI |
| *Keila River at Keila-Joa* | | | |
| Mean annual flow | 6.8 $m^3/s$ | 10.0 | 54.2 |
| Mean winter hydropower | 305 kW | 25.6 | 34.3 |
| Mean spring hydropower | 332 kW | 7.7 | 19.6 |
| Mean summer hydropower | 99 kW | 40.4 | 68.6 |
| Mean autumn hydropower | 237 kW | 8.2 | 39.9 |
| Mean annual hydropower | 243 kW | 16.8 | 34.1 |
| *Kunda River at Kunda Silla* | | | |
| Mean annual flow | 5.2 $m^3/s$ | 21.5 | 57.5 |
| Mean winter hydropower | 127 kW | 63.7 | 109.2 |
| Mean spring hydropower | 218 kW | 26.4 | 24.5 |
| Mean summer hydropower | 73 kW | 11.3 | 9.4 |
| Mean autumn hydropower | 118 kW | 21.3 | 24.5 |
| Mean annual hydropower | 134 kW | 32.1 | 42.6 |
| *Valgejõe River at Nõmmeveski* | | | |
| Mean annual flow | 3.4 $m^3/s$ | 18.5 | 52.8 |
| Mean winter hydropower | 134 kW | 69.6 | 122.3 |
| Mean spring hydropower | 218 kW | 10.3 | 22.6 |
| Mean summer hydropower | 72 kW | 32.0 | 42.7 |
| Mean autumn hydropower | 138 kW | 5.3 | 57.4 |
| Mean annual hydropower | 141 kW | 26.0 | 57.4 |

The coherence between the changes in annual flow and hydropower potential was evident, with some exceptions. Flowrates exceeding the installed hydro plants capacities cannot be exploited for hydropower harvesting, i.e. peak flow cannot be harvested for hydropower production. This limitation was particularly apparent for the Keila River

SHP, where hydropower potential was predicted to rise by 17% and 34% according to the KNMI and DMI climate projections, respectively (Table 7). The projected changes in hydropower potential were notably higher in Kunda and Valgejõe. The Kunda SHP presented a lower increase in hydropower potential during the summer months, compared with the Keila and Valgejõe SHPs. The amount of uncertainty involved in the modeling of Kunda is higher, due to the unexpected behavior of the karst groundwater system. Generally, a notable increase in winter hydropower potential was identified in the SHPs where the installed capacity was unutilized.

A wider study involving six rivers in the West-Estonian basin (Figure 13) was conducted in **Paper II** to investigate the overall effects of climate change on Estonian water resources. In order to assess the impact of climate change on river flow, two scenarios were generated; scenarios 3 and 6, which represented the regional climate model projections from the KNMI and DMI models, respectively. The modeled monthly changes in river flow due to climate change (DMI and KNMI RCMs) for the 2071–2100 period are illustrated in Figure 14.

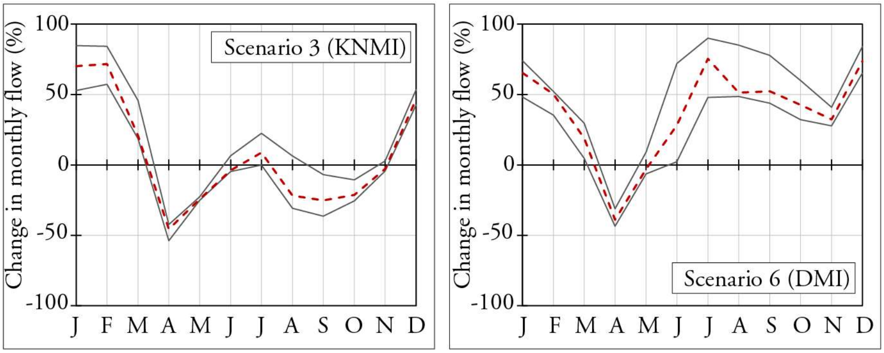

**Figure 14.** Effect of climate change scenario 3 (KNMI) and scenario 6 (DMI) on river monthly flow among the study basins (dashed line corresponds to median modeled change) (II).

According to the KNMI and DMI models, yearly flow was expected to increase among all study basins by approximately 10% and 26%, respectively. Both climate models predicted a notable decrease in April (40–50%), corresponding to the typical yearly peak flow from snowmelt. The third similarity among scenarios was the approximately 50–70% increase in winter flow. A notable disagreement in summer and autumn flows were evident between scenarios 3 and 6. Scenario 3 (KNMI) predicted a decrease in flow for the summer and autumn months, whereas scenario 6 (DMI) predicted a notable increase in the flow of approximately 40–80%. The signals from both climate models were thus unclear during these periods and represent uncertainties in future climate interpretations.

### 5.6. Impact of land-use change on water resources (II)

The generated static land-use change scenario maps L1 and L2 (Figure 15) were inserted into the calibrated SWAT model to simulate the effects of deforestation and afforestation on river flow in the study rivers.

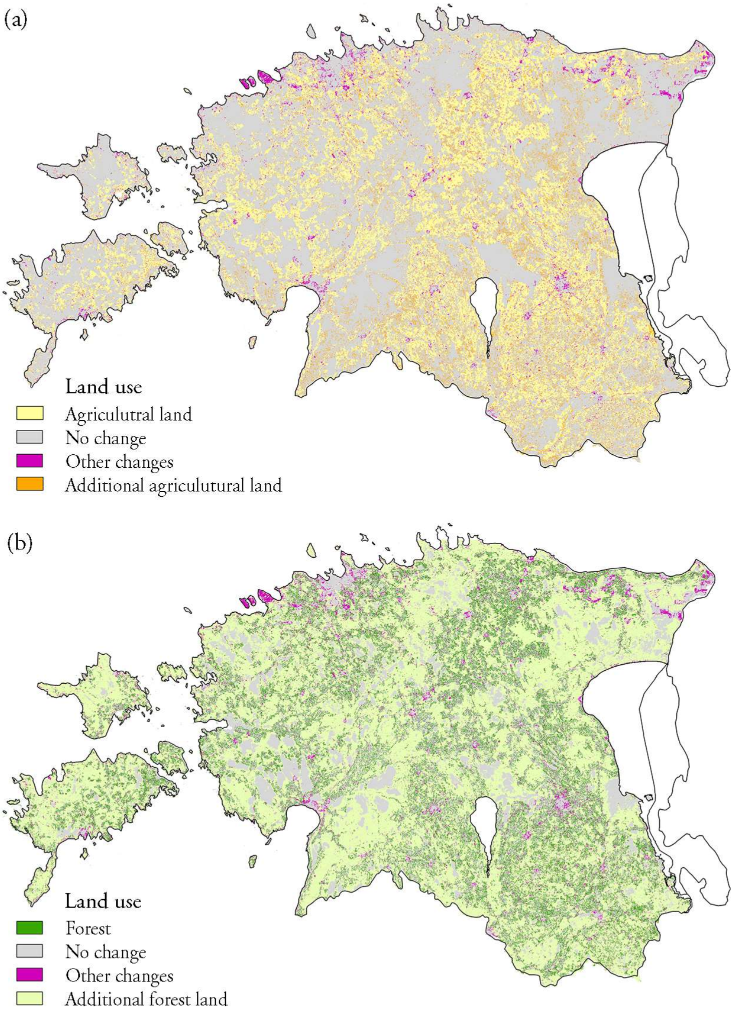

**Figure 15.** Spatial pattern changes in land use between the baseline (L0) (1971–2000) and the future period (2071–2100) under (a) the deforestation land use scenario L1 and (b) the afforestation land use scenario L2 (**II**).

In land use scenario L1 deforestation was stimulated by the demand for additional agricultural land, which was estimated to increase approximately by 20%. The afforestation scenario L2 presented an average forest land cover increase of 25%. Urban areas were predicted to significantly expand (around 50%) in the future, whereas both land-use scenarios predicted a decrease in grassland (Table 8).

**Table 8**. Characteristics of land-use change scenarios in the studied watersheds (II).

| Watershed | Scenario | Forest (mature) | Forest (young) | Cropland | Grassland | Orchard | Water | Urban | Wetlands |
|---|---|---|---|---|---|---|---|---|---|
| Jägala<br>(Kehra)<br>903 km$^2$ | L0 (km$^2$) | 396.1 | 91.6 | 214.6 | 59.9 | 9.9 | 24.6 | 21.1 | 85.1 |
| | L1 (change in %) | -29.0 | 77.1 | 22.8 | -32.6 | 43.0 | - | 51.3 | - |
| | L2 (change in %) | 1.4 | 110.9 | -51.2 | -20.1 | 43.0 | - | 51.3 | - |
| Kasari<br>(Kasari)<br>3213 km$^2$ | L0 (km$^2$) | 1314 | 311.6 | 817.4 | 217.3 | 34.6 | 95.8 | 61.2 | 339.5 |
| | L1 (change in %) | -26.3 | 83.3 | 15.0 | -34.4 | 22.2 | - | 49.1 | - |
| | L2 (change in %) | 3.6 | 117.3 | -49.8 | -20.1 | 22.2 | - | 49.1 | - |
| Keila<br>(Keila)<br>635 km$^2$ | L0 (km$^2$) | 204.8 | 46.4 | 206.3 | 63.1 | 20.4 | 15.0 | 22.3 | 56.7 |
| | L1 (change in %) | -26.1 | 52.3 | 16.0 | -42.8 | 30.3 | - | 76.9 | - |
| | L2 (change in %) | 23.9 | 111.8 | -50.6 | -30.9 | 30.3 | - | 76.9 | - |
| Pärnu<br>(Oore)<br>5160 km$^2$ | L0 (km$^2$) | 2135 | 632.4 | 1257 | 333.7 | 64.9 | 180.9 | 109.6 | 444.3 |
| | L1 (change in %) | -21.3 | 18.7 | 28.9 | -30.1 | 14.1 | - | 59.0 | - |
| | L2 (change in %) | 11.6 | 46.2 | -44.7 | -16.0 | 14.1 | - | 59.0 | - |
| Pärnu<br>(Tahkuse)<br>2080 km$^2$ | L0 (km$^2$) | 827.9 | 235.6 | 646.9 | 117.5 | 23.0 | 64.9 | 45.1 | 119.1 |
| | L1 (change in %) | -25.2 | 33.3 | 20.9 | -33.3 | 27.2 | - | 62.6 | - |
| | L2 (change in %) | 12.2 | 67.2 | -43.1 | -12.3 | 27.2 | - | 62.6 | - |
| Valgejõgi<br>(Vanaküla)<br>404 km$^2$ | L0 (km$^2$) | 180.4 | 39.3 | 85.6 | 29.9 | 3.9 | 7.0 | 11.8 | 46.1 |
| | L1 (change in %) | -15.9 | 26.1 | 22.5 | -30.7 | 48.3 | - | 54.1 | - |
| | L2 (change in %) | 11.9 | 58.0 | -54.8 | -18.7 | 48.3 | - | 54.1 | - |
| Vihterpalu<br>(Vihterpalu)<br>474 km$^2$ | L0 (km$^2$) | 231.8 | 51.6 | 51.4 | 20.0 | 2.2 | 13.5 | 6.1 | 97.4 |
| | L1 (change in %) | -25.5 | 99.1 | 18.8 | -26.7 | 34.2 | - | 51.4 | - |
| | L2 (change in %) | -12.5 | 112.0 | -57.3 | -14.9 | 34.2 | - | 51.4 | - |

According to scenario 1, the possible changes in flow were relatively insignificant, as the annual average flow was expected to increase by approximately 1.3% (Figure 16). The median flow was expected to increase by a maximum of 4% in the second half of the year. In the first half of the year, the effect of deforestation on river flow was practically non-existent. As can be seen from Table 8, the reason for this was the relatively small share of land for deforestation, with an average of -8.8%, whereas the scale of afforestation was significantly larger (up to 40%).

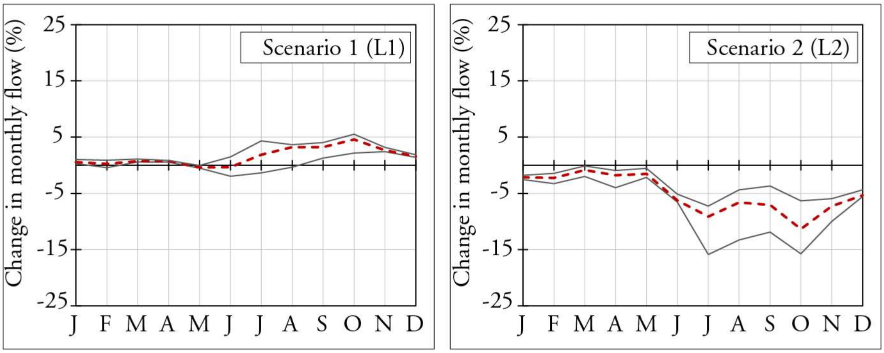

**Figure 166.** Effect of deforestation (scenario 1, L1) and afforestation (scenario 2, L2) on river monthly flow among the study basins (dashed line corresponds the median modeled change) (II).

Scenario 2 was characterized as the afforestation scenario, with a projected average increase in forest area of approximately 25%. The effect of afforestation on river flow was more pronounced than that of deforestation. This was particularly prominent in the Keila River basin, where the baseline forest cover was initially slightly below 40%, but notably increased to 55% (Table 8). The increased forest land could potentially decrease the average annual river runoff by over 7% (Keila River), whereas the average decrease over all basins remained around 4.5%. In summary, the afforestation extent exceeded deforestation and affected river flow more, according to the generated land-use maps. Furthermore, according to Figure 16, the magnitude of the deforestation effect was marginal and was not further analyzed in scenarios 4 and 7 (the combined effects of deforestation and climate change).

The effects of deforestation and afforestation on yearly river flow in the West-Estonian basin district are shown in Figure 17. The effect of forest change on river flow can be summarized as follows: a 5% forest change induces a 1% change in annual average flow. An evident linear trend between these two parameters can be observed ($R^2$=0.97) (Figure 17). Changes in annual flow were more influenced in the afforestation scenario (L2) and during the warm period, whereas the effect was comparably weak in the deforestation scenario (L1) and during the cold period.

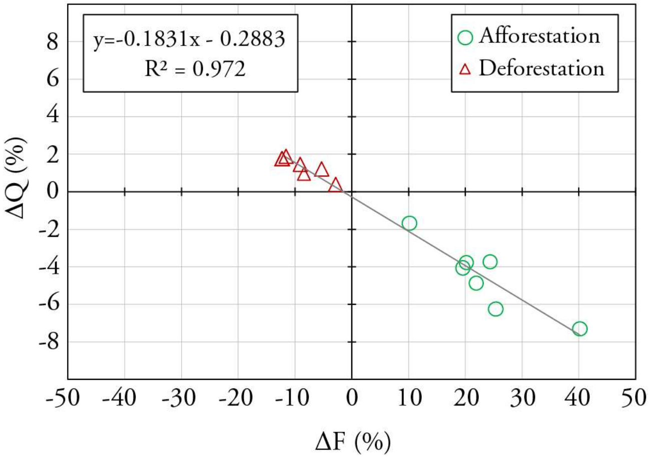

**Figure 17.** Relationship between forest (ΔF) cover- and annual flow (ΔQ) change in the studied basins (II).

## 5.7. Combined effects of land-use and climate change on water resources (II)

Considering the combined impacts of climate and land-use change, the average annual flow of the West-Estonian basin district is expected to increase in the future. The effects of deforestation (Scenarios 4 and 7) were not further investigated due to their marginal impact on flow. When climate change was considered together with land-use change (afforestation), the latter's impact on flow was not as pronounced as the former's. Afforestation induced an average reduction of annual flow by 5%, whereas climate change caused an annual increase of 10-33%, according to the KNMI and DMI climate model projections, respectively. The monthly interquartile range of flow change in scenarios 5 and 8 considerably narrowed when the generated deforestation map L2 was applied with RCMs (Figure 18).

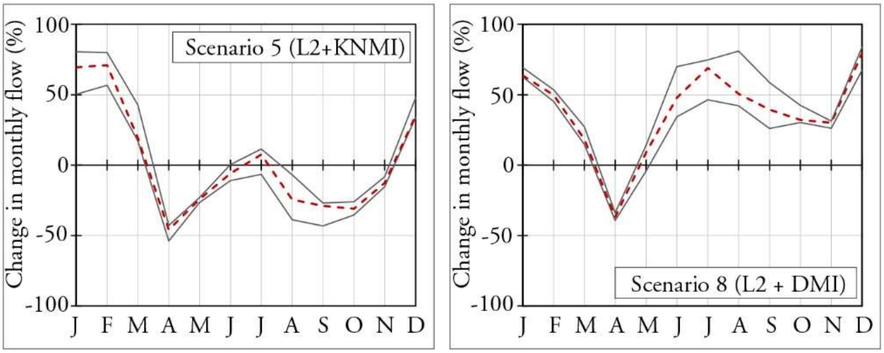

**Figure 18**. Effect of climate and land-use change, scenarios 5 (KNMI RCM and afforestation) and scenario 8 (DMI RCM and afforestation), on monthly river flow among the study basins (dashed line corresponds to the median change, solid lines present the interquartile range) (**II**).

This is especially true for Scenario 8, where the modeled monthly runoff impact “difference” between study basins on winter and spring flows is small (< 10%). Possible changes in the future runoff for the summer and autumn months are unclear. While Scenario 5 shows a decrease (around 20%), Scenario 8 predicts a large increase (around 50%). These differences are inherited from the climate change scenarios, the impact of afforestation is secondary.

# 6. DISCUSSION

The VHA method was developed to estimate the accuracy of SHP sizing and siting using GIS. Verification through location-specific installed capacities enabled the evaluation of separate uncertainties originating from the input data quality, including the resolution of the DEM and the hydrological component. With the developed VHA method, the process of sizing SHPs and identifying new unutilized locations for hydropower harvesting in any given river became reliable and automated, while requiring a minimal amount of input data.

Assessing the technical hydropower potential at any location along a river requires a hydrological component. The use of measured discharge data is rarely available along the entire river length, and therefore, various techniques are used for estimating the hydrological component data (Punys et al., 2011). River discharge can be estimated using rainfall and evaporation distribution maps (Bayazıt et al., 2017). These estimations, however, are rarely precise enough to provide accurate input information for SHP sizing. A more reliable assessment of water resources requires complex hydrological modeling (De Vos et al., 2010; Kusre et al., 2010; Latkovska et al., 2012). These models require diverse information as input data. The proposed VHA method used the annual specific discharge map as the hydrological component, which is simple to construct and only uses the gauged data of the region of interest, thus requiring a moderate amount of data.

Verification of the VHA methodology revealed an excellent overall linear fit between the virtual and installed capacities; however, the accuracy for smaller plants was lower compared with for SHP plants with a capacity exceeding 1 MW. This result was partially expected, because for smaller capacities, the importance of the input data quality and site-specific factors (turbine selection, penstock length etc.) increases. Apart from being reliable, this method has the ability to efficiently assess the technical hydropower potential on river segments along the entire river. If the capacity of the SHP presents sufficient interest, then an optimizing process can be carried out for further analysis (Hosseini et al., 2005). Low-head sites possess the greatest potential for expanding the SHP (Paish, 2002), thus demonstrating the rationale for the development of accurate assessment tools.

The verified VHA method was applied to assess the technically feasible hydropower potential in Estonia, which was estimated, excluding the Narva River, to be approximately 80 MW; considerably higher than that previously reported 30 MW (Raesaar, 2005). The previous assessment methodology was not been described, and therefore, cannot be replicated, rendering the differences between the estimates unclear. However, it should be noted that the previous estimation was carried out when spatial analytical capabilities of GIS were unavailable.

Climate-related uncertainties should be carefully considered to assess the global and regional trends that alter the hydropower potential. The integration of land-use and climate change models within a hydrological model like SWAT can improve the prediction efficiency of future hydrologic response. Using a combination of both models provides even more realistic simulation of the processes taking place within the system. The hydrological model provided insight on the relative importance of land use versus climate change effects on river flow.

Snow-melt dominated regions in North-Europe are expected to receive increased flow during winter and lower flow in the spring (Arheimer and Lindström, 2015; Donnelly et al., 2017). These findings are consistent with those of the current study. The effect of climate change on spring flow is evident, whereas the impact of land-use change is marginal. This stems from the projected increase in temperature, which translates to a shorter snow season and less snow accumulation during winter; however, no clear agreement exists among the climate scenarios and how the autumn flow will be affected in Estonian rivers.

Different climate change studies have analyzed certain aspects of nature by using different input data quality, methods, and assumptions, thus hindering the straightforward comparison of their results. Karlsson et al. (2016) evaluated the sensitivity of the results to the choice of hydrological model. Although hydrological models demonstrated similar performance during calibration, the mean flow response to climate change may significantly vary (up to 30% among the hydrological models used). Even with such variations, the choice of climate model was determined to be the dominant factor influencing the mean flow projection at the end of the century.

Piniewski et al. (2017) evaluated the robustness (Knutti and Sedláček, 2013) of the climate change signal in an ensemble of nine bias-corrected

EURO-CORDEX simulations over two large basins in Poland, which drain to the Baltic Sea. It was discovered that although the investigated climate models agreed on the sign of precipitation change, the annual total precipitation projections were insufficiently robust (low signal-to-noise ratio). Depending on the climate model used, the change in seasonal precipitation varied substantially. According to their study, the seasonal precipitation in the RCP 4.5 scenario was more robust than the RCP 8.5.

Future hydrological simulations should further combine the impacts of climate change with land-use change, as they could considerably influence the future river flow (El-Khoury et al., 2015). The magnitude of impact that land-use change has on runoff, varies. Theoretically, an increase in the forest area cover will lead to a higher water holding capacity in the basin area, and vice versa. The effect of deforestation on river flow was analyzed in a small (97 km$^2$) Slovakian basin (Hlásny et al., 2015). Deforestation induced an increase in the total flow by approximately 20%. The effects of land-use change on flow can have the same significance as climate change (Tong et al., 2012). In the current study, a 5% increase in forest land caused a 1% reduction in annual flow, indicating a strong linear correlation. Changes in annual runoff were further influenced from increasing forested land (L2) during the warm period, whereas deforestation (L1) did not have a significant effect during the cold period.

The land-use representation in a hydrological model can either be static or dynamic. In the current study, static "averaged" land-use map was used for the whole baseline period of 30 years, due to the lack of dynamic maps for this period. In order to achieve a better comparison with the future, static "averaged" land-use change scenario maps L1 and L2 were implemented in SWAT. The static map approach provides a relatively good approximation of the hydrological impacts, if linear land-use change are assumed (Wagner et al., 2017). In the Baltics, however, land-use changes have been driven by political decisions, and thus have a rapid and unpredictable nature. As changes have been stochastic, this study assumed a straightforward linear development of land-use change. The importance of dynamic land-use changes should not be neglected (Castillo et al., 2014; Wagner and Waske, 2016).

The abovementioned results emphasize the importance of applying climate change models in conjunction with land-use models. Although climate change is the prominent force inducing changes in the flow regime, land-use change scenarios should be considered as well in future impact studies. This study highlighted, that high flow periods could be efficiently exploited by increasing the number of turbines at SHPs, i.e. increasing the installed capacity. Furthermore, since analysis assessed the current technically feasible hydropower potential to be notably higher compared with the results of previous studies, hydropower should be considered in addressing the national renewable energy targets set in Estonia.

# 7. CONCLUSIONS

Hydropower is expected to play an important role in satisfying the increasing global demand for energy. As the EU is gradually abandoning fossil fuels and moving towards RESs, Estonia is obligated to follow this course. Accurate assessment of current and future RESs is essential for developing Estonia's future energy portfolio. A reliable VHA method was developed to aid the sizing and siting of SHPs to exploit the technical hydropower potential. The proposed VHA method was automated in GIS, and only required a DEM and the gauged river flow as input data. A synthetic river network with topographic attributes was directly derived from the DEM. The generated rivers were divided into equal user-defined segments starting from the river outlet. VHPS were located at the end of each segment. River flow was used to generate the SDM that was used to distribute average specific discharge value to each VHPS. The virtual hydropower plant capacity was computed from the attributed flow and net head, which was multiplied with the overall system efficiency (i.e., 75%) for each VHPS. The developed approach was implemented for Estonia, where data from twenty currently operating or abandoned SHPs in thirteen rivers were used for method verification. The VHA method was able to produce a realistic output for SHP siting and sizing, highlighting unexploited opportunities to install micro- and mini-hydropower plants in the analyzed rivers.

Based on the validity of the method, the technical hydropower potential was assessed for the territory of Estonia (excluding the Narva River). The total technically feasible hydropower potential in Estonia was calculated to be approximately 80 MW, which was considerably higher than that previously reported 30 MW (Raesaar, 2005). This hydropower potential is unevenly distributed between RBDs in Estonia. Most of the hydropower potential lies in the West-Estonian RBD (52 MW). One third of the total hydropower potential in Estonia could be technically generated in the East-Estonian RDB (26 MW), whereas no notable hydropower potential was found in the Koiva RDB (2 MW). Therefore, the technically feasible hydropower potential in Estonia is significantly greater than previously estimated.

The SWAT model was applied to assess the potential impact of future climate and land-use change on river flow in Estonia. This study is the first to employ and advanced hydrological model of this caliber, in Estonian rivers. The model was calibrated and validated over a long period of over 40 years. The SWAT model demonstrated satisfactory performance with evaluation criteria values (NSE and KGE) exceeding 0.70 for all the river basins. The calibrated SWAT model was then used to estimate the effect of land-use change on water resources. For this, two hypothetical land-use change maps were generated for Estonia, and two climate change model projections were bias corrected and used.

According to the modeling results, the annual average flow, and thus, hydropower potential is expected to increase in Estonia by the end of the century, compared with the baseline period. Although the trend in hydropower potential is positive, the annual average flow response to climate change varies. Depending on the RCM applied, the hydropower potential is expected to increase between 10% and 50%. According to the KNMI RCM model, the effect of climate change on river flow is low, whereas the DMI model suggested high changes in river flows. The two RCMs were in good correspondence for the winter and spring periods, where notable changes were identified. However, the magnitude of the change during the summer and autumn periods varied significantly among the climate change scenarios.

Possible changes in land-use do not alter the monthly flow variation as substantially, as climate change. The following general rule can be applied to Estonia; a 5% forest cover reduction induces a 1% increase in annual flow. The impact of land-use change on flow is important on an annual scale in the study region. Interestingly, it was discovered that the combined effects of land-use and climate change were non-additive in the study. High-flow periods could be better exploited by increasing the number of turbines at SHPs.

The current study estimated the technical hydropower potential to be more than two-fold higher than that previously estimated. Thus, hydropower could contribute to current and future energy demands in Estonia. In general, these findings are beneficial to policy makers they contribute to a deeper understanding of natural and human influences on river flow, thus aiding the design of long-term strategies for forest management, and harnessing the positive impacts of overall increases in the river flow (e.g., increased hydropower potential). The installation of additional turbines, along with upgrading existing turbines, could increase the installed capacity. Furthermore, with the projected overall increase of hydropower potential in Estonia, the construction of new stations becomes more economically feasible and profitable.

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# SUMMARY IN ESTONIAN

## Maakasutuse ja kliimamuutuse mõju Eesti jõgede hüdroenergeetilisele potentsiaalile

### Sissejuhatus

Veeressursidega seonduvad küsimused on viimastel kümnenditel olnud ülemaailmselt üks huvipakkuvamaid temaatikaid teadlaste seas. Seda just seetõttu, et vee ajaline ja koguseline kättesaadavus on kliimamuutuse tõttu muutumas. Enamik teadlasi on veendunud, et kliimamuutuse üheks põhjuseks on inimtegevus, mille käigus paisatakse atmosfääri üha rohkem kasvuhoonegaase ning muudetakse oluliselt maakasutust. Sellised tegevused mõjutavad veeringet, mis omakorda muudab veeressursside ajalist ja koguselist jaotust veekogudes. Kliimamuutusest põhjustatud veeressursside ümberjaotus on globaalselt juba tõestust leidnud ning teadlased usuvad selle nähtuse mõju süvenemist ka tulevikus.

Üks muutuvaid veeressursikasutusi on veeenergia tootmine, sest hüdroelektrijaama (HEJ) tootlikkus sõltub otseselt jões voolava vee hulgast. Kui vooluhulga dünaamika jões muutub, muutub ka hüdroenergeetiline potentsiaal. Kuigi kliimamuutused seostuvad pigem negatiivsete mõjudega, võib hüdroenergeetiline potentsiaal mõnes piirkonnas hoopis suureneda, kui veebilanss positiivsemaks muutub. Kuna tegu on taastuvenergiaga, on hüdroenergia olulise tähtsusega just elektrienergia tootmises, aidates vähendada CO2 heitkoguseid.

Euroopa Liidu (EL) energiapoliitika üks põhisuundi on juba aastaid olnud energia säästmine ning taastuvatest allikatest toodetud energia osakaalu suurendamine, seades eesmärgiks kasvatada aastaks 2030 taastuvenergia osakaal 32 protsendini lõpptarbimisest. Kuigi selline osakaal on saavutatav, raskendab selle saavutamist elektrinõudluse pidev suurenemine. Euroopa Liidu liikmesriigina osaleb ühise energiapoliitika elluviimises ka Eesti. Riigisiseste meetmete kavandamiseks ja rakendamiseks on vaja teada, kui suur on Eesti taastuvenergiapotentsiaal ja kuidas see tulevikus muutuda võib.

Aastakümneid tagasi ilmunud Eesti Nõukogude Entsüklopeedias on Eesti jõgede (v.a Narva jõgi) tehniliselt rakendatavaks potentsiaaliks hinnatud 30 MW (Raesaar, 2005). Et hindamismetoodikat pole kirjeldatud, ei ole võimalik seda arvu kontrollida. Kliima- ja maakasutuse muutumine on mõjutanud ka Eesti jõgede hüdroenergeetilist potentsiaali. Nende muutuste jätkumine avaldab mõju ka hüdroenergia tootlikkusele, ent kui suuresti võib Eesti jõgede hüdroenergeetiline potentsiaal muutuda, on teadmata.

## Töö eesmärgid

Doktoritööl on kaks põhisuunda: 1) tuginedes geograafilistele informatsioonisüsteemidele (GIS) anda uus hinnang Eesti jõgede tehniliselt rakendatavale hüdroenergeetilisele potentsiaalile; 2) hüdroloogilise mudeli SWAT abil hinnata, kuidas kliima- ja maakasutuse muutus võib tulevikus mõjutada Eesti jõgede vooluhulkade jaotust ja suurust, sh hüdroenergeetilist potentsiaali.

Uurimistöö eesmärgid:

- anda uus hinnang Eesti jõgede tehniliselt rakendatavale hüdroenergeetilisele potentsiaalile;
- kalibreerides ja valideerides hüdroloogilise mudeli SWAT parameetreid hinnata selle mudeli kasutatavust Eesti jõgede hüdroenergeetilise potentsiaali määramisel;
- hüdroloogilise mudeli SWAT abil hinnata kliima- ja maakasutuse muutumise mõju Eesti jõgede vooluhulkadele;
- hinnata, kuidas vooluhulkade muutumine võib tulevikus mõjutada Eesti olemasolevate hüdroelektrijaamade tootlikkust ja üleüldist hüdroenergeetilist potentsiaali.

Doktoritöö eesmärkide saavutamiseks püstitati järgmised ülesanded:

- koostada SWAT-mudel Eesti suurema hüdroenergeetilise potentsiaaliga jõgedele (v.a Narva jõgi);
- koostatud mudeleid kalibreerides ja valideerides määrata neile jõgedele mudeli parameetrid;
- hinnata mudeli SWAT kasutatavust Eesti jõgedel, tuginedes nii kvalitatiivsetele kui ka kvantitatiivsetele hindamismeetoditele;
- tuletada meetod, mis võimaldab piisava täpsusega määrata hüdroenergia tootmise poolest soodsad jõeristlõiked ning arvutada võimalike veejõujaamade hüdroenergeetiline võimsus;
- valida kliimamudelid ja vajaduse korral teha nihkekorrektuur;

- koostada Eesti maakasutuse muutumise stsenaariumid;
- uurida nii maakasutuse kui ka kliima võimaliku muutumise nii eraldi kui ka kombineeritud mõju Eesti jõgede veeressurssidele.

## Materjal ja metoodika

Doktoritöö võtab kokku kolme artikli põhitulemused, milles käsitletakse põhjalikult hüdroenergia kasutamise muutumist Eestis. Doktoritöös antakse uus hinnang Eesti (v.a Narva jõe) tehnilisele hüdroenergeetilisele potentsiaalile, rakendades kolmandas artiklis (III) tuletatud meetodit. Analüüsitakse põhjalikult, kuidas jaguneb tehniline hüdroenergeetiline potentsiaal Eesti vesikondade vahel. Doktoritöös antakse ka hinnang, millise võimsusega hüdroelektrijaamu oleks võimalik Eesti vesikondadesse rajada.

Kolmandas artiklis (III) tuletatakse meetod tehnilise hüdroenergeetilise potentsiaali esialgseks hindamiseks väheste andmete põhjal. Meetodi täpsusele antakse nii kvalitatiivne kui ka kvantitatiivne hinnang, tuginedes nii varem töötanud kui ka praegu toimivate Eesti hüdroelektrijaamade paiknemisele ja võimsusele.

Artiklites I ja II keskenduti võimalike tulevikumuutuste mõju hindamisele Eesti jõgede vooluhulkadele. Selleks valiti kliimamudelid ning koostati maakasutuse tulevikustsenaariumid, mis sisendati hüdroloogilisse mudelisse SWAT. Eesti jõgede jaoks määrati mudeli parameetrid ning anti hinnang mudeli kasutatavuse kohta nendel jõgedel. Kliima- ja maakasutuse muutuse mõju hinnati nende jõgede jaoks (v.a Narva jõgi), millel on Eestis suur hüdroenergeetiline potentsiaal. Artiklis I analüüsiti kliimamuutuse mõju hüdroenergia tootlikkusele kolme hüdroelektrijaama näitel ning artiklis II peale kliima- ka maakasutuse muutuse üldist mõju Eesti jõgede veeressurssidele.

## Kokkuvõte doktoritöö tulemustest ja järeldused

Doktoritöös anti uus hinnang Eesti jõgede hüdroenergeetilisele potentsiaalile. Selleks tuletati meetod jõe tehnilise hüdroenergeetilise potentsiaali arvutamiseks, kasutades sisendina kõrgus- ja äravoolumoodulikaarti. Tuletatud meetodi kohaselt jaotatakse jõgi kindla pikkusega lõikudeks, mille otsas olevatele virtuaalsetele hüdroelektrijaamadele arvutatakse virtuaalne võimsus. Neid virtuaalseid võimsusi kokku liites saadigi Eesti jõgede hüdroenergeetiline potentsiaal. Meetodi täpsust (jaamade võimsus ja paiknemine) valideeriti kahekümne hüdroelektrijaama andmete põhjal. Tuletatud meetod osutus piisavalt täpseks uute HEJ-de paiknemise ja võimsuse hindamiseks. Eesti jõgede (v.a Narva jõgi) tehnilise hüdroenergeetilise potentsiaali suuruseks hinnati ligikaudu 80 MW, sellest Lääne-Eesti vesikonnas 52 MW, Ida-Eesti vesikonnas 26 MW ja Koiva vesikonnas 2 MW.

Maakasutuse ja kliima muutumise mõju Eesti jõgede vooluhulkadele hinnati maailmas laialdaselt kasutatud hüdroloogilise mudeli SWAT abil, kalibreerides ja valideerides seda Eesti suurema hüdroenergeetilise potentsiaaliga jõgede jaoks. Selgus, et mudel SWAT suudab piisava täpsusega matemaatiliselt kirjeldada Eesti jõgedes kulgevaid looduslikke protsesse.

Kasutatud kliimamudeleid tuli esmalt korrigeerida, sest nad olid võrreldes mõõdetud kliimaandmetega nihkes. Selleks kasutati laialt levinud statistilisi meetodeid. Koostati ka kaks realistlikku Eesti maakasutuse muutumise stsenaariumit 21. sajandi lõpuks. Seejärel sisendati kalibreeritud mudelitesse maakasutuse ja kliima muutumise stsenaariumite kombinatsioone, et hinnata nende muutuste nii individuaalset kui ka kombineeritud mõju Eesti jõgede vooluhulkadele.

Maakasutuse muutumise mõju jõe vooluhulkadele on märgatav vegetatsiooniperioodil, mil taimestik mõjutab oluliselt veebilanssi. Ootuspäraselt on täheldatav metsa raadamise üleüldine positiivne mõju jõe veebilansile – aastakeskmine vooluhulk on raadamiseelsest 1–2 protsenti suurem. Hoopis suurem on metsastumise mõju – hüdroloogiline modelleerimine näitab, et jõe aastakeskmine vooluhulk väheneb umbes 5 protsenti. Erinevused on seletatavad prognoositava metsasuse muutuse suurusega, kui jõgede valgaladel on stsenaariumite järgi rohkem maad metsasuse suurenemiseks kui metsade raadamiseks. Ilmneb tugev lineaarne seos metsasuse ja aastakeskmise vooluhulga muutuse vahel. Seda seost võib üldistada järgmiselt: metsasuse viieprotsendine muutus muudab jõe aastakeskmist vooluhulka 1 % võrra.

Kuigi maakasutuse muutumine mõjutab Eesti jõgede aastakeskmist vooluhulka, jääb esmajärguliseks ikkagi kliimamuutuse mõju. Kliimamuutuse mõju Eesti jõgede aastakeskmisele vooluhulgale on positiivne — olenevalt kasutatud kliimamudelist 10 kuni 26 protsenti. Kuigi aasta lõikes on kliimamuutuse mõju suund selge, siis kuude lõikes sõltub see kasutatavast kliimamudelist. Aprillikuus, mil Eesti jõgedes on tavaliselt suurveeaeg, on sajandi lõpuks oodata keskmise vooluhulga ligikaudu 50-protsendilist vähenemist. See on tingitud eelkõige lumikatte vähenemisest ja varasemast sulamisest talvekuudel, mil on oodata keskmiste vooluhulkade suurenemist üle 50 protsendi. Selgusetuks jäävad suve- ja sügiskuud, mil ühe kliimamudeli järgi on oodata vooluhulkade olulist suurenemist, teise järgi aga suve keskmine vooluhulk ei muutu üldse ning sügisel on oodata vooluhulkade umbes 20-protsendilist vähenemist.

Peale üldise mõju veeressurssidele uuriti doktoritöös detailselt kliimamuutuse mõju olemasolevatele hüdroelektrijaamadele. Selleks valiti välja kolm praegu toimivat või varem töötanud hüdroelektrijaama (Keila-Joa, Nõmmeveski, Kunda) ning uuriti, kuidas nende jaamade tootlikkus võib tulevikus muutuda. Arvestati jaamade installeeritud võimsust, seega kui jõe vooluhulk on jaama nimivooluhulgast suurem, jääb osa veejõust kasutamata. Selline olukord tekiks kõige sagedamini Keila-Joa HEJs, kus talvel võiks tootlikkus olla ligikaudu 30 protsenti suurem. Kasutamata jääv potentsiaal on veelgi suurem (60 kuni 120 protsenti) Kunda ja Nõmmeveski HEJs. Kui kolmest uuritud HEJst on Kundas suvel oodata hüdroenergeetilise potentsiaali suurenemist umbes 10 protsenti, siis ülejäänud kahes jaamas on oodatav kasv üle 30 protsendi.

Kokkuvõtlikult:

- Eesti jõgede (v.a Narva jõgi) tehniline hüdroenergeetiline potentsiaal on seni hinnatust märkimisväärselt suurem, olles ligikaudu 80 MW.
- Eestis leiab praegu rakendust vaid ligikaudu 10 % kogu Eesti tehnilisest hüdroenergeetilisest potentsiaalist.
- Eestis on kasutamata võrdlemisi suure hüdroenergeetilise potentsiaaliga kohti, kuhu oleks majanduslikult mõistlik hüdroelektrijaamu rajada.
- Eesti jõgede hüdroloogilise režiimi kirjeldamiseks sobib hüdroloogiline mudel SWAT.
- Modelleeritud kliimamuutuse mõju aastakeskmisele vooluhulgale on Eesti jõgedes 10 kuni 26 %.

- Hüdroenergeetiline potentsiaal on Eestis suurenemas. Selle positiivse mõju ärakasutamiseks on soovitatav olemasolevaid hüdroelektrijaamu laiendada või uuendada
- Eesti jõgede hüdroenergeetilise potentsiaali suurenemine teeb uute hüdroelektrijaamade rajamise majanduslikult otstarbekaks.

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# I

# ORIGINAL PUBLICATIONS

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# Modeling future changes in the North-Estonian hydropower production by using SWAT

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## ABSTRACT

Climate change is altering temperature, precipitation, and other climatic parameters, affecting sectors dependent on water resources, e.g. energy production. The purpose of this study is to analyze the possible influences of climate change on hydropower potential in North Estonia. In Estonian run-of-river hydropower plants, energy comes mainly from water volume. Thus, changes in hydropower production are related to changes in river runoff. The Soil and Water Assessment Tool (SWAT) model is used to study runoff responses to climate change in Kunda, Keila and Valgejõe river basins. A sequential uncertainty fitting algorithm is used for calibration and validation of hydrological models. Two modeling studies from EURO-CORDEX high-resolution simulations are used: RACMO regional climate model (RCM) from the Netherlands (KNMI) and HIRHAM5 RCM from Denmark (DMI). Hydrological model efficiency is evaluated with coefficient of determination ($R^2$), Nash–Sutcliffe efficiency (NSE) and percent bias (PBIAS). The NSE values range from 0.71 to 0.77 during calibration and validation. The PBIAS reveals no significant bias. Daily discharge data of the baseline period (1971–2000) and the future period (2071–2100) for KNMI and DMI scenarios reveal an overall increase in hydropower potential. Larger changes are predicted by the DMI model, while KNMI prediction is lower, 25% and 45% respectively.

**Key words** | climate change impact, Estonia, run-of-river, small hydropower plant, SWAT

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## INTRODUCTION

Small hydropower (SHP) has been a source of electricity generation in Europe since the beginning of 20th century. SHP represents about 9% of renewable and 1.2% of the total electricity generation in the European Union (Kougias *et al.* 2014). In 2010, Estonia had 47 SHP plants with a total installed capacity of 8 MW, the aim is to have 55 plants with a total installed capacity of 9 MW by 2020 (Liu *et al.* 2013). A renewable energy support scheme is interested in increasing the number of small or micro hydropower plants as a feed-in tariff or a fixed premium is legally meant to be paid by the utility (Liu *et al.* 2013). However, there exists a contradictory standpoint by public organizations referring to the very low hydropower share of total electricity production (less than 0.5%) in Estonia (Punys & Pelican 2007) and to the environmental considerations, i.e. the migration of fish being blocked or adversely affected by the hydraulic structures. Thus, an evaluation of the impacts of climate change on river discharge will provide valuable information to policy makers.

Estonian topography is relatively flat and rivers have small average slopes. There are over 7,000 rivers and streams in Estonia, however discharge of less than 50 rivers exceeds 2 $m^3$/s, and only 14 rivers discharge over 10 $m^3$/s (Raesaar 2006). Thus, as the hydroenergetic potential is proportional to the head and the rate of discharge of the water, large hydropower plants with a high dam and large reservoir for flow regulation cannot be utilized in Estonia. Nevertheless, there are many rivers suitable for small and micro hydro power plants. For example, in northern Estonia where the steep escarpment of the Baltic Klint is cut through by river valleys.

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Thus, due to the conditions described, hydro power plants in Estonia are mainly small, except the Narva Hydropower station which is owned by the Russian Federation and is operating in the border river. Small scale hydro power plants (SHP) are defined as 'run-of-river' plants which do not require a large impoundment of water, with little or no control of discharge, sometimes implementing diversion schemes to utilize the natural topographic gradient (Kumar *et al.* 2011). The energy comes mainly from the water volume and not from the head of water (Gaudard & Romeiro 2014).

SHPs are believed to be 'clean' and 'green' compared to large hydropower plants (Kumar *et al.* 2011), having conditionally low environmental impact (Gaudard & Romeiro 2014). However, lately this perception has been questioned (Premalatha *et al.* 2014). Estonian SHPs are facing many administrative barriers (ESHA 2012). To build and operate a hydropower plant, one needs a *Permit for the special use of water* (concession) which defines the permit owner's rights and obligations. The licensing procedure for the sector is time consuming. The authorization procedure takes from 4 months to 4 years. Concessions have a duration of only 5 years. Minimal residual flow is prescribed in the water use licensing procedure and is defined as a fraction of flow duration curve (95%). Mitigation measures, i.e. constructing fish passes, are often requested (ESHA 2012).

The 'run-of-river' hydropower plants are particularly dependent on river discharge. Thus, changes in pattern and amount of available water have a profound effect on hydropower generation. Possible changes in future water storage will differ from region to region around the globe. Li *et al.* (2015) used regional climate model (RCM) RegCM4 as a driving force to investigate the potential impact of climate change on hydrology over continental Southern Africa. By using the results from an ensemble of 16 or more CMIP3-CGCMs (coupled global climate models), Zhang *et al.* (2015) investigated how future changes in temperature and precipitation might influence total runoff in the headwaters of the Yellow River basin.

There have been several studies generalizing the impacts of climate change on hydropower by using the delta change approach (e.g. Lehner *et al.* 2005; Carless & Whitehead 2013; Gaudard & Romeiro 2014). Also the spatial resolution has been coarse (Lehner *et al.* 2005). The main objective of this study is to use daily generated climate data from the EURO-CORDEX (Coordinated Downscaling Experiment – European Domain) project and detailed spatial information to study future changes in the North-Estonian hydropower production.

## METHODOLOGY

To evaluate the potential changes in hydropower production, the following main actions are taken (Figure 1). First, basins are selected and parameterized. Various data such as land use, elevation and soil are acquired. Secondly the historical climate and discharge (1970–2010) for hydrological model calibration and validation is obtained from the national weather service. Then all mentioned data are adjusted to hydrological model SWAT which is used to model river discharges for the historical period. Different model efficiency evaluation criteria are used to calibrate and validate the model against measured discharge to get a representative hydrological model for study areas. The

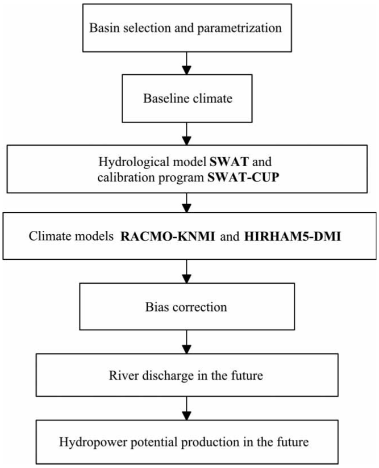

**Figure 1** | Conceptual framework of the study to model future changes in the North-Estonian hydropower production.

RCM models RACMO-KNMI and HIRHAM5-DMI outputs (precipitation and temperature) are bias corrected. Bias corrected climate is used as input for the calibrated hydrological model, to model river discharges for the future period. Finally, the hydropower potential is calculated and the change is evaluated.

## Site description

Keila, Kunda and Valgejõe River basins are chosen as study areas to represent climate change impacts on hydropower potential in North Estonia. The location of river basins are presented in Figure 2. Each of the river basins drain into the Gulf of Finland.

Keila has the largest watershed among the three study areas (Table 1). According to the land use and land cover database Estonian National Topographic Database, most common land use types in the three study basins being arable land, forested land and wetland. The dominant land use for all study areas is arable land, covering around 45–60% of the area. Kunda basin is only covered 5% by wetland, while the corresponding land use coverage in Keila and Valgejõe are 12% and 16%, respectively. Forested land accounts for 28%, 40% and 44% of the land surface in Keila, Kunda and Valgejõe, respectively. All case-study regions have relatively flat slopes, with an average slope of around 1%.

The average annual measured precipitation in Keila, Kunda and Valgejõe is 725 mm, 644 mm and 701 mm,

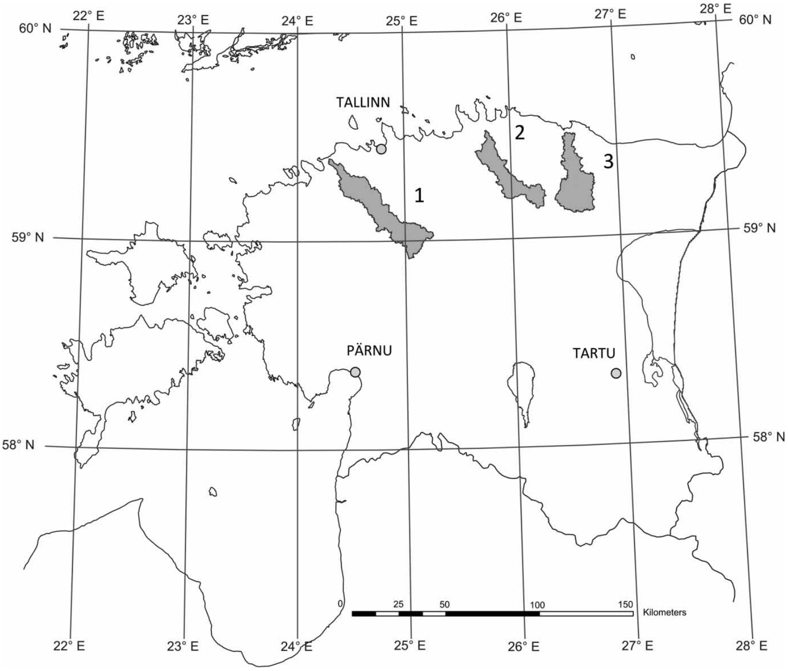

**Figure 2** | Study area locations: 1-Keila; 2-Valgejõe; and 3-Kunda River basins.

respectively. Around 20% of precipitation is snowfall. Long-term average actual evapotranspiration rate is around 400 mm per annum. The average annual temperature during the baseline period 1971–2000 was 4.5 °C. The coldest month is February, with an average temperature of –6.6 °C, followed by January with an average temperature of –6.2 °C. The warmest month is July, with an average temperature of 15.8 °C.

Kunda river is the most challenging for simulation, since its flows are significantly affected by karstic aquifer. It is estimated that groundwater contributes over 50% of flow to the river discharge (HELCOM 2011). In Estonia, the typical river hydrograph has peak discharges in spring and fall, from which the spring is more abundant in water due to snow melt. Observed daily discharge data for the period 1970–2010 are available in all three study basins, which are used for model calibration and validation.

The first fully automatic hydropower plant was built in 1893 on Kunda River, where a Francis turbine with capacity of 210 kW was installed. Today Kaplan reaction turbines have been installed in all three plants. The SHP characteristics of the three basins are provided in Table 1.

## Climate change

Climate impact assessment requires scenarios of future climate to be translated into potential changes in the quantity and timing of river runoff. Modeling results from the EURO-CORDEX project (Jacob *et al.* 2013) are used as future climate data input. EURO-CORDEX is part of CORDEX initiative (Giorgi *et al.* 2009), which coordinates regional downscaling of CMIP5 project to all terrestrial regions of Earth. Different institutions run their climate models on a similar grid within the EURO-CORDEX project, and make data available on the same grid. Therefore, it is possible to conduct a common model evaluation (Kotlarski *et al.* 2014) and provide common climate projections for climate change impact, adaptation and mitigation studies (Giorgi *et al.* 2009). Within the EURO-CORDEX project, models are being run with two resolutions: 50 and 12 km, and both cover all European land areas, the Black Sea, the Mediterranean Sea and Iceland. For the current project, two modeling studies are used from EURO-CORDEX high-resolution simulations: RACMO model with the boundaries from EC-EARTH r1i1p1 ensemble member from the Netherlands (KNMI) (Van Meijgaard *et al.* 2008) and HIRHAM5 model with the boundaries from EC-EARTH r3i1p1 ensemble member from Denmark (DMI) (Christensen *et al.* 2007).

While it could be argued that using the full available ensemble from EURO-CORDEX would be more informative, authors decided that two models are enough for the current study, as they already give quite different results and the analysis of a full model ensemble is a topic for further studies. RCP4.5 climate change (Figure 3) scenario was selected, as it is the baseline scenario in CMIP5 project and is supported by 20 climate modeling groups.

Climate models in general are mathematical representations based on physical principles which estimate higher for some climate variables (e.g. temperature) than for others (e.g. precipitation) (IPCC 2001). RCMs are known to be biased, causing even more uncertainties in the future hydropower potential change prediction. Despite biases, RCM's still produce variables which are physically coherent. Muerth *et al.* (2013) found that bias correction of regional climate simulations provide a closer to reality representation of the climate in the use of hydrological models.

For the whole study region, both initial climate projections have cold biases year round. A larger bias is found during the spring and summer period, where it is around −2 °C according to RACMO-DMI and −3 °C according to HIRLAM5-KNMI. Both projections have cold biases of less than –1 °C for the rest of the period.

**Table 1** | Physical and power characteristics of hydropower plants

| Basin | Plant name | Area (km$^2$) | Capacity (kW) | H (m) | Hydrometrical station | Residual flow (m$^3$/s) |
|---|---|---|---|---|---|---|
| 1. Keila | Keila Joa SHP | 678 | 365 | 6.2 | Keila | 0.64 |
| 2. Valgejõe | Nõmmeveski SHP | 405 | 370 | 8.6 | Vanaküla | 0.76 |
| 3. Kunda | Kunda SHP | 492 | 336 | 6.4 | Sämi | 1.44 |

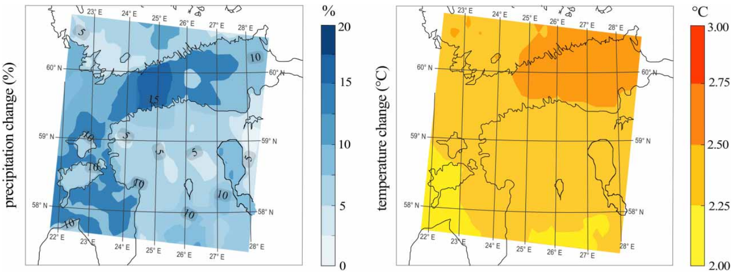

**Figure 3** | Difference between the average precipitation (left) and temperature (right) in the period 2071–2100 and in the period 1971–2000 obtained from the RCP4.5 model for the study area.

The precipitation amounts in RACMO-DMI are overestimated in winter and spring, while HIRLAM5-KNMI overestimates in winter and underestimates during summer months. In terms of average annual precipitation, there is a clear overestimation of around 100 mm by RACMO-DMI model. There is a tendency of both climate model projections to simulate too many low-intensity rain events.

Near-surface air temperature is modified by monthly additive correction. The local intensity scaling method (LOCI) (Widmann *et al.* 2003; Schmidli *et al.* 2006) is used as a bias correction method for precipitation. The LOCI method improves the possible positive bias towards wet-day frequencies, thus reducing excessive drizzle days and improving the overall hydrological cycle in the model. Both bias correction methods were used for their simplicity. Bias corrected temperature and precipitation for both historical projections are shown in Figures 4 and 5, respectively. It is assumed that the modeled climate bias behavior does not change with time. Named bias correction methods are used for future climate, which is used as input data for SWAT to model possible hydropower potential change in the future.

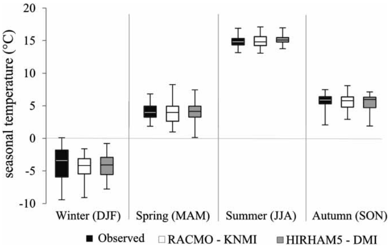

**Figure 4** | Box plot showing bias corrected climate models (RACMO and HIRHAM5) ability to simulate baseline period (1971–2000) temperature seasonally.

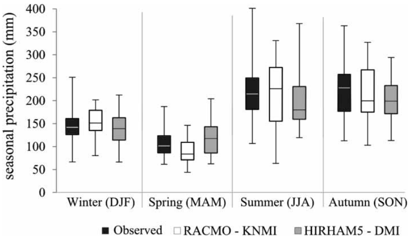

**Figure 5** | Box plot showing bias corrected climate models (RACMO and HIRHAM5) ability to simulate baseline period (1971–2000) precipitation seasonally.

According to the output of both climate model projections, it is estimated that the average temperature will increase by 1.9 °C in KNMI and by as much as 2.5 °C in DMI by 2100 compared to the baseline period. The projected mean monthly temperature and precipitation are summarized in Figures 6 and 7. The most significant increase in temperatures is likely to happen during the winter months, where temperature of around 5 °C higher are predicted. No relevant changes in the average temperature will happen during summer months according to both climate models.

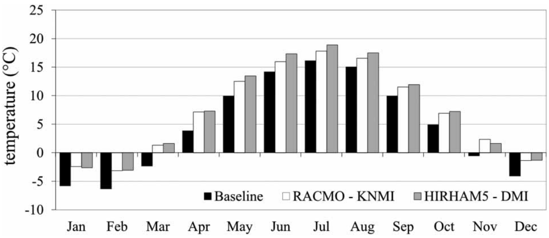

**Figure 6** | Projected mean monthly temperature according to RACMO-KNMI and HIRHAM5-DMI climate models for 2071–2100 compared to the baseline period 1971–2000.

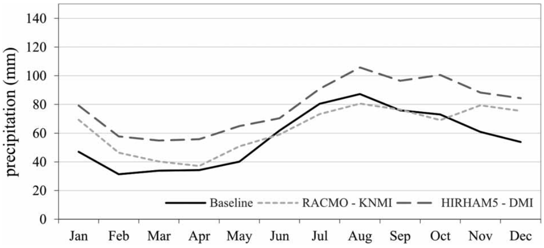

**Figure 7** | Projected mean monthly precipitation according to RACMO-KNMI and HIRHAM5-DMI climate models for 2071–2100 compared to the baseline period 1971–2000.

KNMI tends to predict lower changes in temperature, compared to DMI. The DMI model predicts an overall 30% increase in precipitation, which means potentially higher flows throughout the year. The KNMI model predicts an overall 10% increase in precipitation, except for the summer months, where a slight reduction in monthly precipitation is expected. This suggests a reduction in summer runoff.

## Hydrological model and inputs

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998; Neitsch *et al.* 2005) was applied to simulate hydrologic processes in the three study basins. SWAT is a physically-based, semi-distributed hydrological model, which uses process-based equations to simulate different hydrologic responses. Although the model time step is daily, SWAT was designed as a long-term yield model and is not designed to simulate single-event flood accurately.

One of the reasons for selecting the SWAT model was that it has been widely and successfully used in snowmelt regions to simulate the hydrologic response (e.g. Abbaspour *et al.* 2007; Ahl *et al.* 2008). Furthermore it has also been used around the world for the estimation of climate impacts (e.g. Marshall & Randhir 2008; Ficklin *et al.* 2009; Franczky & Change 2009). The SWAT model has not been widely used as a tool for evaluating hydropower potential change (Haguma *et al.* 2014; Song *et al.* 2014).

SWAT requires a significant amount of data and parameters for development and calibration. These include a digital elevation map (DEM), land use map, soil map and weather data. Climate inputs consist of precipitation, solar radiation, maximum and minimum temperature, wind speed and relative humidity. In a SWAT model, a watershed is subdivided into a number of sub-basins, which are then further subdivided into hydrologic response units that consist of homogeneous land use, slope and soil characteristics.

In this study the daily maximum and minimum temperature, wind speed, humidity and solar radiation data are available for all study basins. Daily precipitation data were used from six meteorological stations. Daily discharge data are available for Kunda, Keila and Valgejõe river hydrological stations. A high-resolution DEM with a 10 m grid size derived from light detection and ranging was used. Due to the absence of realistic land use change scenarios in study basins, the same land use map was implemented in current study. This uncertainty has to be considered, while analyzing the results.

The SWAT model was calibrated and validated with the SWAT CUP software. For this the SUFI2 (Sequential Uncertainty Fitting) algorithm was used. In SUFI2, parameter uncertainty takes into account the various uncertainty sources like rainfall, measured data, etc.

## Model evaluation criteria

Three different efficiency criteria are used to evaluate the model performance. These include: coefficient of determination ($R^2$), Nash–Sutcliffe efficiency (NSE) and relative BIAS (PBIAS).

$$R^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2}} \right)^2 \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{2}$$

$$PBIAS = \frac{\sum_{i=1}^{n} (O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100\% \tag{3}$$

In the equations, O is measured and P modeled discharge values, n is the length of the time series. One of the major drawbacks of $R^2$ (Equation (1)) is the fact that only the dispersion is quantified. Thus a model which systematically over- or underestimates will still result in good $R^2$ values. This is the main reason why $R^2$ cannot be considered as a sole criteria.

The NSE (Equation (2)) is a normalized statistic that determines the relative magnitude of the residual variance ('noise') compared to the measured data variance ('information') (Nash & Sutcliffe 1970). As stated by Sevat & Dezetter (1991) NSE is the best objective function for reflecting the overall fit of a hydrograph. NSE is very sensitive to peak flows, at the expense of better performance during low flow conditions. Since the objective is to model hydropower potential change, where low flow does not play a key role, NSE and $R^2$ are appropriate to be used as qualitative model evaluation criteria.

PBIAS (Equation (3)) measures the average tendency of the simulated data to be smaller or larger than their observed data counterparts (Gupta *et al.* 1999). Simulation results are 'unsatisfactory' when PBIAS is larger than 25%. Values below 10% are considered to be 'very good'. Values ranging from 10% to 25% are rated from 'good' to 'satisfactory' during calibration and validation (Van Liew *et al.* 2007).

## Hydropower

In Estonia most of the hydropower plants are classified as low head, with a head below 10 m. The energy comes mainly from the water volume and not from the head of water. In all study basins, Kaplan reaction turbines are installed. These are most suitable for low-head sites because of their higher specific speeds and flat efficiency curve where part-load performance is an important factor.

Kaplan turbine works between 30 and 100% of the maximum design discharge. These turbines have a high hydraulic efficiency in the range 70 to over 90%. Study basins plants are considered typical run-of-rivers with almost no storage capacity, thus electric output depends on the available water. During high flow periods, some of the potentially available hydropower cannot be harvested, while during low flow periods, the generating capacity will be low or no hydroelectricity is generated. The general formula for any hydropower system calculation is:

$$P = \eta \times \rho \times g \times Q \times H \tag{4}$$

where P is the mechanical power which is produced at the turbine shaft (watts), $\eta$ is the hydraulic efficiency of the turbine, g is the acceleration due to gravity (m/s$^2$) and $\rho$ is the density of water volume (kg/m$^3$), Q is the flow rate passing through the turbine (m$^3$/s) and H is the effective pressure head (m).

According to Equation (4) the changing flow rate and the hydraulic efficiency are functions from flow rate. These are the main parameters affecting the energy outcome from run-of-river hydropower plants. Thus a change in river flow rate, means a change in hydropower. In hydropower calculations, some limitations must be taken into account.

Hydropower plants in Estonia must guarantee a minimal residual flow (e.g. through the spillway), i.e. water cannot be extracted while river runoff is lower than minimal residual flow. The upper threshold for energy generation is limited by a maximum flowrate of the turbine. Thus the available water for energy generation is the range between the maximum flow rate of the turbine and available water for consumption. For efficiency reasons of the Kaplan turbines, only higher than 30% of the first turbine's maximum flow rate is extracted for energy generation. Technical parameters of hydropower plants and limitations by water permits have been implemented in the present study.

## RESULTS

### Calibration and validation of the hydrological model

A period of 1970–2010 is used to model the hydrology, from which the first 2 years are left for the model warm-up. The SWAT model is calibrated (1972–1997) and validated (1998–2010) for all study basins. Qualitative and quantitative statistical methods are utilized for model performance evaluation. Calibration and validation results reveal a good fit between the observed and simulated daily discharges (Table 2). Statistical criteria NSE values range from 0.71 to 0.77. The best fit between the observed and simulated flows are found in the Keila basin (Figure 8), where NSE values are 0.77 and 0.72 for calibration and validation, respectively.

**Table 2** | SWAT model calibration and validation results

| | Keila | Valgejõe | Kunda |
|---|---|---|---|
| $R^2$ | 0.78 | 0.75 | 0.77 |
| NSE | 0.77 | 0.74 | 0.73 |
| PBIAS | 0.5% | −1.4% | −3.2% |
| $R^2$ | 0.73 | 0.72 | 0.75 |
| NSE | 0.72 | 0.71 | 0.72 |
| PBIAS | 1.9% | −3.3% | −8.5% |

Validation results show that the SWAT model can effectively represent the hydrological processes in the study basins. PBIAS reveals almost no bias for Keila river basin. PBIAS values for Kunda and Valgejõe indicate a slight model bias towards overestimation, however model performance is still considered 'very good' (Van Liew *et al.* 2007). Thus, the water balance for study basins is physically representative by the SWAT model.

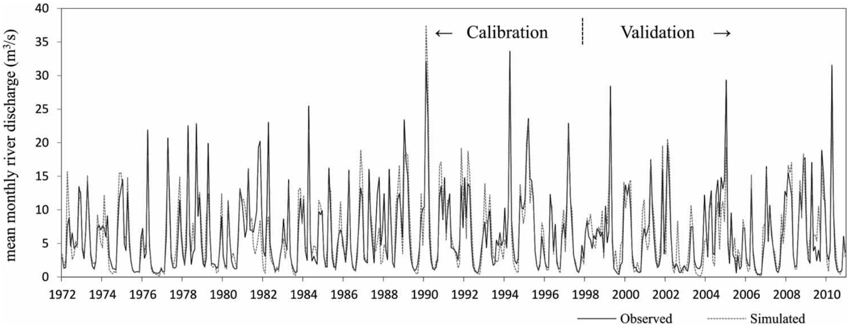

**Figure 8** | Observed and simulated mean monthly discharge in Keila River for the calibration (1972–1997) and validation (1998–2010) period.

Tolson & Shoemaker (2004) stated that SWAT is not designed to simulate a single extreme event and the model usually underestimates largest flow events. A similar tendency is observed in this study. However, this underestimation does not significantly affect hydropower harvesting in the current study, because peak flows exceed maximum flowrate of the turbines.

### Potential change of hydropower by 2100

The simulation results of the SWAT hydrological model indicate a change in river runoff for both climate scenarios. The mean increase in annual discharge of 15% and 55% was predicted for North Estonia by climate projections KNMI and DMI, respectively (Table 3). The spring peak in the study basins tends to occur earlier and be smaller compared to the baseline period. This pattern was more pronounced in the DMI climate projection, resulting from an increase in precipitation (Figure 7) and lesser winter snow accumulation. A significant increase in autumn discharge was projected by the same model.

**Table 3** | Projected changes in runoff and hydropower potential

| | | Change (%) | |
|---|---|---|---|
| **Hydroclimate** | **Baseline** | **RACMO KNMI** | **HIRHAM5 DMI** |
| *Keila River at Keila-Joa* | | | |
| Mean annual runoff | 6.8 m$^3$/s | 10.0 | 54.2 |
| Mean winter hydropower | 305 kW | 25.6 | 34.3 |
| Mean spring hydropower | 332 kW | 7.7 | 19.6 |
| Mean summer hydropower | 99 kW | 40.4 | 68.6 |
| Mean autumn hydropower | 237 kW | 8.2 | 39.9 |
| Mean annual hydropower | 243 kW | 16.8 | 34.1 |
| *Kunda River at Kunda Silla* | | | |
| Mean annual runoff | 5.2 m$^3$/s | 21.5 | 57.5 |
| Mean winter hydropower | 127 kW | 63.7 | 109.2 |
| Mean spring hydropower | 218 kW | 26.4 | 24.5 |
| Mean summer hydropower | 73 kW | 11.3 | 9.4 |
| Mean autumn hydropower | 118 kW | 21.3 | 24.5 |
| Mean annual hydropower | 134 kW | 32.1 | 42.6 |
| *Valgejõe River at Nõmmeveski* | | | |
| Mean annual runoff | 3.4 m$^3$/s | 18.5 | 52.8 |
| Mean winter hydropower | 134 kW | 69.6 | 122.3 |
| Mean spring hydropower | 218 kW | 10.3 | 22.6 |
| Mean summer hydropower | 72 kW | 32.0 | 42.7 |
| Mean autumn hydropower | 138 kW | 5.3 | 57.4 |
| Mean annual hydropower | 141 kW | 26.0 | 57.4 |

Coherence between changes in annual discharge and hydropower potential was evident with some exception. Flowrates exceeding installed hydro plant capacity cannot be used for hydropower harvesting. Keila River SHP is a good example of this behavior: hydropower potential is predicted to rise 17% and 34%, according to the KNMI and DMI climate projections, respectively. The projected changes in the hydropower potential were higher in Kunda and Valgejõe. Generally, significant increase in winter hydropower potential is modeled in SHP, where installed capacity is available (Table 3). Kunda SHP revealed a lower increase in hydropower potential for summer months, compared to Keila and Valgejõe SHP.

The amount of uncertainty involved in modeling of Kunda is higher because the physical groundwater system of the karst aquifer may behave unexpectedly.

## DISCUSSION

Climate-induced changes in temperature and precipitation are the driving factors in modeling river runoff. According to the climate projections used, the impact on future river discharge in North Estonia can be remarkable. In the Baltic states, Bolle *et al.* (2008) found that annual river runoff is forecasted to increase in North Latvia, which agrees with the results of the current study. However another study by Apsite *et al.* (2010) predicts a decrease in annual river runoff. Contradicting results in Latvian river runoff can be explained by the use of different climate models, scenarios and assumptions. Kriaučiūnienė *et al.* (2008) predicted a remarkable increase in Lithuanian winter river runoff due to the shortening of the snow period, while spring runoff peak decreases and shifts to an earlier period by the end of the century.

A comprehensive study of the climate change impact on the hydropower potential in Europe by Lehner *et al.* (2005) suggests an increase in the hydropower potential in North Europe by the end of 21st century. In Finland and Sweden, the increased runoff will give potentially 19%

higher hydropower in both countries. Our results are in agreement with the findings of Lehner *et al.* (2005) who found an increase of 29% in Estonia whereas slightly higher hydropower potential was found in the current study with a mean value of 35% for North-Estonian study basins (Table 3).

High flow periods could be better exploited by increasing the number of turbines at SHP, i.e. increasing the installed capacity.

Future simulations do not take into account changes caused by climate change itself, e.g. land use and vegetation. El-Khoury *et al.* (2015) and Song *et al.* (2014) studies showed that land use change can influence future river discharge considerably. Combining the impacts of climate change, land use, technology and policy will help to improve prediction quality. In spite of the uncertainties in hydropower potential modeling, the results provide a sound basis to energy policy makers for river management in North Estonia.

## CONCLUSIONS

In this study the impact of climate change on water resources in North Estonia was assessed. Keila, Kunda and Valgejõe study basins were selected, and basin scale hydrology was modeled with the hydrological model SWAT. Two different climate projections (RACMO-KNMI and HIRHAM5-DMI) were bias corrected and used as input for calibrated hydrological models. Change in hydropower potential for run-of-river hydropower plants was calculated from modeled river discharges.

Modeling results indicate an annual increase in water discharge and thus hydropower potential increases in all study basins due to the changes in climate. High flow periods could be better exploited by increasing the number of turbines at SHP. It can be concluded that the climate change impact on hydropower potential in North Estonia is likely to be positive.

The results provide a sound basis for energy policy makers towards river management in North Estonia. For future work, it is recommended to implement different land use change scenarios, taking into account developments in technology and policy.

## ACKNOWLEDGEMENTS

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# II

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# Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model

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ABSTRACT

Combined and separate impact of climate and land use change on the future river runoff was assessed in the eastern Baltic Sea region by using the SWAT (The Soil and Water Assessment Tool) hydrological model. SWAT was applied to assess how plausible changes in climate and land use may affect the river hydrology by the end of the century. The model was calibrated and validated for a period from 1970 to 2010 (41 years) using daily river runoff data. Statistical and visual analysis of the achieved model presented adequate fit to the observed data allowing the reproduction of the current hydrological conditions of the basins for future analysis. The following conclusions from the study were made: 1) a strong linear correlation between forest cover change and annual river flow change was found; 2) the impact of land use change on runoff is important on an annual scale; 3) the scale of a basin is not important on the hydrological response to forest cover change; 4) the combined effect of land use and climate change was found to be non-additive. Findings of this study would help policy makers, to improve land and water management decisions and in formulating strategies to harness the positive impacts of possible overall increase in river runoff in the north-eastern Baltic Sea region.

## 1. Introduction

The statistical distribution of weather patterns is changing. Changes in air temperature and precipitation influence the hydrologic cycle and, moreover, the water resources. Climate change is caused by a possible combination of natural processes and human activity, although the extent of anthropogenic activities is uncertain. According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, the global linear trend (1906–2005) for the annual near surface mean temperature is an increase of 0.74 °C per decade (IPCC, 2007). Furthermore, according to Tietäväinen et al. (2010) the rate of warming has tripled during the last 50 year (up to 0.30C per decade) in the Northern part of the Baltic Sea (Finland). The quality of the data for trend analysis in the first part of the 20-th century is considered low, and the credibility of the data in the second half can be considered as medium (Hartmann et al., 2013). This uncertainty is carried to future predictions, since this data is used as base to drive climate models.

The trends in runoff are influenced by changes in precipitation and temperature, where latter seems to have a stronger impact (The BACC II Author Team, 2015). Jaagus (2006) analyzed trends in the time series of air temperature and precipitation in Estonia during 1951–2000. There has been a statistically significant increase in air temperature during the cold period. In precipitation, increasing trends are present from October until March, and also in June. The duration of snow cover has decreased in Estonia 17–20 and 21–36 days, on the inland and coast, respectively. An increase in winter discharge has been detected in the Baltic Sea sub-basins. This is due to the higher temperatures, causing earlier snowmelt (BACC Author Team, 2008). It is evident from the above that in the eastern Baltic Sea region, the climate is changing.

Hydrological models are one of the tools to assess the possible changes in the future hydrology and water resources. Some of the widely used in the Baltic Sea region are the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2005), HBV (Bergström and Forsman, 1973; Lindström et al., 1997), Hydrological Predictions for the Environment (HYPE) (Lindström et al., 2010) and Hydrological Simulation Program Fortran (HSPF) (Bicknell et al., 1997). Hydrological models in these studies take into account the climate change impact on water quantity (Kjellström and Lind, 2009; Kriaučiūnienė et al., 2008; Latkovska et al., 2012; Øygarden et al., 2014; Tamm et al., 2015) or quality (Arheimer et al., 2012; Donnelly et al., 2011; Rankinen et al., 2016). However, there are no regional studies about the sole impact of land use change nor combined impact of climate and land-use change on future water resources in the eastern Baltic Sea region. The closest study in this topic has been carried out in the Narew basin, located in the North-East of Poland (Piniewski et al., 2014).

General Circulation Models (GCMs) are one of the basis of future

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climate studies, however, they have a coarse resolution (Flato et al., 2013). Stone (2003) found that in climate change impact studies, the resolution of the climate model plays an important role in estimating water yields in a basin. To overcome this limitation, one of the solutions is to use finer scale regional climate models (RCMs) which are forced by boundary and initial conditions generated by a CGM (Giorgi et al., 1990; Wang et al., 2004). Prein et al. (2016) demonstrated how RCMs clearly added value by improving the representation of spatial precipitation patterns. However, a study by Di Luca et al. (2013) suggests that RCMs may add relatively low additional value to surface temperature. However, they found that the largest potential for added value appears in coastline regions due to different warming of land and water surfaces.

Besides climate change, changes in land use may have a significant effect on hydrology (Wang et al., 2006), and thus, on water resources. At least one-third of the land surface has been modified by humans (Ellis, 2011). This tendency is likely to continue in the future to cope with the growing demand for resources (MEA, 2005). Global forest area has declined over 3% in the period from 1990 to 2015. The conversion of forest land to agricultural use has been the most significant driver for this tendency (Smith et al., 2016). However, in the Baltics, the recent land use change trend has been the opposite. After the Baltic States regained independence from the Soviet Union in 1991, the decrease in the agricultural land use started. This trend can largely be explained by the natural expansion of forest on abandoned agricultural lands and by afforestation, where less fertile lands were planted with trees (Palang et al., 1998). According to FAO (2010) 52% of the total area of Estonia is covered by forest, whereas around 23% is agricultural land. Besides changes in forest and agricultural land, urban land use increase in Estonia has been significant (Roose et al., 2013). Thus the main drivers for land use changes in the Baltics have been both political and economical.

Anthropogenic land-use and land-cover change affects the hydrologic cycle through evapotranspiration and the interception of water. Climate- and land use-induced changes in precipitation and evaporation directly affect the amount of available water, which can theoretically be used for hydropower production or for other uses of water resources.

The extent of climate and land use change effects on water resources vary, being dependent on the region analyzed and scenarios considered (IPCC, 2007). These impact studies should be regionalized in order to achieve a better understanding of the future. This paper proposes to use a semi-distributed hydrological model, the SWAT model (Soil and Water Assessment Tool), to estimate potential impacts of land use (deforestation and afforestation) and climate change on water resources in the West-Estonian river basin district, located in the north-eastern Baltic Sea region. The generated information from climate and land use change scenarios can be useful for relevant policies as guidance for adaption and mitigation measures. The joint effect of climate- and land use change on regional water resources has not been explored to date in the study area.

## 2. Study area

This study was conducted on the north-eastern Baltic Sea region, in the West-Estonian river basin district. The Baltic Sea drainage basin is about 1,745,000 km$^2$, which is divided into multiple sub-basins. The Baltic Sea is almost entirely enclosed by land, only connection to the North Sea is through the narrow Straits of Denmark. West-Estonian river basin district flows either to The Gulf of Riga or to the Gulf of Finland, which is the eastern arm of the Baltic Sea.

The West-Estonian river basin district is situated in the west of Estonia and covers an area of approximately 23,500 km$^2$ (Fig. 1), which is around half of the whole territory of Estonia. The climatic region of the study area can be described as semi-continental (coastal) and continental (inland). The weather is often breezy and humid due to the proximity of the Baltic Sea. The average annual precipitation and actual evaporation in the study area is around 700 and 400 mm, respectively. The average annual temperature in the West-Estonian river basin district was 5.1 °C during the period from 1971 to 2000. The local topography consists of relatively flat ground, with the basin district altitude ranging from 141 m above sea level to 0 m at the coast (drains to the Baltic Sea).

Forests and other wooded areas occupy 52% of the total area of the study basins in the baseline period (Table 1), whereas around 30% is agricultural land and 18% is considered other (urban, wetlands, water bodies etc.). Land use varies in a significant way between study basins. Vihterpalu river basin can be considered highly forested, with almost 60% covered by forest, but only 14% is used for agriculture. From all of the study basins, Keila basin has the largest coverage of agricultural land (around 42%) and just below 40% is categorized as forest.

## 3. Methods

The procedure for estimating the impacts of possible future climate and land-use change on hydrological behavior, is as follows: (1) parametrization and calibration of the SWAT hydrological model by using current climatic inputs, land-use map and observed river flow; (2) two regional climate models (RCMs) are applied (Luhamaa et al., 2014) and bias corrected against observed climate; (3) land-use change scenarios are generated for the end of the 21th century; (4) future scenarios are generated, based on the combinations of changing climate and land use; (5) the modelling results of the current and the future period are compared with the interquartile range. In the interquartile range, the extreme values (outliers) are excluded.

### 3.1. Hydrological model SWAT

The hydrological model SWAT is a widely used semi-physically based and a semi-distributed model that can simulate long term runoff and water quality. SWAT has been used in various water quality and quantity studies (Easton et al., 2010; Gassman et al., 2007). In SWAT, a basin can be partitioned into subbasins, and then further into combinations of unique soil, land use and management characteristics also known as hydrological response units (HRU) which are linked to the river network. It is assumed that HRUs are non-spatially distributed. Rainfall and evaporation is calculated for each HRU. In this study, thresholds for defining HRUs were set at 10% for soil and 10% for land use. Potential evapotranspiration was estimated by using the Hargreaves method (Hargreaves and Samani, 1982), for surface runoff calculation, the modified USDA Soil Conversion Service (SCS) curve number method was used.

Observed runoff data was used to calibrate the SWAT model by the software SWAT-CUP, using the SUFI-2 (Sequential Uncertainty Fitting Procedure Version 2) algorithm (Abbaspour, 2008). River runoff from all the study basins was calibrated and validated against daily measured data from 1970 to 2010 (a 41 year continuous period). Calibration was made with observed data from 1970 to 1997 and validation with observed data from 1998 to 2010. Two-year data (1968–1969) was set as a warm-up period.

The goodness of fit was evaluated qualitatively (visually) and quantitatively with the widely used Nash-Sutcliffe coefficient of efficiency (NSE, Nash and Sutcliffe, 1970), percent bias (PBIAS) and Kling-Gupta Efficiency (KGE, Gupta et al., 2009). Using an excessively over-or underestimating hydrological model for future studies (investigating possible changes in water resources), may lead to wrong conclusions. Thus, an acceptable PBIAS value in this study was set to 10% for daily streamflow and NSE/KGE values should exceed 0.65 to be considered satisfactory.

### 3.2. Climate scenarios

Regional scenarios of future climate are needed in order to assess future climate change impact on water resources with a hydrological

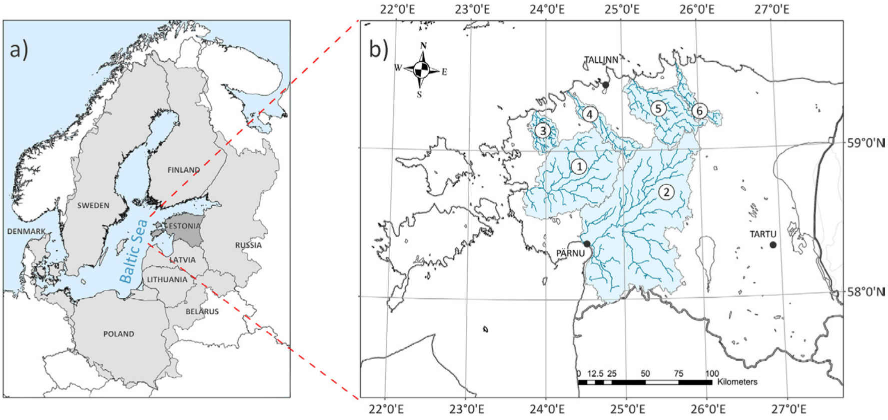

**Fig. 1.** Geographical location of the Baltic Sea drainage basin (a) and the location of the study West-Estonian basin district (b) in Estonia (1-Kasari, 2-Pärnu, 3-Vihterpalu, 4-Keila, 5-Jägala and 6-Valgejõgi).

**Table 1**
Characteristics of land-use change scenarios in the study basins.

| Basin | Scenario | Forest (mature) | Forest (young) | Cropland | Grassland | Orchard | Water | Urban | Wetlands |
|---|---|---|---|---|---|---|---|---|---|
| Jägala (Kehra) 903 $km^2$ | L0 ($km^2$) | 396.1 | 91.6 | 214.6 | 59.9 | 9.9 | 24.6 | 21.1 | 85.1 |
| | L1 (change in %) | −29.0 | 77.1 | 22.8 | −32.6 | 43.0 | – | 51.3 | – |
| | L2 (change in %) | 1.4 | 110.9 | −51.2 | −20.1 | 43.0 | – | 51.3 | – |
| Kasari (Kasari) 3213 $km^2$ | L0 ($km^2$) | 1314.1 | 311.6 | 817.4 | 217.3 | 34.6 | 95.8 | 61.2 | 339.5 |
| | L1 (change in %) | −26.3 | 83.3 | 15.0 | −34.4 | 22.2 | – | 49.1 | – |
| | L2 (change in %) | 3.6 | 117.3 | −49.8 | −20.1 | 22.2 | – | 49.1 | – |
| Keila (Keila) 635 $km^2$ | L0 ($km^2$) | 204.8 | 46.4 | 206.3 | 63.1 | 20.4 | 15.0 | 22.3 | 56.7 |
| | L1 (change in %) | −26.1 | 52.3 | 16.0 | −42.8 | 30.3 | – | 76.9 | – |
| | L2 (change in %) | 23.9 | 111.8 | −50.6 | −30.9 | 30.3 | – | 76.9 | – |
| Pärnu (Oore) 5160 $km^2$ | L0 ($km^2$) | 2135.9 | 632.4 | 1257.8 | 333.7 | 64.9 | 180.9 | 109.6 | 444.3 |
| | L1 (change in %) | −21.3 | 18.7 | 28.9 | −30.1 | 14.1 | – | 59.0 | – |
| | L2 (change in %) | 11.6 | 46.2 | −44.7 | −16.0 | 14.1 | – | 59.0 | – |
| Pärnu (Tahkuse) 2080 $km^2$ | L0 ($km^2$) | 827.9 | 235.6 | 646.9 | 117.5 | 23.0 | 64.9 | 45.1 | 119.1 |
| | L1 (change in %) | −25.2 | 33.3 | 20.9 | −33.3 | 27.2 | – | 62.6 | – |
| | L2 (change in %) | 12.2 | 67.2 | −43.1 | −12.3 | 27.2 | – | 62.6 | – |
| Valgejõgi (Vanaküla) 404 $km^2$ | L0 ($km^2$) | 180.4 | 39.3 | 85.6 | 29.9 | 3.9 | 7.0 | 11.8 | 46.1 |
| | L1 (change in %) | −15.9 | 26.1 | 22.5 | −30.7 | 48.3 | – | 54.1 | – |
| | L2 (change in %) | 11.9 | 58.0 | −54.8 | −18.7 | 48.3 | – | 54.1 | – |
| Vihterpalu (Vihterpalu) 474 $km^2$ | L0 ($km^2$) | 231.8 | 51.6 | 51.4 | 20.0 | 2.2 | 13.5 | 6.1 | 97.4 |
| | L1 (change in %) | −25.5 | 99.1 | 18.8 | −26.7 | 34.2 | – | 51.4 | – |
| | L2 (change in %) | −12.5 | 112.0 | −57.3 | −14.9 | 34.2 | – | 51.4 | – |

model. Modelling results from the EURO-CORDEX project (Jacob et al., 2014) are used as a SWAT model input for future climate. EURO-CORDEX is an international climate downscaling initiative that aims to provide high-resolution climate scenarios for the whole Europe.

Within the EURO-CORDEX project, models are being run with two resolutions: 50 and 12 km, and both cover the Baltic Sea region and thus, the study area. For the current study, two different RCMs from EURO-CORDEX high-resolution simulations are used: (a) RACMO (Regional Atmospheric Climate Model) climate model with the boundaries from EC-EARTH.

r1i1p1 developed by the Regional Climate Division of KNMI (KNMI) (Van Meijgaard et al., 2008); (b) HIRHAM5 (High-Resolution Limited-Area Model) regional climate model with the boundaries from EC-EARTH r3i1p1 run by the Danish Meteorological Institute (DMI) (Christensen et al., 2007). RCMs applied in this study follow from the analysis done by the Estonian Environment Agency (Luhamaa et al., 2014). Both RCMs contain projections for the historical period (1971–2000) and for the future period (2071–2100), which were used in the current study. To achieve a better comparison with the historical data, RCM data was applied only to existing meteorological stations.

Both future projections are forced by RCP4.5 (Representative Concentration Pathway 4.5) which can be considered as a stabilization scenario in which total radiative forcing is almost stabilized by the end of the 21th century (Clarke et al., 2007; Smith and Wigley, 2006). RCP4.5 assumes relatively ambitious emissions reductions and should be considered "optimistic". It should be kept in mind that climate change scenarios can be interpreted as plausible descriptions of possible future climatic conditions.

Although RCMs give added value over the more coarse GCMs, dynamical downscaling may not be able to notably improve the simulation skills of those simulated by the GCMs (Rockel et al., 2008). Thus, dynamically downscaled climate may still produce biases among the downscaled climate which are inherited from the GCM, and carried to the future impact predictions. Despite this finding, RCMs still provide a better description of local climatic conditions. In order to use these RCMs in impact studies, they should be bias corrected. Air temperature (daily minimum and maximum) is modified with the well-known delta method, by monthly additive correction. For precipitation, the local intensity scaling method (LOCI) (Schmidli et al., 2006; Widmann et al., 2003) is used. A more detailed description of the bias correction and its overall performance for the study basins is described in a previous work (Tamm et al., 2015).

### 3.3. Compilation of land use scenarios

Land use changes are driven by various factors (e.g., population change and economic development). It is recognized worldwide that the arable land areas per capita will be decreasing during next decades (FAO, 2002; FAO, 2009). At the same time the abandonment of agricultural land has occurred (Leal Filho et al., 2016). The main trend in Estonian land use change during the 20th century has been the decrease in agricultural land from 65% in 1918 to 30% in 1994 and the increase of forest cover from 21% to 43%, respectively (Mander and Palang, 1999). Thus, conversions between forest and agricultural land have been the main contributors to land use change. In current study, three land use scenarios were developed for the compilation of the land use maps for the SWAT modelling. The procedures of generating the land use change maps are summarized in a flow chart (Fig. 2).

Firstly, during the land use scenario compilation, it was assumed that wetlands and protected areas will not change, because of their natural character. Secondly, future urbanization is related on the local master plans, i.e. areas reserved for staged urban development are used for urban growth modelling. Thirdly, a forest growth model was applied. The stand diameter of 6 cm at breast height (DBH) was used as a criteria for the division of forest areas into young and old. For the prediction of future forest coverage age class, maturity age from the national law (Forest Act, Rules of Forest Management) was used to determine the harvesting time, i.e., when the forest type changes from old to young. Storylines for three land use scenarios were generated. The first land use scenario is the *Baseline scenario* (L0), which takes the assumption that the land use will remain unchanged during the 21th century and it will be the basis for the two other scenarios (Table 1).

The *Deforestation scenario* (L1) takes the assumption that the dominating global trend will be the increase of agricultural land and land-use intensification due to the growing global demand on food and biofuel (Alexandratos and Bruinsma, 2012; Tilman et al., 2011). Agricultural land use coverage in 1990, at the end of the Soviet era characterized by extensive agriculture was chosen to represent high share of agricultural land. According to Palang et al. (1999) 14310 km2 of area was used for agriculture in this year. Due to political reasons, this number is inflated and the realistic figure was somewhat lower (Palang et al., 1999). Thus, 10% was reduced from this number, resulting an area of roughly 13,000 km$^2$ which will be used as a criteria to be reached by the end of the 21th century. This scenario predicts an overall increase of agricultural land around 30%, compared to the baseline scenario.

In the *Afforestation scenario* (L2), it is hypothesized that agricultural sector will produce food predominantly for the Estonian domestic market. It is estimated that between 0.15 and 1.1 ha of land is needed to feed a person in a year, depending on the diet (Peters et al., 2016). Estimated figure of 0.5 ha per person was multiplied with the projected population size of 1 million persons with the projected population size of 1 million persons (United Nations, 2013) by the end of the 21th century, yielding an area of 5000 km2 which is needed for intensive agriculture in Estonia. Thus, in this scenario, agricultural land will decrease around 50%, compared to the baseline scenario, predicting a more forested Estonia.

The entire map of Estonia was divided into grid cells with a spatial resolution of 100 m.

Complex Value Index (CVI) was calculated for each cell taking into account a number of different parameters (e.g. soil fertility, area of a plot, shape, distance from a city, etc.) (Maasikamäe et al., 2014). The CVI can be considered as a quality index of a cell, the higher the CVI value, the less susceptible to change. Next, a new cell from the grid was randomly selected for evaluation. The CVI value was compared to a random number from 0 to 1, to evaluate the transition probability. If the CVI of a cell was lower than the random number and the change was logical according to the storyline (e.g. from agricultural land to forest), the transition was accepted. This procedure was looped until a target value corresponding to the storyline. The outcome of the land use modelling was a static map, according to the storyline. The baseline map was replaced by the generated map to carry out hydrological modelling with SWAT.

### 3.4. Climate and land use scenario combinations

In order to assess the impacts of climate and land use change on runoff, eight scenario combinations (Table 2) were established. Scenarios 1 and 2 only takes into account the change in the land use and can be considered as deforestation and afforestation scenarios, respectively. In Scenario 3 and Scenario 6, the land use remained constant (baseline) while the regional climate models KNMI (C1) and DMI (C2) projections were applied for the period 2071–2100, respectively. The rest of the four remaining scenarios used a combination of both, future climate and land use. Linking climate change models and land use can result in a more realistic scenario for future impact study.

## 4. Results

### 4.1. Calibration and validation of the SWAT model for runoff

The initial SWAT model consists of default parameter values, which in order to achieve the best model fit between simulated and measured daily discharge data, need to be calibrated.

For this, eighteen parameters were selected based on various research papers dealing with sensitivity analysis and calibration studies. The selected initial and fitted parameter ranges over all the study basins are reported in Table 3. The calibrated parameter set was transferred back to ArcSWAT by updating the .mdb databases, with SQL sentences. HRU analysis was rerun, after what the SWAT input files were rewritten and the model rerun. The highest attention in creating the model set-up was paid to snow processes. The extent of snowmelt and its timing is crucial in achieving a representative model of the study basins hydrology.

The SWAT model “goodness” of a fit (quantitative) between the daily observed and simulated runoff during the calibration and validation period is presented in Table 4. Authors would like to note, that objective function used with the SUFI2 algorithm for automatic calibration was the KGE. The advantage of using the KGE for calibration is the fact that NSE is sensitive to errors in extreme values and less sensitive to errors in overall distribution, compared to the KGE (Gupta et al., 2009). All of the study basins have a good agreement between the observed and simulated runoff. The average PBIAS for all the study basins for calibration was just around 0.8%, showing quite a small bias towards underestimation. Validation showed similar magnitude of underestimation. It can be said, that no significant model over- or underestimation was found, all the values were in the proposed acceptable range of 10%. Relatively small fluctuations in PBIAS values imply that the water balance is modelled adequately, which is one of the recommendations for a future impact evaluation.

As can be seen in Fig. 2, the SWAT model underestimated some of the peak flows during the calibration and validation period. This can be partly explained by the spatial variability of precipitation, i.e. rainfall may fall more or less intensely at the location of the rain gauges,

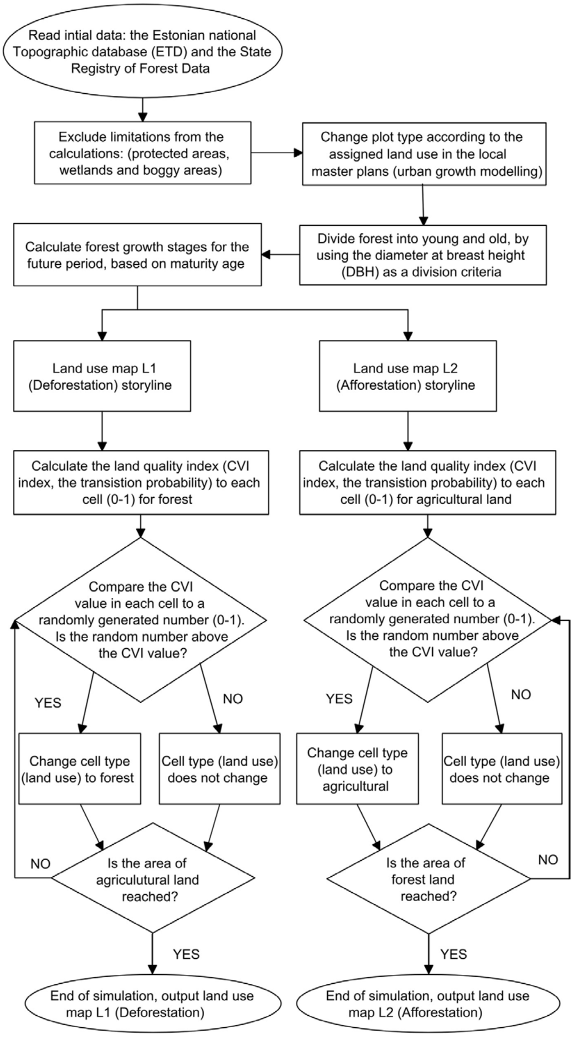

**Fig. 2.** Flow chart for the implementation of the land use change model.

introducing uncertainty in the total estimate of precipitation and thus, in the model calibration. NSE and KGE quantitative statistics indicate a "good" to "very good" performance (Moriasi et al., 2007) for both periods (Table 3). Thus, these modelling results give confidence in the representativeness on the water balance of the study basins. Considering the long period of time (41 years) used for calibration and validation, the SWAT model demonstrated more than satisfactory performance.

**Table 2**
Summary of generated model scenarios (C0 accounts for baseline climate; C1 accounts for KNMI RCM; C2 accounts for DMI RCM; L0 accounts for baseline land use; L1 accounts for deforestation scenario; L2 accounts for afforestation scenario).

| Scenario | Climate | Land use |
|---|---|---|
| 1 | C0 1971–2000 | L1 2071–2100 |
| 2 | | L2 2071–2100 |
| 3 | C1 2071–2100 | L0 1971–2000 |
| 4 | | L1 2071–2100 |
| 5 | | L2 2071–2100 |
| 6 | C2 2071–2100 | L0 1971–2000 |
| 7 | | L1 2071–2100 |
| 8 | | L2 2071–2100 |

### 4.2. Land use change impact on runoff regime (Scenarios 1 and 2)

The land use change scenario maps L1 and L2 (Fig. 4) were inserted into the calibrated SWAT model to simulate deforestation and afforestation effect on river runoff. In the land use scenario L1, deforestation is driven by the demand for additional agricultural land, leading to an average estimated increase in agricultural land of roughly 20%. Afforestation scenario L2 shows an average forest land cover increase of 25%. Urban areas are predicted to expand significantly (around 50%) in the future, whereas both land use scenarios predict the decrease of grassland (Table 1).

According to Scenario 1, possible changes on runoff are relatively small, annual average flow is expected to raise around 1.3% (Fig. 5). The median flow is expected to increase in the second half of the year up to 4%. In the first half of the year, the effect of deforestation on river flow is almost non-existent. As can be seen from Table 1, the reason of the small change is the fact, that deforestation is relatively small with an average of −8.8%, whereas the scale of afforestation is significantly larger (up to 40%).

Scenario 2 can be described as an afforestation scenario. Projected average increase in forest is around 25%. The effect of afforestation in river flow is more pronounced than in deforestation. This is especially true for the Keila river basin, where the baseline forest cover is slightly below 40%, but increases significantly to 55% (Table 1). The increase in forest land cover can decrease average yearly river runoff over 7% (Keila river), whereas the average change over all basins is around −4.5%. Thus, afforestation extent is larger than deforestation and affects river runoff more, with current generated land use maps. Furthermore, according to Fig. 3, the magnitude of deforestation is marginal, it is not further analyzed in Scenarios 4 and 7 (the combined effect of deforestation and climate change).

**Table 4**
Calibration and validation results for the north-eastern Baltic Sea study region.

| River - Station | Calibration (1970–1997) | | | Validation (1998–2010) | | |
|---|---|---|---|---|---|---|
| | NSE | KGE | PBIAS | NSE | KGE | PBIAS |
| Kasari - Kasari | 0.73 | 0.79 | 5.4% | 0.70 | 0.81 | −2.3% |
| Pärnu - Oore | 0.80 | 0.90 | −0.7% | 0.75 | 0.87 | 2.6% |
| Pärnu - Tahkuse | 0.76 | 0.86 | 2.9% | 0.71 | 0.80 | 8.7% |
| Vihterpalu - Vihterpalu | 0.77 | 0.86 | 2.4% | 0.74 | 0.86 | −3.6% |
| Keila - Keila | 0.74 | 0.86 | 1.5% | 0.73 | 0.85 | −2.7% |
| Jägala - Kehra | 0.79 | 0.89 | −4.4% | 0.74 | 0.86 | 1.8% |
| Valgejõgi - Vanaküla | 0.77 | 0.89 | −1.5% | 0.71 | 0.85 | 4.3% |
| Average | 0.77 | 0.86 | 0.8% | 0.73 | 0.84 | 1.2% |

The effect of deforestation and afforestation on yearly river flow is shown on Fig. 6. The effect on forest change on runoff can be generalized as follows: 5% forest change causes a 1% change in runoff. As can be seen from the figure, there is a strong linear trend between these two parameters ($R^2 = 0.97$).

### 4.3. Climate change impact (Scenarios 3 and 6)

Besides land use, climate is expected to change in the future period as well. In order to assess the sole impact of climate change on river flow, two scenarios are generated. Scenarios 3 and 6, which represent regional climate model projections from KNMI and DMI, respectively. Changes in stream flow due to climate change (DMI and KNMI RCMs) are illustrated in Fig. 7, which describes the average possible changes for the period 2071–2100. According to the KNMI and DMI model, yearly flow is expected to increase among all the study basins around 10% and 26%, respectively. Both climate models predict a significant decrease in April (40–50%), when typical yearly peak flow occurs from snowmelt. The third major similarity among scenarios is the increase of the winter flow of around 50–70%. Significant differences in the

**Table 3**
Summary of the parameters used for calibration and the fitted ranges over all the study basins.

| Process | Parameter [a] | Description and units | Initial parameter range | Fitted parameter range over all the study basins |
|---|---|---|---|---|
| Groundwater | v_GW_DELAY.gw | Groundwater delay time (days) | 0.5 … 4.0 | 1.31 … 2.19 |
| | v_ALPHA_BF.gw | Base flow alpha factor (days) | 0.05 … 0.25 | 0.10 … 0.18 |
| | v_GWQMN.gw | Threshold depth of water in the shallow aquifer required for return flow to occur (mm) | 0.01 … 15.0 | 2.38 … 7.75 |
| | v_GW_REVAP.gw | Groundwater "revap" coefficient | 0.02 … 0.20 | 0.07 … 0.10 |
| | v__REVAPMN.gw | Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm) | 0.1 … 15 | 9.05 … 14.55 |
| Surface | r_CN2.mgt | Initial SCS runoff curve number for moisture condition II | −0.15 … 0.15 | −0.05 … 0.18 |
| | v__SURLAG.bsn | Surface runoff lag coefficient | 0.05 … 0.15 | 0.06 … 0.13 |
| | v_OV_N.hru | Manning's "n" value for overland flow | 0.1 … 0.4 | 0.14 … 0.32 |
| | v_CH_N2.rte | Manning's "n" value for the main channel | 0.02 … 0.1 | 0.03 … 0.05 |
| | v_EPCO.hru | Plant uptake compensation factor | 0.5 … 1.0 | 0.37 … 0.72 |
| | v_ESCO.hru | Soil evaporation compensation factor | 0.5 … 1.0 | 0.74 … 0.98 |
| Soil | r_SOL_AWC.sol | Available water capacity of the soil layer (mm $H_2O$/mm soil) | −0.2 … 0.2 | −0.32 … 0.42 |
| | r_SOL_K.sol | Saturated hydraulic conductivity (mm/h) | −0.2 … 0.2 | −0.05 … 0.38 |
| | r_SOL_BD.sol | Moist bulk density (mg/$m^3$) | −0.2 … 0.2 | −0.19 … 0.16 |
| Snow | v_SFTMP.bsn | Snowfall temperature (°C) | −1.5 … 1.5 | −1.4 … -0.50 |
| | v__SMTMP.bsn | Snowmelt temperature (°C) | 0.0 … 2.0 | 0.11 … 0.85 |
| | v__SNOCOVMX.bsn | Minimum snow water content that corresponds to 100% snow cover (mm H2O) | 40 … 80 | 43.9 … 76.5 |
| | v__SNO50COV.bsn | Fraction of SNOCOVMX that corresponds to 50% snow cover | 0.4 … 0.7 | 0.44 … 0.64 |

[a] r_: parameter value is multiplied by (1 + a given value) or relative change; v_: parameter value is replaced by given value or absolute change.

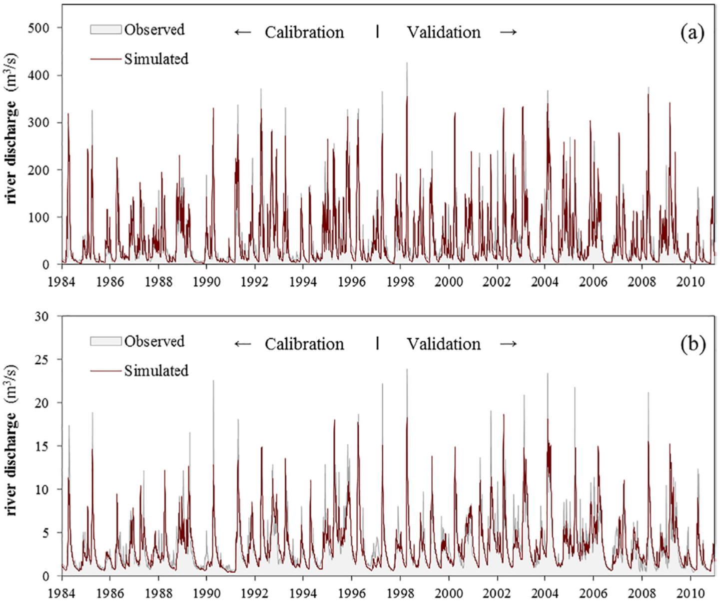

**Fig. 3.** Observed and simulated daily runoff hydrograph at (a) Pärnu river [Oore], (b) Valgejõgi [Vanaküla] in the period 1984–2010.

summer and autumn runoff are evident between Scenarios 3 and 6. Scenario 3 (KNMI) predicts a decrease in runoff for summer and autumn months whereas Scenarios 6 (DMI) reveals a significant increase of runoff around 40–80%. Thus, the signals from both climate models are unclear during this period and add uncertainties to future climate interpretations.

### *4.4. Combined impact of land use and climate change (Scenarios 5 and 8)*

Under the combined impact of climate and land use change, the average annual runoff of the study basins is expected to increase in the future. The effect of deforestation (Scenarios 4 and 7) was not further investigated, because of its marginal impact on runoff. When climate change was considered together with land use change (afforestation), the latter impact on runoff was not so pronounced, compared to climate change. The effect of afforestation was an average reduction of annual runoff by 5% over all study basins. Whereas, the effect of climate change was an annual increase of 10% to 33%, with KNMI and DMI climate model projections, respectively. It is interesting to note that the monthly interquartile range of runoff change in Scenario 5 and 8 clearly narrows, when the generated deforestation map L2 is applied with climate models (Fig. 8). This is especially true for Scenario 8, where the modelled monthly runoff impact “difference” between study basins on winter and spring flows is small (< 10%). Possible changes in the future runoff for the summer and autumn months are unclear. While Scenario 5 shows a decrease (around 20%), whereas Scenario 8 predicts a large increase (around 50%). These differences are inherited from the climate change scenarios, the impact of afforestation is secondary.

## 5. Discussion

The integration of land use change and climate change models with a hydrological model like SWAT, can improve the efficiency of predicting the hydrologic response. Using a combination of both models gives a more realistic description of the processes taking place in the system. The hydrological model gave some answers on the relative importance of land use versus climate change effect on river runoff.

Snow-melt dominated regions in North-Europe are expected to receive more runoff during winter and less is the spring months (Arheimer and Lindström, 2015; Donnelly et al., 2017). These findings are consistent with the current study. The climate change effect on spring runoff is evident, compared with the land use change, where its impact is marginal. This is because the projected increase in temperature, which translates to a shorter snow season and less snow accumulation in winter. However, there is no clear agreement among the climate scenarios, how the autumn runoff will be affected in the study area (Fig. 5).

Different climate change studies analyze certain aspects of the nature, by using different input data quality, methods and assumptions, hindering the straightforward comparison of the results between studies. Karlsson et al. (2016) evaluated the sensitivity of the results to the choice of hydrological model. Although hydrological models showed similar performance during calibration, the mean discharge response to climate change may vary significantly (up to 30% among the used hydrological models). Even with such variations, they found that the choice of the climate model was the dominant factor influencing the mean discharge at the end of the century.

Piniewski et al. (2017) evaluated the robustness (Knutti and

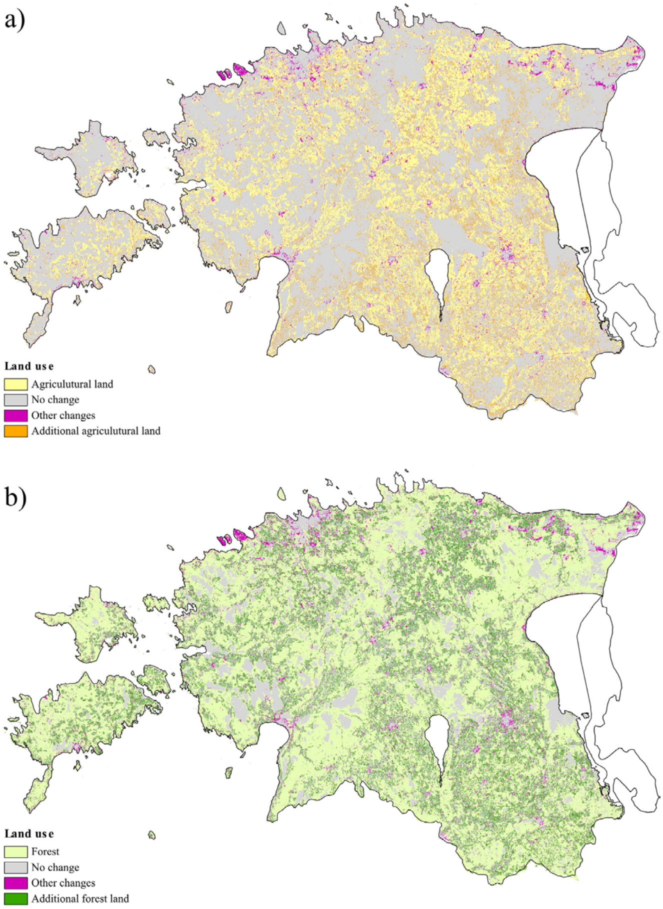

**Fig. 4.** Spatial pattern changes in land use between the baseline (1971–2000) and the future period (2071–2100) under (a) the deforestation and (b) the afforestation land use scenario.

Sedláček, 2013) of the climate change signal in an ensemble of nine bias-corrected EURO-CORDEX simulations over two large basins in Poland, which drain to the Baltic Sea. They found that although the investigated climate models agree on the sign of precipitation change, annual total precipitation projections are not robust (low signal-to-noise ratio). Depending on the climate model used, the change in seasonal precipitation can vary greatly. It can be generalized from their study that seasonal precipitation in the RCP 4.5 scenario shows more robustness than the RCP 8.5. Jacob et al. (2014) showed that future changes among an ensemble of EURO-CORDEX simulations for mean annual temperature are significant and robust in the same Eastern Europe region. Thus, although using only two RsCM's, KNMI and DMI forced by a RCP 4.5, the uncertainty in the interpretation of results increases.

The land use representation in a hydrological model can be either static or dynamic. In current study, a static "averaged" land use map is used for the whole baseline period of 30 years. This is mainly because the lack of dynamic maps for this period. In order to achieve a better comparison basis with the future, static "averaged" land use change scenario maps L1 and L2 were implemented to SWAT. Wagner et al. (2017) found that using a static map approach provides a relatively good approximation of the hydrological impacts if a linear land use

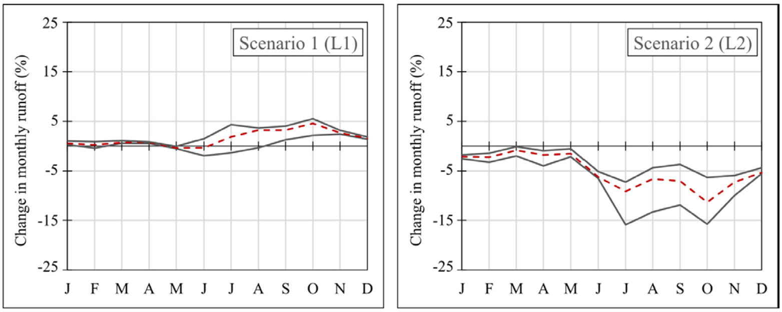

**Fig. 5.** The effect of deforestation (Scenario 1) and afforestation (Scenario 2) on river monthly flow among the study basins (dashed is the median modelled change, solid lines represent the interquartile range).

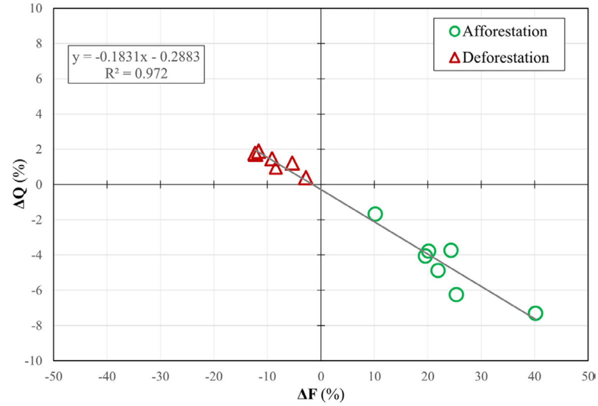

**Fig. 6.** The relationship between forest (ΔF) cover- and annual runoff (ΔQ) change in the study basins.

change is assumed. However, in the Baltics, land use changes have been driven by political decisions, i.e. such rapid changes are unpredictable. Thus, a linear development of land use changes is assumed. However, the importance of a dynamic representation of land use changes should not be neglected (Castillo et al., 2014; Wagner and Waske, 2016).

The magnitude of the land use change impact on runoff varies. Theoretically, increase in the forest cover will lead to higher water-holding capacity of the basin area, and vice versa. Deforestation effect on runoff was analyzed in a small (97 km$^2$) Slovakian basin (Hlásny et al., 2015). The deforestation induced an increase in the total runoff by 20.4%. Tong et al. (2012) found that the effect of land use on runoff can be as significant as climate change (mean daily flow increased 29.1%). In the current study, a 5% forest increase causes around a 1% reduction in annual runoff, revealing a strong linear trend. Changes in annual runoff were more affected in the case of increasing forested land (L2) and during the warm period, whereas deforestation (L1) and during the cold period, the effect is comparably weak.

Zhang et al. (2016) compared the sensitivities of annual runoff to forest cover change in large (≥1000km$^2$) and small (< 1000km$^2$) basins. The hydrological regime was found to be less influential factor in small basins than in large ones. Out of the seven basins used in this study, three can be considered large and four can be categorized as small, however no notable importance on the basin scale was detected.

These results emphasize the importance to apply climate change models with land use. Climate change still seems to be the driving force in the possible changes in runoff regime. However, land use change scenarios should not be discarded from future impact studies. This study did not cover the possible impact on water quality, which is probably more affected by the land use change, compared to quantity (Dimitriou and Mentzafou, 2016; Trang et al., 2017).

## 6. Conclusion

In this study, the SWAT model was applied to assess the potential impact of future climate change and land use change on river runoff in the north-eastern Baltic Sea region. The model was calibrated and validated for the period of 41 years. The SWAT model demonstrated more than satisfactory performance. The calibrated SWAT model was used as

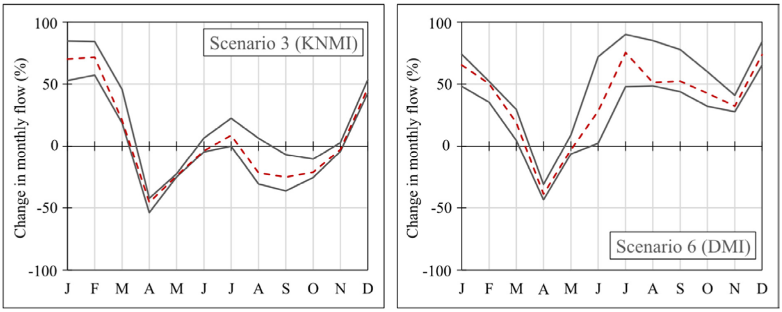

**Fig. 7.** The effect of climate change Scenario 3 (KNMI RCM) and Scenario 6 (DMI RCM) on river monthly flow among the study basins (dashed is the median change, solid lines present the interquartile range).

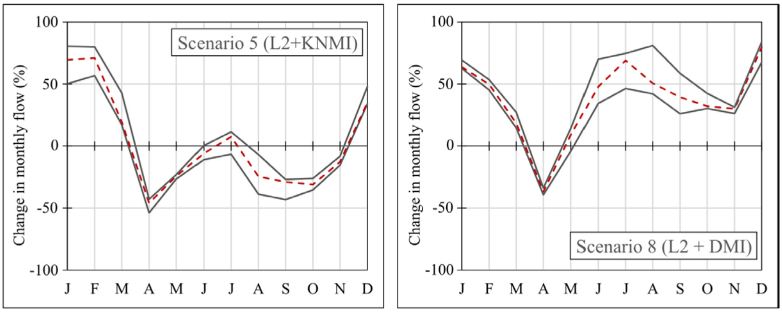

**Fig. 8.** The effect of climate and land use change Scenario 5 (KNMI RCM and afforestation) and Scenario 8 (DMI RCM and afforestation) on river monthly flow among the study basins (dashed is the median change, solid lines present the interquartile range).

a tool to estimate possible water resource changes in the future. For this, two hypothetical (but plausible) land use change maps were generated and two climate change model projections were used. From these maps and models, different scenarios were generated and assessed. According to the results, annual average flow is expected to increase by the end of the century, compared to the baseline period. There is a strong agreement among RCMs for winter and spring, where notable changes were found. However, the magnitude of the change (during the summer and autumn period) varies greatly among the climate change scenarios.

The principal finding of this study is the strong linear correlation between forest cover change and river flow change. It can be generalized to the study region, a 5% forest cover reduction causes a 1% increase in annual runoff. Secondly, land use change impact on runoff is important on an annual scale, in the study region. However it was found that changes in land use does not alter the monthly runoff variation as significantly as climate change. Thirdly, the combined effect of land use and climate change was found to be non-additive in the study.

In general, findings from the would be beneficial to policy makers as it contributes to a deeper understanding of natural and man-made processes, to develop long term strategies in forest management and to harness the positive impacts of overall increase (e.g. increased hydropower potential) in the north-eastern Baltic Sea region river runoff.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.catena.2018.04.029. These data include the Google map of the most important areas described in this article.

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# III

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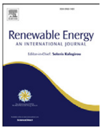

# Verification of a robust method for sizing and siting the small hydropower run-of-river plant potential by using GIS

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ABSTRACT

The global renewable energy potential estimates vary hundredfold, while the estimates for global hydropower vary fourfold. Thus, an accurate method of assessing the small hydropower (SHP) potential at regional and (sub)-national scales is required. This study aims to present and verify a robust method for sizing and siting the SHP potential by utilizing the capabilities of GIS. The proposed virtual hydropower assessment (VHA) method identifies suitable locations for hydropower production based on digital elevation and specific discharge maps. VHA was conducted for Estonia, a low-lying country in Europe. Twenty operational or abandoned SHP in thirteen rivers were used for verification. There is a good overall agreement between the computed virtual and installed capacities. The VHA method provided a realistic output for SHP location siting and revealed some unexploited opportunities to install micro and mini-hydro schemes in all of the analyzed rivers. Further research is required with a larger verification data sample for the VHA method to investigate the effects of the digital elevation model resolution, river segment length, and hydrological components. The outcomes of this study provide a reliable and robust method of assessing the SHP potential worldwide, particularly in countries where meteorological and hydrological data are scarce.

## 1. Introduction

Despite the continuing slowdown in the population growth rate [1], the global demand for energy is still expected to increase by 25% by 2040 [2]. Renewable energy (RE) sources, including biomass, hydro, solar, geothermal, and wind resources, are expected to play an important part in meeting this need. This is mainly due to the ability of RE to mitigate the negative effects of climate change [3]. The changing climate conditions have already redistributed water resources in different regions [4,5], and this phenomenon is expected to continue in the future [6,7]. In the context of RE and hydropower potential, these changes will either be positive or negative, depending on the region of interest [8].

Various types of potentials can be defined when assessing RE sources. The theoretical potential is the total natural energy of a given renewable source. Much of this theoretical potential remains undeveloped due to technological, environmental, and economic constraints. The technical potential is the energy that can be utilized with the existing technology. The exploitable potential also considers non-technical factors, such as environmental restrictions (mainly the possible negative environmental impacts and the availability of land). The economic potential is the exploitable potential that is financially beneficial if utilized, and depends on the cost of the facility and the energy price. The exploitable and economic potential are highly location-dependent, therefore, they require in-depth analysis at each potential site. This is likely the main reason why most RE assessment studies have focused on the theoretical and technical potential.

The current published estimates for the total RE technical potential vary greatly as they highly depend on the method used [9]. The potential of various RE sources is usually estimated using spatial tools, such as geographic information systems (GIS). Various studies have conducted GIS assessments for estimating the potentials of wind [10,11], solar energy [12,13], biomass [14,15], and geothermal [16,17] sources and their locations. Hydropower has received an extensive amount of interest at various scales. In this decade, four studies have estimated the global hydropower theoretical potential to be between 31 and 128 PW h per year [18–21]. These estimates are sensitive to the assumptions made and quality of the input data used (such as the resolution of the digital elevation

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map). It is estimated that the global available economical hydropower potential (available at a cost below US\$0.10 $kWh^{-1}$) is 5.7 PW h per year, located primarily in the Asia Pacific region (37%), South America (28%), and Africa (25%) [22]. Many studies have focused on assessing the potentials of hydropower at regional and (sub-)national scales [23–28], most of which focus on synthesizing streamflow for ungauged rivers, which has been achieved by hydrological modeling [23,26,27], flow-duration curves [24,28], or an alternative method [25,29]. Depending on the method followed, an extensive amount of input data may be required. Thus, a robust method may be needed for the regions where data are scarce, limited, or sparsely distributed.

Hydropower projects can be classified according to the size, head, and facility type. This study addresses small-scale hydropower plants, which have a capacity size of up to 10 MW. This approach of classifying small and large-scale hydropower plants is common in Europe [30]. Small hydropower (SHP) can be further classified into mini (<1 MW), micro (<100 kW), and pico (<5 kW) plants. The most common types of facility are pumped storage, reservoir storage, and run-of-river (RoR) hydropower [31]. This study focuses on RoR-type plants, which may exhibit significant fluctuations in energy production as it is directly affected by weather conditions and its highly limited ability to store water.

Hydropower production is often subject to various constraints that limit its full technical potential. These limitations can be classified as social, environmental, operational, and regulatory [32–35]. Depending on the type of constraint, considering these limitations with GIS can either be straightforward or problematic. For example, extracting naturally protected areas from the analysis is simple in GIS, while considering the social or operational aspects could be more difficult. Despite its shortcomings, hydropower is still expected to play an important role in the RE portfolio [36,37]. Furthermore, besides hydropower production, dams and their associated reservoirs can store water for later use. This will become more important with the increasing demand for drinking and irrigation water in the future [38].

Estonia's energy policy is currently in a transitioning from environmentally intensive oil shale-based energy production to clean renewable energy sources. Electricity production from renewable sources has been increasing annually. The reported growth in 2017 was 13% from that of 2016. However, coal persists as one of the most important energy source in the country. Since joining the European Union (EU), the annual hydropower output in Estonia has increased from 14 GWh in 2006 to 42 GWh in 2012. Despite the strict environmental policies regarding the expansion of hydropower, hydropower generation in Estonia has increased almost three-fold since joining the EU (Fig. 1). The average annual increase in hydropower production over the last 25 years is approximately 1.6 GWh. This trend will probably slow and cease in the near-future due to the ever-increasing environmental standards and requirements for hydropower production in Estonia.

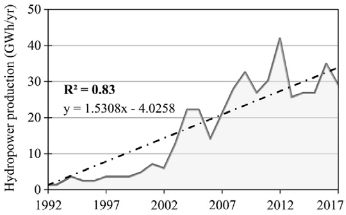

**Fig. 1.** Annual hydropower production and trend (dash-dotted line) in Estonia from 1992 to 2017.

The siting of locations to produce energy through hydropower is important for local investors and policymakers. A GIS-based assessment method can rapidly and robustly identify unutilized SHP plant locations. The estimation of various hydropower potentials has gained significant interest, however, verification, particularly that of the siting of hydropower locations, has not been demonstrated to date. This may be one of the reasons for the great differences in the global and regional estimates of theoretical and exploitable hydropower potentials. Hence, a verified method for the sizing and siting of SHPs with GIS tools is necessary for a credible result.

We hypothesize that the use of specific discharge maps as the hydrological component allows the rapid and precise evaluation of exploitable SHP potentials for large, poorly gauged regions. This hypothesis is tested in a low-land country, Estonia, where most of the hydropower is produced by RoR-type plants. The accuracy of the proposed model is verified using installed plants for comparison. Model verification will provide insight into the overall accuracy of this GIS hydropower sizing and siting method.

## 2. Material and methods

In the numerous hydropower potential assessment studies, GIS is the most commonly applied tool for assessing the energy potential at local and regional scales. Searching for new, appropriate locations to produce hydropower can be a resource-intensive task, requiring expensive field studies and extensive hydrological analysis. This study attempts to minimize the amount of input data necessary for assessing the technical hydropower potential. The flowchart of the proposed virtual hydropower assessment (VHA) method for sizing and siting SHP sites for hydropower generation along a river is presented in Fig. 2. The necessary topographic attributes of the river watershed are all derived from the digital elevation model (DEM). To calculate the hydropower capacity, historical river discharge data are used to generate the mean annual

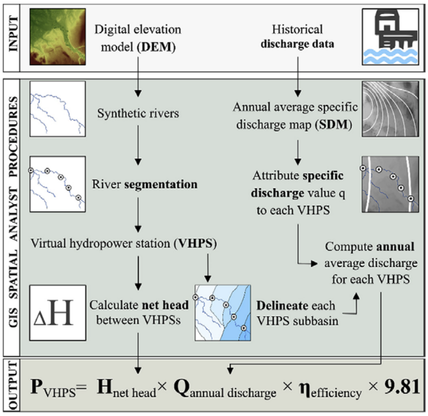

**Fig. 2.** Virtual hydropower assessment framework.

specific discharge map (SDM) by using GIS. VHA is a robust straightforward method, which does not rely on site specific parameters, e.g., penstock length, turbine type and efficiency.

As shown in the methodological framework, a synthetic river network is directly derived from the DEM using the built-in flow routing algorithms of ArcGIS. The generated rivers are divided into equal segments with a user-defined distance moving upstream to the end of each segment, where a virtual hydropower station (VHPS) is located. This study uses a distance of 1000 m. The calculated elevation difference between the VHPSs is specified as the net head for power calculation. The DEM is also used for delineating the subbasin areas for each VHPS moving downstream, i.e., indexing begins upstream. Historical discharge data from the nearby gauging stations are used to generate the SDM. The inverse distance weighting (IDW) interpolation technique is applied in GIS to generate the SDM, and an average specific discharge value from the SDM is attributed to each VHPS.

The magnitude of the hydropower production potential is directly dependent on the discharge, specific weight of water, and the hydraulic net head. The virtual hydropower plant capacity at any given location can be calculated as follows:

$$P_{VHPS} = \Delta \mathrm{hQ}\eta \mathrm{g} \tag{1}$$

where $P_{VHPS}$ is the computed virtual hydropower plant capacity (kW), Δh is the net head (m) computed from the elevation differences between the VHPSs, Q is the discharge rate ($m^3s^{-1}$), η is the overall system efficiency (unitless), which is assumed to be 75% (0.75), and g is the acceleration due to gravity (9.81 $ms^{-2}$). The VHA method uses the annual average discharge as the hydrological component for each VHPS, which is derived from the SDM as follows:

$$\begin{aligned}
&\forall_i : i = 1 \ldots n-1 \quad Q_i = A_i q_i + Q_{i+1} \text{and} \quad Q_n = A_n q_n \\
&Q = Q_1 = A_1 q_1 + Q_2 = A_1 q_1 + A_2 q_2 + Q_3 = \\
&= A_1 q_1 + A_2 q_2 + \ldots + Q_n = \\
&= A_1 q_1 + A_2 q_2 + \ldots + A_n q_n = \\
&= \sum_{i=1}^{n} A_i q_i
\end{aligned} \tag{2}$$

The discharge rate Q ($m^3s^{-1}$) for the first VHPS is obtained by multiplying the annual average specific discharge value q ($m^3s^{-1}km^{-2}$) of the first VHPS with the subbasin area A ($km^2$). Moving downstream to the next VHPS, its subbasin is delineated. The area gained for the given river segment is multiplied by the specific discharge value of the corresponding VHPS. The multiplication result is added to the previous discharge rate to obtain the discharge rate of that VHPS. The same procedure is repeated to obtain the discharge for every VHPS is until the river mouth (Equation (2)).

### 2.1. *Method verification*

The performance of the proposed VHA method, should be investigated to ensure its suitability. Historically installed and currently operating hydropower plants can be used to verify the capacity and the location. Many of the previous hydropower-siting studies have discarded the need to verify the accuracy of the proposed methods, thus, reducing the credibility of their results. Typically, a combination of qualitative and quantitative criteria is applied to determine the representativeness of a proposed method or model. These include statistical methods, such as the coefficient of determination (R2) or even simple graphical XY plots for visual comparison.

$$R^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2}} \right)^2 \tag{3}$$

where O and P are the installed and computed values, respectively, and n is the number of hydropower stations used for assessment. The R2 statistic ranges from 0 to 1, where 0 indicates no correlation and 1 indicates a perfect correlation between the model and reality.

## 3. Study area

The proposed VHA method was applied to all of the larger rivers in Estonia, where hydropower has been or is currently being harvested. Estonia is situated between 57.5° and 59.5° N on the eastern coast of the Baltic Sea (Fig. 3). With an average elevation of around 50 m above sea level, the majority of its hydropower potential originates from the river discharge rate, rather than the net head. There are over 7000 streams and rivers in Estonia, most of which are short and have a relatively small annual river discharge rate.

Estonian hydrological regimes are characterized by large seasonal variations in river flows. A low winter discharge is followed by a snowmelt-driven spring flood peak, followed by low discharge in summer and higher precipitation-induced flows in the fall. The uneven seasonal water availability, particularly the water shortages during summer, affects the water supply for hydropower production. The seasonal fluctuations and small river runoff only allow SHP generation through RoR-type hydropower plants.

Most hydropower potential estimation methods utilize GIS functionality to directly extract the net head from the DEM by using various GIS tools [29,39,40]. The proposed VHA method requires a DEM for the net head calculation and the delineation of subbasins for each virtual station. In this study, the freely available Estonian Land Board 2012–2017 elevation data were used with a resolution of 25 m. The hydrological data necessary for SDM generation were obtained from the Estonian Weather Service website of the Estonian Environment Agency. Data from 32 river discharge-gauging stations were used to generate the SDM for the whole of Estonia (Fig. 4).

## 4. Results

The proposed hydropower sizing and siting VHA method was applied to Estonia to evaluate its usability in RoR-type SHP plants through various built-in ArcGIS spatial analyst procedures. To evaluate the performance of the developed method, its results were compared with the design and installed capacity of larger Estonian hydropower plants. Data from twenty currently operating or abandoned SHP in thirteen rivers were used for verification of sizing (Table 1). Fig. 5a shows the goodness-of-fit of the proposed model. The fitted linear regression with an R2 value of 0.97 and slope of 1 demonstrates no overall significant difference between the installed and computed virtual capacities. Furthermore, visual inspection revealed no systematic over- or underestimation, excluding one outlier (marked with an asterisk) in Keila River.

Fig. 5b shows a weaker correlation of 0.53 between the computed virtual capacities and the installed capacities of mini SHP with a narrower range of 0.5 MW. This result is expected, as social, environmental, and other local conditions have a greater effect on the design than they would on larger hydropower schemes. Also, the proposed model does not directly consider the hydropower turbine type, generator efficiency, or the penstock head losses. To determine whether the model estimates are biased and usable, residual plot analysis was conducted (Fig. 6).

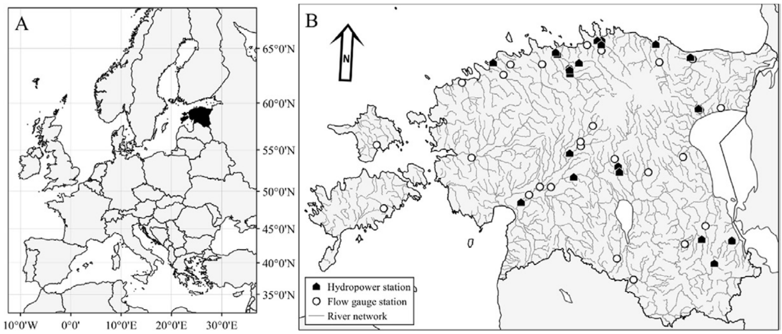

**Fig. 3.** (A) Location of the study area in Europe (marked in black); (B) map of Estonia with rivers, discharge gauging and hydropower stations.

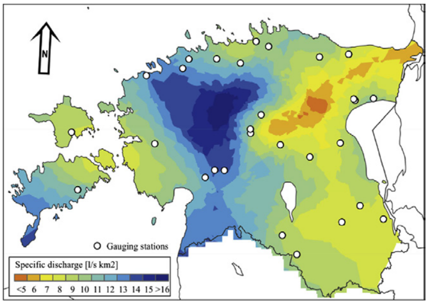

**Fig. 4.** Specific discharge map of the study area with the location of discharge gauging stations.

The residual plot shows that all residuals, excluding one distinguishable outlier, are within the same range of approximately ±100 kW, i.e. residuals in higher capacities tend to be relatively lower. There is no clear trend towards positive or negative values, indicating an overall insignificant bias. Keila River differs to that of other SHPs, with a significantly higher residual value of approximately 350 kW. This discrepancy can be attributed to the existing local terrain conditions and method simplifications. These uncertainties are inevitable due to the assumptions of the VHA method, as well as the spatial and temporal accuracy of the data. This robust method produces acceptable results, and is usable for estimating the initial technical hydropower potential.

In-depth analysis was conducted to estimate the sizing and siting accuracy. The results of applying the proposed VHA method to the Jägala, Keila, and Valgejõe Rivers are shown in Fig. 7. The dash-dotted bar correspond to the installed capacity (kW) of the plants, while the solid bars indicate the computed virtual capacity of the river. These North-Estonian rivers flow to the Baltic Sea. In the upper reaches of the rivers, the hydropower potential is relatively small due to the low discharge rate. Thus, Fig. 7 presents the results for the first 35 km from the river mouth.

**Table 1**
Summary of the SHP stations used in the study (H - net head, Q - design discharge, P-capacity).

| River (SHP) | H (m) | Q ($m^3/s$) | P (kW) |
|---|---|---|---|
| Ahja (Saesaare) | 8.0 | 3.0 | 194 |
| Jägala (Linnamäe) | 10.0 | 13.5 | 1152 |
| Jägala (Jägala-Joa) | 17.0 | 13.5 | 2000 |
| Jägala (Kaunissaare) | 3.5 | 9.2 | 246 |
| Jägala (Tammiku) | 2.5 | 10.0 | 220 |
| Keila (Keila-Joa) | 8.7 | 5.5 | 365 |
| Kunda (Kunda-Vana) | 9.0 | 7.0 | 400 |
| Kunda (Kunda-Silla) | 6.4 | 7.0 | 336 |
| Loobu (Joaveski) | 11.0 | 3.0 | 300 |
| Navesti (Tamme) | 2.8 | 6.8 | 158 |
| Purtse (Sillaoru) | 7.8 | 8.0 | 300 |
| Põltsamaa (Kamari II) | 5.0 | 7.2 | 311 |
| Põltsamaa (Silla) | 2.5 | 8.0 | 185 |
| Pärnu (Jändja) | 2.5 | 4.0 | 190 |
| Pärnu (Sindi) | 3.2 | 50.0 | 1290 |
| Rannapungerja (Tudulinna) | 6.0 | 2.5 | 150 |
| Soodla (Soodla) | 12.0 | 1.6 | 155 |
| Valgejõgi (Kotka) | 6.5 | 4.5 | 160 |
| Valgejõgi (Nõmmeveski) | 8.0 | 4.3 | 200 |
| Võhandu (Leevaku) | 3.0 | 7.9 | 184 |
| Võhandu (Räpina) | 5.0 | 9.0 | 350 |

There are five SHPs installed along the Jägala River (Fig. 7a), which were used to assess the sizing and siting accuracy. Approximately half of the river segments have a relatively low hydropower potential, only allowing the generation of micro- or pico-hydropower with low economic feasibility. There is a good agreement between the computed virtual and installed capacity in all cases, and the siting is consistent with the installed SHP locations. Unutilized hydropower locations with a capacity above 100 kW were identified. For example, a new mini SHP with a capacity of around 300 kW could be built 28 km upstream of the river.

Most of the hydropower potential of the Keila River is located near the river's mouth (Fig. 7b). This result clearly deviates from those of other rivers, where most of the suitable locations for hydropower production have already been occupied. The only currently operating SHP in Keila River has an installed capacity of 365 kW, which is over twofold lower than the computed virtual capacity. Additionally, the VHA method identified unutilized potential hydropower sites at the river mouth that have a similar capacity to the operating station. This river segment will likely

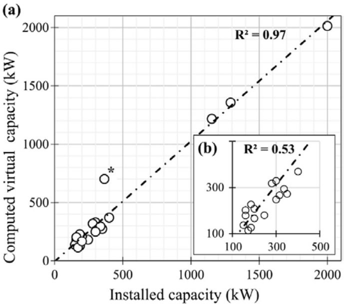

**Fig. 5.** Goodness-of-fit plot for the virtual and installed SHP capacities for larger Estonian hydropower plants.

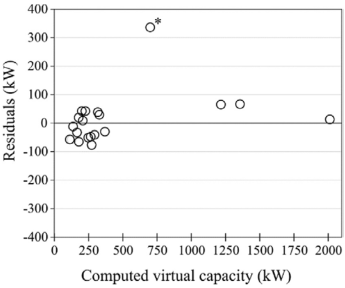

**Fig. 6.** Residual plot of the proposed VHA method.

remain unexploited due to environmental constraints.

Close to the mouths of the Jägala and Keila Rivers, the river valleys cut into the Baltic Klint, yielding higher net head. There are more suitable locations for hydropower production in the middle reaches of the Valgejõe River. The best locations for hydropower production identified by the VHA method are in good accordance with the already installed SHP locations (Fig. 7c). The sizing of the virtual capacities was also successful, as the differences between the virtual and installed capacities are negligible. Most of the suitable locations for hydropower production have already been exploited. However, there are still some potential areas for installing micro- and mini-hydro schemes in all of the rivers used for verifying the VHA method.

## 5. Discussion

To our knowledge, this study is the first to estimate the accuracy of a SHP sizing and siting method using GIS. GIS has been widely used for screening environmentally sensitive areas that are not suitable for hydropower production [41]. Several GIS-based site-selection tools have been presented [42,43], in hydropower studies to only validate river discharge. Verification with the location-specific installed capacities allows the separate uncertainties originating from the input data quality to be evaluated, including the resolution of the DEM and the hydrological component used. With the suggested VHA method, identifying and sizing new unutilized locations for SHP harvesting in any given river is robust and automated, and requires a minimal amount of input data.

Assessing the technical hydropower potential at any location along a river requires a hydrological component. The use of measured discharge data is always preferred, but they are rarely available along the entire river length. There are various alternatives for estimating the required discharge data based on different techniques [42]. River discharge can be estimated from rainfall and evaporation distribution maps [39]. However, reliably assessing water resources requires more complex hydrological modeling [26,44–46]. For example, the hydrological model SWAT was used to assess the theoretical hydropower potential of a hilly watershed in the Kopili River Basin, India [26]. However, the SWAT model requires diverse information for use [47]. A more simple method of obtaining discharge values for an ungauged location is the drainage-area ratio method [48], where existing discharge data series or statistics are transferred to nearby areas. One of the main limitations of this method is that it assumes that discharge scales directly with the watershed area, thus, it is inapplicable for heterogeneous watersheds [49]. The annual specific discharge map used in this study is simple to construct and only uses the gauged data of the region of interest, requiring a modest amount of data.

The verification of the methodology revealed an excellent overall linear fit between the virtual and installed capacities. However, the accuracy for smaller plants is lower than that for SHP plants with a capacity of over 1 MW. This finding should be considered when sizing and siting mini and micro hydropower plants. This result is somewhat expected, because, with smaller capacities, the importance of the input data quality and site-specific factors (turbine selection, penstock length) increases. Albeit the method is robust, it has the ability to efficiently assess the hydropower potential on river segments along the whole river and if the capacity of the SHP tends to be attractive, then an optimizing process can be carried out for further analysis [50]. Finally, the installed capacity is derived from the site-specific technical and non-technical parameters. Thus, the proposed VHA method is suitable for regional analysis and for the initial screening of suitable locations.

The accuracy of the net head calculation depends directly on the DEM's resolution. Although finer scale DEMs are available in the study area, a DEM with a resolution of 25 m was implemented, corresponding to the globally available Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model. Usually, a coarser DEM results in a decreased representation of the watershed area and the net head. Zaidi and Khan used a 30 m DEM in a mountainous area and suggested its possible limitations in flat areas [51]. This study demonstrated the suitability of using a 25 m DEM for hydropower potential assessment in flat areas. The greatest potential for expanding SHP lies in low-head sites [52], demonstrating the rationale for the development of accurate SHP assessment tools.

The proposed VHA method uses a fixed distance for river segmentation. However, this may vary depending on the planned SHP capacity, river profile, and other factors. Thus, the length of the river segment can be adjusted accordingly. Other criteria associated with the sizing and siting of hydropower potential are the social, environmental, operational, and regulatory limitations, which must be considered in a hydropower project-feasibility study. Climate-related uncertainty should be considered carefully [53–55] to assess the global and regional trends altering the hydropower potential. The verification of the VHA method allows the predicted aspects to be systematically analyzed to identify uncertainties derived from the input data. A method verification procedure should be implemented to other renewable resource studies to

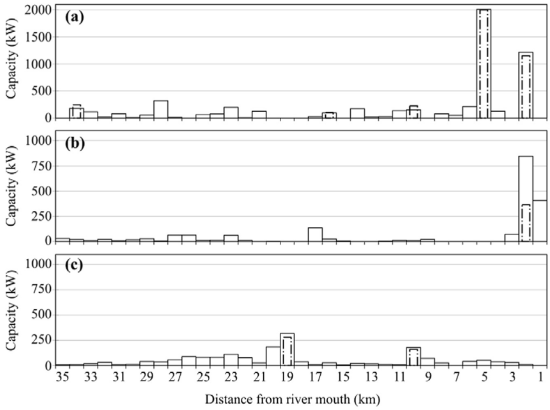

**Fig. 7.** Results of the VHA method, including the computed virtual hydropower station locations and capacities compared to installed plants (dash-dotted line) in three Estonian rivers: a) Jägala, b) Keila, and c) Valgejõe.

increase the reliability of the results.

## 6. Conclusion

Hydropower is expected to play an important part in satisfying the increasing global demand for energy. A method has been developed for the sizing and siting of technical hydropower potential. The proposed VHA method is robust and automated in GIS, and only requires a DEM and the gauged river discharge as input data. A synthetic river network with the topographic attributes are directly derived from the DEM. The generated rivers are divided into equal user-defined segments starting from river outlet. VHPS are located to the end of each segment. River discharge is used to generate the SDM that will be used to attribute average specific discharge value to each VHPS. The virtual hydropower plant capacity is computed from the attributed discharge and net head, which is multiplied with the overall system efficiency (e.g. 75%) for each VHPS.

The developed approach was implemented for Estonia, where data from twenty currently operating or abandoned SHP in thirteen rivers were used for method verification. The VHA method could produce a realistic output for SHP location siting and capacity sizing, revealing some unexploited opportunities to install micro- and mini-hydro schemes in all of the analyzed rivers. Verification procedures for hydropower and RE capacity provide more reliable assessments. Further research is required with a larger verification data set for the VHA method to investigate the effect of the DEM resolution, river segment distance, and hydrological components. The outcomes of this study provide a reliable and robust method for assessing SHP potential worldwide, and especially in countries where meteorological and hydrological data are scarce.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRediT authorship contribution statement

**Ottar Tamm:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Toomas Tamm:** Writing - review & editing, Resources, Supervision.

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# CURRICULUM VITAE

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**Education:**

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| 2013 - 2020 | PhD studies, Estonian University of Life Sciences, Institute of Forestry and Rural Engineering |
| 2011 - 2012 | ERASMUS exchange student in Czech University of Life Sciences, Faculty of Environmental Engineering, Environmental Modelling |
| 2007 - 2013 | Master's studies, Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Water Management |
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| 2018 – 2020 | T180062MIMV "Applied research in water companies to optimize windrow composting technology for sewage sludge to apply end-of-waste regulation” |
| 2013 – 2016 | 8-2/T13003MIGO "The impact of land-related decisions on the use of land, forest and water resources” |
| 2015 | 8-2/T15070MIVE "Elaborating a methodology for sharing the maintenance costs of agricultural drainage systems into which additional water is conducted |
| 2012 – 2014 | 8-2/T12003MIVE "Assessment of possible changes of Estonian climate and environmental status on the basis of dynamical modeling of atmosphere, ocean and river runoff” |
| 2012 – 2014 | 8-2/T12088PKKS "Promoting Sustainable Urban Drainage Systems in Estonia-Latvia cross-border area to improve the environment for active and sustainable communities” |
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| 2015 | BONUS – Doktoriõpe, hüdroloogiline modelleermine HYPE mudeliga |

Teadustöö põhisuunad:

hüdroloogiline modelleerimine; maakasutuse ja kliima muutuste mõju veeressurssidele; GIS kaugseire ja modelleerimine; hüdroenergia; ekstreemsed hüdroloogilised sündmused (üleujutused/uputused); tsiviilinseneeria; keskkonnainseneeria

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| 2018 – 2023 | V170224PKKK „Säästlike ja kliimakindlate linna sademeveesüsteemide arendamine” |
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| Teaduskraad: | tehnikateaduste magister (veemajandus) 2013. Lõputöö pealkiri: “Kunda jõe hüdroenergeetilise potentsiaali modelleerimine” |

# LIST OF PUBLICATIONS

1.1 Pehme, K.-M., Orupõld, K., Kuusemets, V., **Tamm, O.**, Jani, Y., Tamm, T., Kriipsalu, M. Field Study on the Efficiency of a Methane Degradation Layer Composed of Fine Fraction Soil from Landfill Mining. Sustainability 2020, 12, 6209.

1.1 **Tamm, O.**, Tamm, T. 2019. Verification of a robust method for sizing and siting the small hydropower run-of-river plant potential by using GIS. Renewable Energy, 155, 153-159.

1.1 **Tamm, O.**, Maasikamäe, S., Padari, A., Tamm, T. 2018. Modelling the effects of land use and climate change on the water resources in the eastern Baltic Sea region using the SWAT model. Catena, 167, 78–89.

1.1 Kotta, J., Herkül, K., Jaagus, J., Kaasik, A., Raudsepp, U., Alari, V., Arula, T., Haberman, J., Järvet, A., Kangur, K., Kont, A.; Kull, A., Laanemets, J., Maljutenko, I., Männik, A., Nõges, P., Nõges, T., Ojaveer, H., Peterson, Reihan, A., Rõõm, R., Sepp, M., Suursaar, Ü., **Tamm, O.**, Tamm, T., Tõnisson, H. (2018). Linking atmospheric, terrestrial and aquatic environments in high latitude: Regime shifts in the Estonian regional climate system for the past 50 years. PLOS ONE, 13 (12), ARTN e0209568–20.

1.1 **Tamm, O.**, Luhamaa, A., Tamm, T. 2016. Modeling future changes in the North-Estonian hydropower production by using SWAT. Hydrology Research, 47 (4): 835-846.

2.5 Raudsepp, U., Jaagus, J., Alari, V., Arula, T., Järvet, A., Kont, A., Kotta, J., Kull, A., Laanemets, J., Maljutenko, I., Männik, A., Reihan, A., Rõõm, R., Sepp, M., Suursaar, Ü., **Tamm, O.**, Tamm, T., Tõnisson, H. 2015. Eesti kliima ja keskkonnaseisundi võimalike muutuste hindamine atmosfääri-, mere- ja jõgede äravoolu dünaamiliste mudelite tulemuste põhjal

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5.2 Pehme, K.-M., Heinsoo, M., Tammjärv, K., **Tamm, O.**, Kriipsalu, M. 2017. A Long-Term Study on Methane Degradation Layer Extracted from the Landfill. The Thirty-Second International Conference on Solid Waste Technology and Management. Abstracts of Presentations: The Thirty-Second International Conference on Solid Waste Technology and Management. March 19-22, 2017; Philadelphia, PA USA. Ed. Widener University. Philadelphia, PA, USA: Widener University.

5.2 Heinsoo, M., Pehme, K.-M., Orupõld, K., Kuusemets, V., **Tamm, O.**, Kriipsalu, M. 2016. Methane emissions in previously excavated Kudjape landfill. 10th International Conference on Establishment of Cooperation between Companies and Institutions in the Nordic Countries, the Baltic Sea Region, and the World. Book of Abstracts. Linnaeus ECO-TECH 2016: 10th Linnaeus Eco-Tech 2016 conference, Kalmar, 21 – 23 November 2016. Ed. Alriksson, Stina; Lundström, Jelena; Hogland, William. Sweden: Linnaeus University, 243.

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