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Report

GIS-based mapping of potential pump storage sites in Norway

Description of the tool and first results of the analysis

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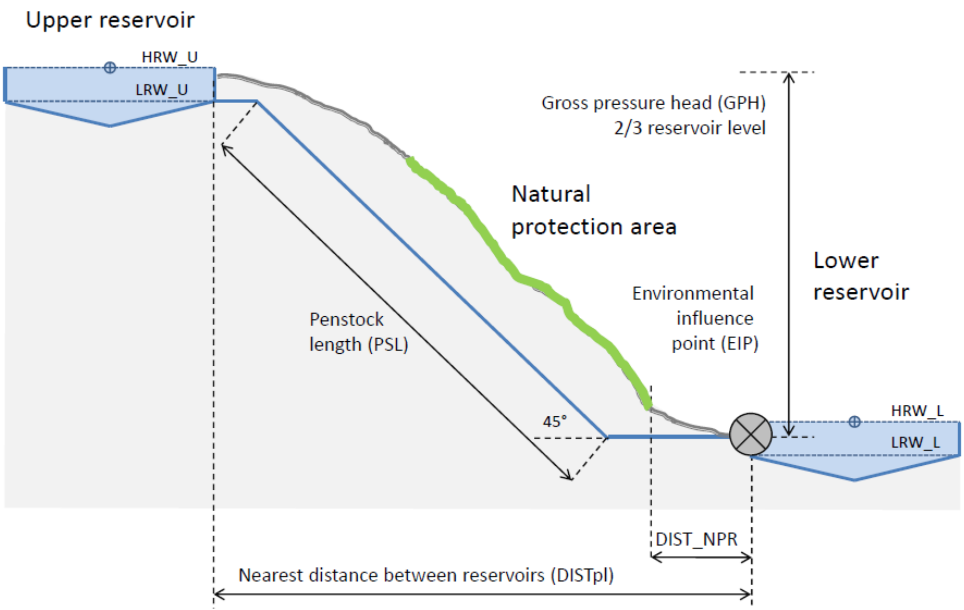

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ABSTRACT

The report describes the development and application of a GIS-tool for the investigation of the pumped storage hydropower (PSH) potential in Norway. The assessment includes existing reservoirs and dams only.

The GIS-tool was built for ArcGIS 10 using Python script tools. It includes a topographical analysis and a screening based on user-defined selection criteria, such as distance between reservoirs, power generation, gross pressure head, storage duration, rate of water level change in the reservoirs and distance to power lines, roads and environmental restriction zones. The result maps showed that in particular the reservoirs in the mountains of South-Norway have a high PSH potential. Many sites are in conflict with environmental restrictions. The screening results were highly influenced by the locally uncertain net inflow rates from reservoirs due to existing power plants. More investigations about the appropriate consideration of environmental issues and a further development of the GIS-tool are necessary.

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2.1	2013-01-29	Final reading version with some formal adjustments, compared to version 2.0.
2.2	2013-02-19	Final version, after inclusion of minor corrections.

Table of contents

Abbreviations frequently used in the text:

DEM	Digital elevation model
DN	Norwegian Directorate for Nature Administration (Direktorat for naturforvaltning)
dW	Water level change rate (in m/hour)
EFTA	European Free Trade Association
EIP	Environmental influence point
EPP	Existing hydro power plant
EU	European Community
FFH	Flora Fauna Habitats Directive
GIS	Geographical Information System
GPH	Gross pressure height
HP	Hydro power
HRW	Highest regulated water level
LRW	Lowest regulated water level
NVE	Norwegian Water Resources and Energy Directorate (Norges vassdrags- og energidirektorat)
P	Power production / capacity (in MW)
PL	Power line
PSH	Pumped storage hydropower
PSL	Penstock length
SKV	Norwegian Mapping Authority (Statens kartverk)
SPA	Special Protection Areas (Birds)
Td	Storage duration (in days)
UNESCO	United Nations Educational, Scientific and Cultural Organization

1 Introduction

1.1 The objectives of this study

Norwegian hydro-electric reservoirs have considerable storage capacity. There is great international and national interest in Norway’s ability to supply balance power services over various time scales to the European electricity market. Pumped storage hydropower (PSH) is currently the only economically viable storage technologies to provide large scale electricity storage, which is vital for accommodating the further development of renewable energy sources and their integration into the power grid. Therefore the technical potential of balance power in Norway and its environmental impacts as well as grid connection have to be studied.

The present document describes the development and application of a GIS-tool which allows studying the potential for pump storage all-over Norway, based on assumptions similar to those described by Solvang et al. (2012).

1.2 State of the art in GIS-based mapping of pumped storage hydropower potential

In many European countries, the assessment of pump storage potential is focussed on the selection of land areas where new reservoirs for pump storage can be built. The basic operation of such GIS modules is the identification of suitable sites based on the criteria such as the "flatness" of the terrain, in combination with further selection routines (Arántegui et al. 2011, Schmidt et al. 2011, Corolly et al. 2012).

Arántegui et al. (2011) developed a methodology aiming at the development of a database of dams (reservoirs) and hydropower schemes with either a storage capacity of more than1 Mio m^3 or a power production greater than 1 MW covering countries of the EU, EFTA, Western Balkan and EU candidate/potential candidates. Their basic steps include an analysis the topography, physical restrictions and the grid (Fig. 1).

Schmid et al. (2011) applied similar approaches when they analysed the potential for pump storage in the federal country of Thüringen (Germany). For the assessment of potential sites, i.e. potential new storage reservoirs, they used the following criteria:

- Topographical suitability (Gross pressure head, Storage volume, Horizontal distance, Areal need, Relief of the upper reservoir area)
- Geology (Stability/Self-support, Permeability, Suitability for subterranean excavation)
- Water resources (Ratio of water resources to turbine capacity)
- Connection to power lines (Distance of the high-voltage network, Distance of the super-grid)
- Existing land use (Single elements of settlements and infrastructure, Roads, Railways, Pipelines, Airports, etc.)
- Environment (FFH/SPA-areas, Natural protection zones / Natural parks / National parks, Biosphere reservations, Water reserves, Landscape protection areas)
- Acceptance (Known conflicts with opposite interests)

Corolly (2012) used Ireland for a case study and investigated the role of energy storage for integrating intermittent renewable energy in the form of wind power. He defined the potential for the creation of two large reservoirs, i.e. 2 Mio m^3, at different altitude and in a horizontal distance of less than 5 km from each other as criteria for the location of suitable PSH sites. The software tool allows identifying potential sites and calculating generic costs based on the specification of an area and a minimum PSH capacity. The capacity and cost calculator includes the following criteria: Power capacity, storage capacity, total investment, operation and maintenance costs and annual repayment. Locations are preferably chosen within "acceptable areas", e.g. zones defined as wind farm development areas.

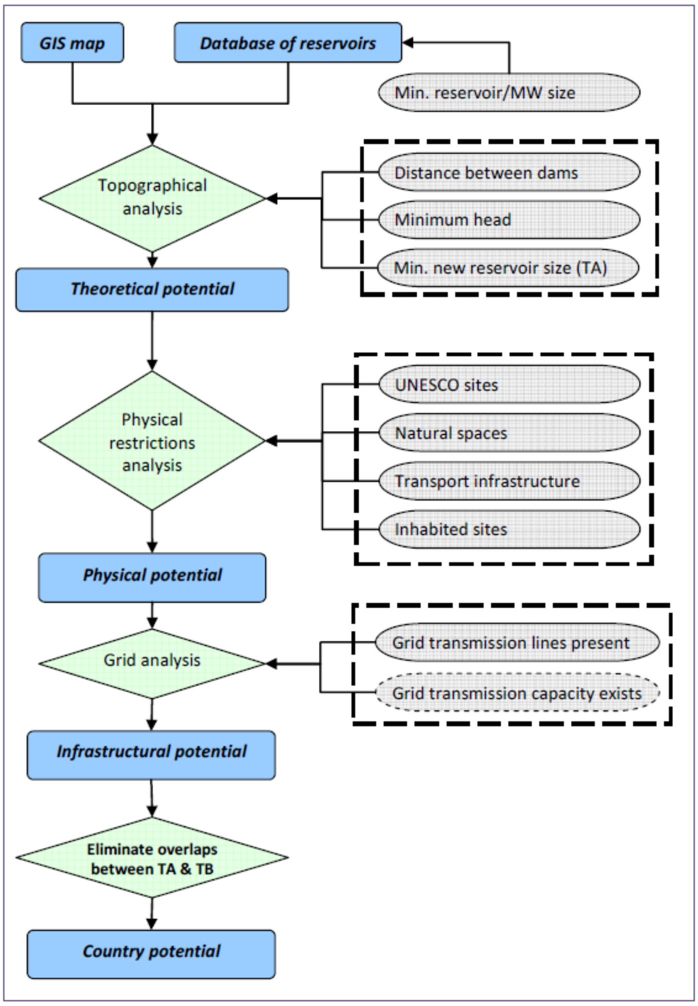


Figure 1: Methodology flow chart for the PSH potential study performed by Arántegui et al. (2011)

The European Commission's Joint Research Centre (JRC) at the Institute for Energy and Transport collaborated with academic partners to develop a GIS-based tool that can be used to identify the potential for transforming single reservoirs into PSH systems both on a national scale and EU-wide. The study distinguishes between short-term storage (6-10 hours), medium-term storage (up to 15 days) and long-time storage (beyond). An expert workshop organized by the JRC gave recommendations for methodological and GIS-aspects, see Table 1 and 2 (Arántegui and Tzimas 2012).

Table 1: Required deliverables of the model suggested by Arántegui and Tzimas (2012)

Deliverables / results	**Scope**			
	National	Region	County	Grid
Energy storage capacity potential, in GWh	x	x	x	x
Indicative power considering 10-hour storage	x	x	x	x
List of assumptions used	x	x	x	x
Split of potential between short-, medium- and long-term	x			x
Detailed list of potential sites			x	
Per selected potential site list of assessed second-reservoir sites			?	
Sensitivity analysis to be defined on demand			x	

Table 2: Criteria recommended by Arántegui and Tzimas (2012)

Criteria	Unit	Scope			
		National	Region	County	Grid
Maximum distance between reservoirs	km	20	20	20	20
Minimum head	m	50 - 200	25 - 200	15 - 200	50 - 200
Minimum usable volume of existing reservoir	10^6 m^3	1	0.1	0.05	1
or: Hydropower installed capacity	MW	10	5	1	10
Topology 2; assumed new reservoir size	m^2	1000	700	700	1000
Topology 2, assumed new reservoir average depth	m	10	7	7	10
Minimum distance to inhabited sites	m	2000	1000	200	2000
Min. distance to existing transportation infrastructure	m	100	100	0	100
Distance to national parks	m	2000	1000	500	2000
Distance to NATURA2000 sites	m	200	100	50	200
Distance to special protection areas	m	200	100	50	200
Minimum distance to UNESCO site	m	2000	1000	500	2000
Maximum distance to suitable grid connection	km	20	20	10	20

1.3 Studies and specific assumptions for pump storage investigations in Norway

In contrast to most studies from other European countries, the assessment of PSH potential in Norway has been focussed on the use of existing lakes or reservoirs for this purpose.
Solvang et al. (2012) selected 19 specific cases in Southern Norway in order to analyse the potential for increasing power output of balance power generation. They showed that it may be technically feasible to increase the design power output of Norwegian hydro-electric power stations by 20,000 MW without constructing new reservoirs or exceeding the current stipulations with regard to the highest and lowest regulated water levels. It was assumed that new power stations would be constructed with new tunnels from an upstream reservoir and outlet into a reservoir, a fjord or the sea. New power stations were usually located adjacent to existing plants ("power-plant criterion"), and based on existing reservoirs according to the NVE reservoir data base. New tunnels were suggested parallel to existing ones. Maximum power generation occurred simultaneously in both existing and new units. The study included environmental aspects such as limitations for the water level changes in the reservoirs and a short discussion of possible challenges with respect to erosion and altered circulation, water temperature and ice cover.
For a regional study for Central Norway, Capron (2012) chose 32 potential projects outside of National Parks based on subjective assessment of potentially suitable reservoir pairs. The screening included reservoir pairs without existing hydro power stations and natural lakes that were not classified as reservoirs according to the NVE data base. Reservoir connections up to 50 km length were taken into consideration. The capacity of the power plants was estimated based on the assumption of a lake level change of 10 cm per hour at maximum.

For the present study, the following basic assumptions were defined by the working group:

- The location adjacent to existing power plants should be a criterion that can be freely chosen (not mandatory).
- The GIS study will be restricted to NVE reservoirs (No inclusion of additional natural lakes).
- It has to be possible to set a lower limit for power production, e.g. 100 MW, to prevent the installation of very small pump power plants.

- The screening should indicate "the best lines" out of many possible connections from a reservoir, based on parameters such as reservoir volume, gross pressure height, production capacity, rate of water level change and tunnel length.
- Distances to power lines and, maybe, roads have to be included as screening parameters.
- The GIS project should provide the main parameters, which are necessary for the cost estimation, as output.

2 Methods and materials

2.1 Model assumptions and parameter calculation

The calculation model suggested by Solvang et al. (2012) was adopted for this study. It includes the following basic assumptions (see Figure 2):

- The reservoirs were modelled assuming vertical side surfaces as in an upright cylinder between their upper (HRW) and lower regulation limits (LRW).
- The length of the penstock (PSL) is calculated on the basis of the gross pressure head (GPH) and a 45 degree inclination of the penstock.
- The gross pressure head is calculated for a 2/3 filled reservoir.

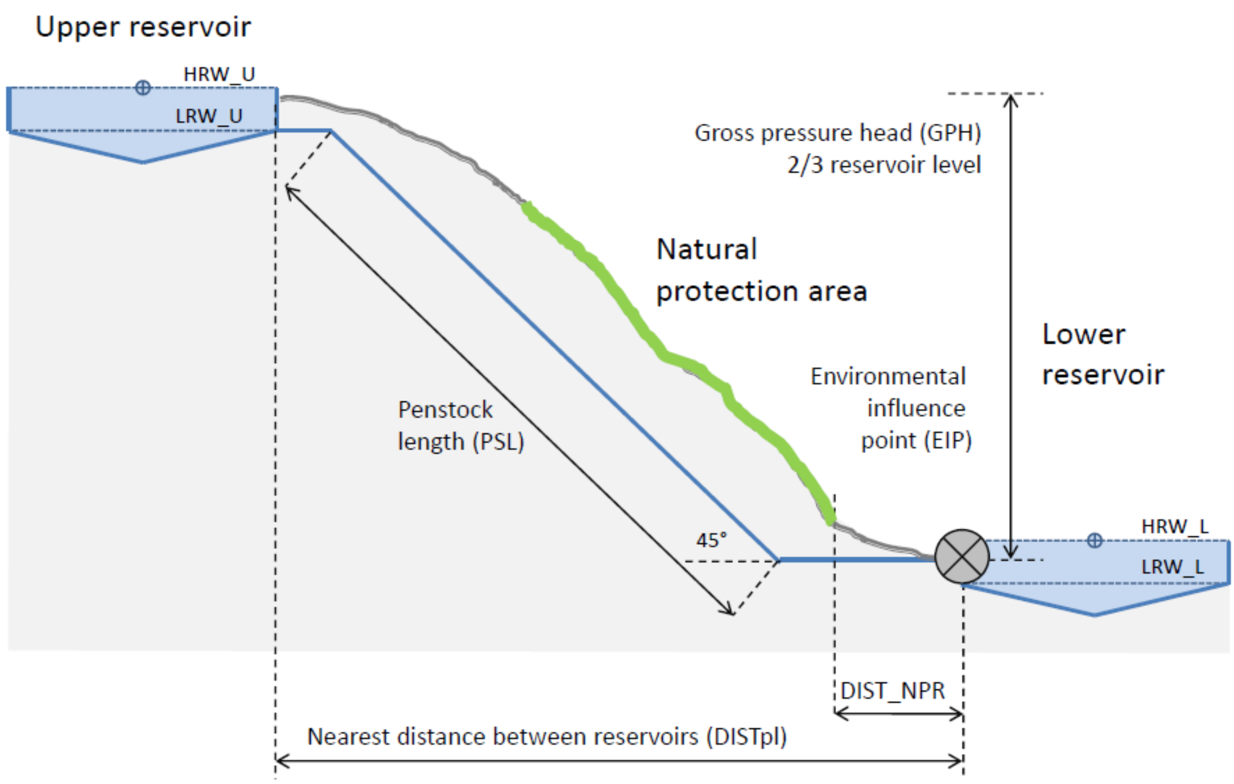


Figure 2: Scheme of the reservoir connection with tunnel and penstock

The horizontal distance between the reservoirs (DISTpl) was calculated as the nearest distance between the connected reservoirs, based on NVE's reservoir polygon data set.

The relationship between generated power and absorption capacity (water flow through turbine, tunnel and penstock) is calculated using the following formula:

$$P = \rho \cdot Q \cdot g \cdot GPH \cdot \eta \tag{1}$$

P = usable power (W)
ρ = density of water (1000 kg/m^3)
Q = water flow / absorption capacity (m^3/s)
g = gravity acceleration (9.81 m/s)
GPH = gross pressure head (m)
η = total efficiency (here set to 0.86)

Following Solvang et al. (2012), the same installed output in MW was assumed for power generation and pumping. The flow rate (m^3/s) during pumping was set to 80 % of the rate during power generation, which means that pumping a given volume of water will take 20 % longer and absorb 20 % more energy than power generation based on the same water volume. For the calculation of the storage potential, assumptions had to be made about the start water level in the reservoirs. The start level was set to 75 % in the upper reservoir and 50 % in the lower reservoir. The "duration of power generation with maximum power" was set to 24 hours (i.e. no pumping) for the calculation of the water level change rates and time for the filling and emptying of the reservoirs. Seepage and any pumping in or out of the reservoirs simultaneously with power generation were disregarded.

It was assumed that maximum power generation (nominal output) would occur simultaneously in both the existing and the new units, without an optimization strategy for power generation and pumping based on the market regime. The inflow and outflow from the reservoirs due to maximum hydro power production in existing power plants was provided as net inflow rate (defined as "inflow minus outflow") by NVE (Arnesen 2013). The comparison with the inflow and outflow rates for selected reservoirs used by Solvang et al. (2012) revealed some differences, which may be related to different data sources and assumptions.

Modern hydro power systems in Norway are characterized by tunnels and power stations inside the mountains. It is assumed that the potential PSH systems will be designed according to these principles, and that already existing reservoirs are used. The environmental impacts of these systems are mainly related to the effects of the reservoir regulation in both reservoirs and the technical infrastructure (transformer etc.), which is usually situated close to the lower reservoir. In the present study, the latter was modelled as "environmental influence point" (EIP) situated at the intersection between the PSH line and the shoreline of the lower reservoir. This point - which in reality represents an area of about 30-50 ha - was used for the calculation of distances to grid and road infrastructure and to environmental restriction areas, such as natural protection areas (Fig. 1). More specific assumptions that were made in connection with the choice of the GIS-routines are documented in Appendix A.

2.2 Basic selection criteria for pumped hydro storage suitability

2.2.1 Topographical analysis

The topographical analysis was carried out to select suitable reservoir pairs by applying the following basic criteria:

1. Distance criterion
2. Terrain criterion
3. Power plant criterion

1. The distance criterion limits the distance between reservoir pairs. International studies assume a maximum distance between PSH reservoir pairs of 20 km (Tab. 1). In Norway, the tunnel length of existing power plants is usually less than 30 km, but new technological developments and the need for balance power may allow for longer distances in future. The default maximum distance between two reservoir pairs was therefore set to 50 km.
2. The terrain criterion prevents the occurrence of "perched tunnels", i.e. PSH reservoir connections stretching over deep fjords or valleys. PSH connections stretching over fjords were excluded using a selection operation ("Select all lines outside of fjords"). For deep inland valleys, the terrain selection is based on a Digital Elevation Model (DEM). The exclusion criterion was that the minimum elevation from the DEM along the connection line was lower than the LRW of the lower reservoir.
3. The optional power plant criterion was introduced because new PSH sites in Norway should preferably be located close to existing power plants. All of the lakes that are classified as "reservoirs" and included in this study are somehow related to an existing power plant. However, some of the reservoirs are part of a reservoir chain or reservoir network within a hydro power system and are situated far away from the power plant they belong to. The GIS-operation for the power plant criterion allows excluding PSH lines which are not associated with an existing power plant (EPP) near the lower reservoir. In addition, the user can define a minimum installed capacity for the EPP (Default: 10 MW) to exclude small hydro power plants.

2.2.2 Production- and environment-related selection criteria

Boundary conditions for future pump storage capacities include restrictions related to the technical infrastructure and environmental issues:

- New pump storage plant must have a minimum installed capacity.
- There must be transmission capacities for the produced electricity.
- There should be roads not too far from a new pump storage plant.
- The water level changes (m/hour) in the upper reservoir and lower reservoir are limited because of environmental considerations (fish stranding etc.) and erosion issues.
- Areas with environmental restrictions (e.g. natural protection zones) should not be affected.

Table 3 gives an overview of the selection criteria. The minimum power generation in the tool can be set by the user, with a default of 100 MW. The default value for the distance between the EIP and suitable grid infrastructure was set to 20 km. Application of this constraint is based on the available grid data, which may be incomplete due to security or other considerations. The default value for distance to roads was set to 10 km. It was assumed that all types of dams are suitable for PSH use, regardless of the dam construction type (rock-fill, concrete etc.).

The power generation for a given gross pressure head depends on the maximum absorption capacity (discharge in m^3/s) of the system, see Eq. 1. This absorption capacity is related to the reservoir storage volumes and restrictions for the water level changes in the upper and lower reservoirs. Low storage volumes are associated with high rates of water level decrease in the upper reservoir and high rates of water level rise in the lower reservoir during power generation, vice versa during pumping. There are large uncertainties about the rates of water level change that can be allowed in reservoirs from an environmental point of view. Previous investigations assumed a maximum rate of water level change of 0.13 m/hour, based on stranding experiments in rivers (Halleraker et al. 2003). This value was set as default in the present study, but can be changed by the user.

Table 3: User-defined criteria and default values used in the present study

Criteria	Unit	Default	Note
Maximum distance between reservoirs	km	50	Often < 20 km
Minimum head	m	50	
Minimum hydropower installed capacity	MW	100	
Maximum distance to roads	km	10	
Maximum distance to suitable grid connection	km	20	
Maximum rate of water level change in reservoirs	m/hour	0.13	Based on river data; uncertain
Minimum distance to INON areas (not affected by heavy technical installations or constructions)	m	500	Expert assessment needed
Minimum distance to cultural landscape areas of high priority with biological and historical values	m	500	
Minimum distance to wild reindeer areas	m	2000	
Minimum distance to existing and suggested natural protection areas	m	500	

Figure 3 gives an impression of the extent of special areas with nature protection interests, i.e. INON, wild reindeer, cultural landscape and natural protection zones. The minimum distances between the EIP and these areas can be defined by the user. Recent studies suggest minimum distances between 120 m (Thomassen et al. 2012) and 200 m (Tab. 2) for natural and landscape protection areas. INON areas are areas without major infrastructure development (Inngrepsfrie naturområder i Norge - INON) and estimate wilderness areas based on distance from infrastructure. They include all areas at least 1 kilometre away (as the crow flies) from major infrastructure development, such as roads, power lines and railway lines (DN 2012). Regulated reservoirs (and thereby also the EIP situated at the lower reservoir) belong to infrastructure that has been included into the INON methodology, i.e. they are normally outside of the INON zones. The distance from INON will only affect the results if the minimum distance is set to >1 km.
The default values in Table 3 are preliminary and need to be updated or confirmed by ecologists. It is necessary to take into account that the EIP in practice represents an area with a radius of 200-300 m.

Beside this it is investigated whether the reservoirs are situated within a protected water course, i.e. within an area which is protected against hydropower development by NVE. Reservoir pairs were discarded if one or both of them were situated within a protected water course.

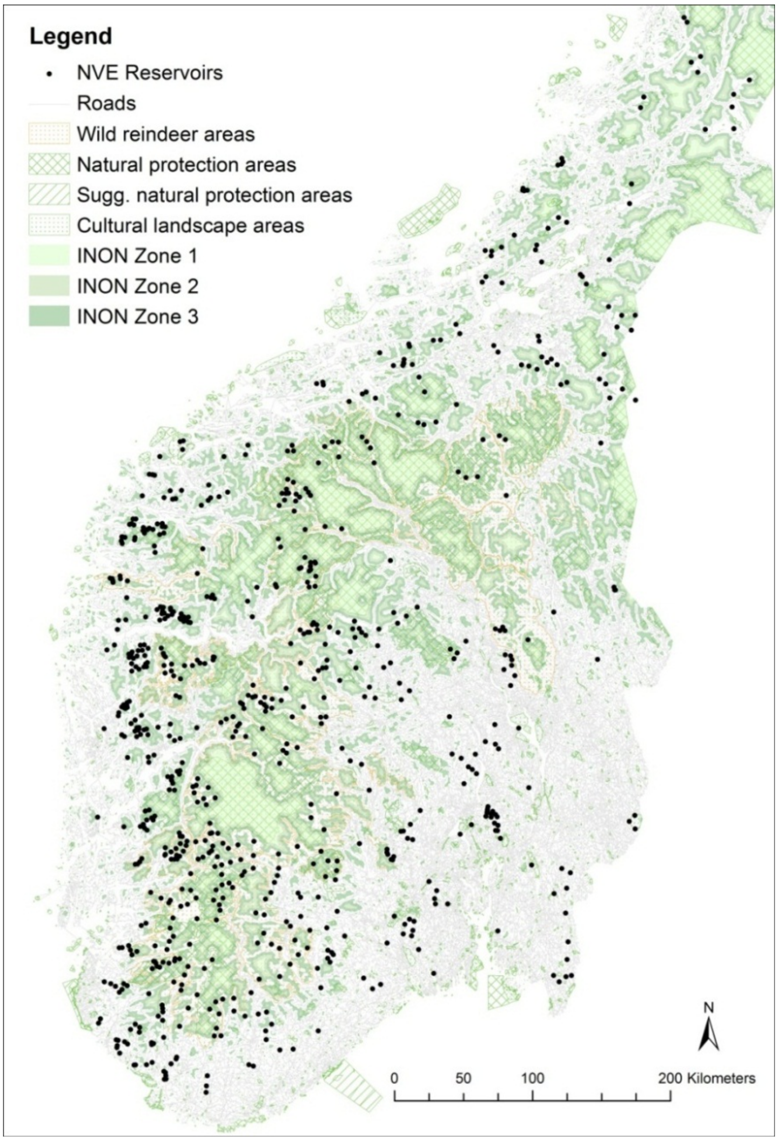


Figure 3: Location of areas with environmental restrictions, based on data from DN

The relevance of UNESCO world heritage sites for the study was investigated. Norway has seven sites at the UNESCO list of nature or culture world heritage (UNESCO 2012):

1. Bryggen i Bergen (1979)
2. Urnes Stave Church (1979)
3. Rock Art of Alta (1985)
4. Røros Mining Town and the Circumference (1980/2010)
5. Vegaøyan -- The Vega Archipelago (2004)
6. West Norwegian Fjords - Geirangerfjord and Nærøyfjord (2005)
7. Struve Geodetic Arc (2005).

Sites No. 1 to 5 are situated in urban areas or at coastal locations which are not relevant for hydropower development. The West Norwegian Fjords (No. 6) can be neglected in this study which is focussed on inland reservoirs. For the Struve Geodetic Arc (No. 7), there are four points in the municipalities of Alta, Kautokeino and Hammerfest in Northern Norway, which were of minor relevance for potential PSH projects. The UNESCO world heritage sites were therefore not included into the GIS analysis.

Table 4 gives an overview of the raw data sets which were used for the GIS analysis. They were provided by or could be downloaded from the following institutions:

- The Norwegian Water Resources and Energy Directorate (NVE)
- The Norwegian Directorate for Nature Management (DN)
- The Norwegian Mapping Authority (SK)

The data from DN and NVE was provided in the projected coordinate system UTM 33N, which was used for the entire study. The topographical data from SK about inland and coastal water-covered areas and roads was given for each district ("fylke") and in several coordinate systems (UTM Zone 32N to UTM Zone 35 N). This data was transformed by merging it into one file for each topic and projecting it as UTM Zone 33N.

Table 4: Raw data used for the GIS study. R = Raster, V = Vector (P = point, L = line, Po = polygon).

Source	Name (Norwegian)	Content	Scale / Res.	Type
NVE	VannKrvP_ekstern201111.shp	Hydro power plants		V-P
NVE	VP_VerneplanF201109.shp	Protected water courses		V-Po
NVE	kraftlinjer – ikke oppdatert.shp	Power lines; provided by F. Arnesen (NVE), 04/ 2012		V-L
NVE	Magasin_polygoner.shp	Reservoir areas and data; prov. by F. Arnesen (NVE), 11/2012		V-Po
SINTEF	EnfoDEMNorgenkm32.rst	DEM		R
SK	N 250 KD: fy**vann_f_coast .shp	Water-covered areas (coastal) for Norwegian districts	1: 250,000	V-Po
SK	N 250 KD: fy**vei_l .shp	Roads for Norwegian districts	1: 250,000	V-L
DN	Inon08_norge.shp	Areas which are not affected by heavy technical installations or constructions	1 : 50,000	V-Po
DN	Villrein_omrade.shp	Wild reindeer areas	1 : 50,000	V-Po
DN	Naturbase_helhetlige_kulturlandscap_utm33.shp	Cultural landscape areas of high priority with biological and historical values	Varying from 1 : 5,000 to 1 : 50,000	V-Po
DN	Naturvernomrader_utm33.shp	Natural protection areas	Varying from 1 : 5,000 to 1 : 50,000	V-Po
DN	Foreslatt_vern_utm33.shp	Suggested natural protection areas	Varying	V-Po

2.3 GIS and modelling tool

2.3.1 GIS and script tools

The tools for the analysis were developed using the Geographical Information System (GIS) ArcGIS Version 10 (ESRI Inc.) with ArcInfo license, including the extensions Spatial Analyst and 3D Analyst (ESRI 2012).
The current version of the GIS-tool is based on Python script tools. Python (www.python.org) is a free, cross-platform, open-source programming language that is both powerful and easy to learn. It is widely used and supported. A Python script tool is a Python script (*.py file) that has been added to a geoprocessing toolbox. Once added as a script tool, it can be opened and executed from the ArcToolbox like any other geoprocessing tool.
The Python script tools for the project were created based on three scripts, a custom toolbox (PumpStorageNorway.tbx) and a definition of the parameters of each script. Table 5 and Figure 4 give an overview of the modelling tools and their functions. The project was organized following the ToolShare folder structure recommended by ESRI (2012). This makes it easy to install the project and run the tools at different computers. A detailed documentation is given in the Appendix.

Table 5: Overview of the modelling tools

ArcTool Model	Description
Tool 1: Topographical analysis	• Calculates nearest polygon distances between NVE reservoir pairs within the search radius and creates a PSH line data set • Removes PSH lines stretching over fjords and deep valleys ("Terrain criterion") • Assigns existing power plants (EPP) to reservoirs and selects PSH lines that have a EPP close to their lower reservoir ("Power plant criterion")
Tool 2: Calculation of restriction parameters	• Calculates the position of environmental influence points (EIP) • Computes the distances of the EIP to nearest power line, road and environmentally restricted areas • Calculates distances of the reservoirs to HP protected areas • Reads the values from net inflow table
Tool 3: Screening	• Calculates parameters based on user-defined selection criteria • Selects suitable PSH connections between reservoirs

The minimum distance to hydro power (HP) protected areas in Tool 2 is calculated based on the two end points of the PSH connection line (default) or based on the respective reservoir polygons, in both cases with a maximum searching distance of 3 km.

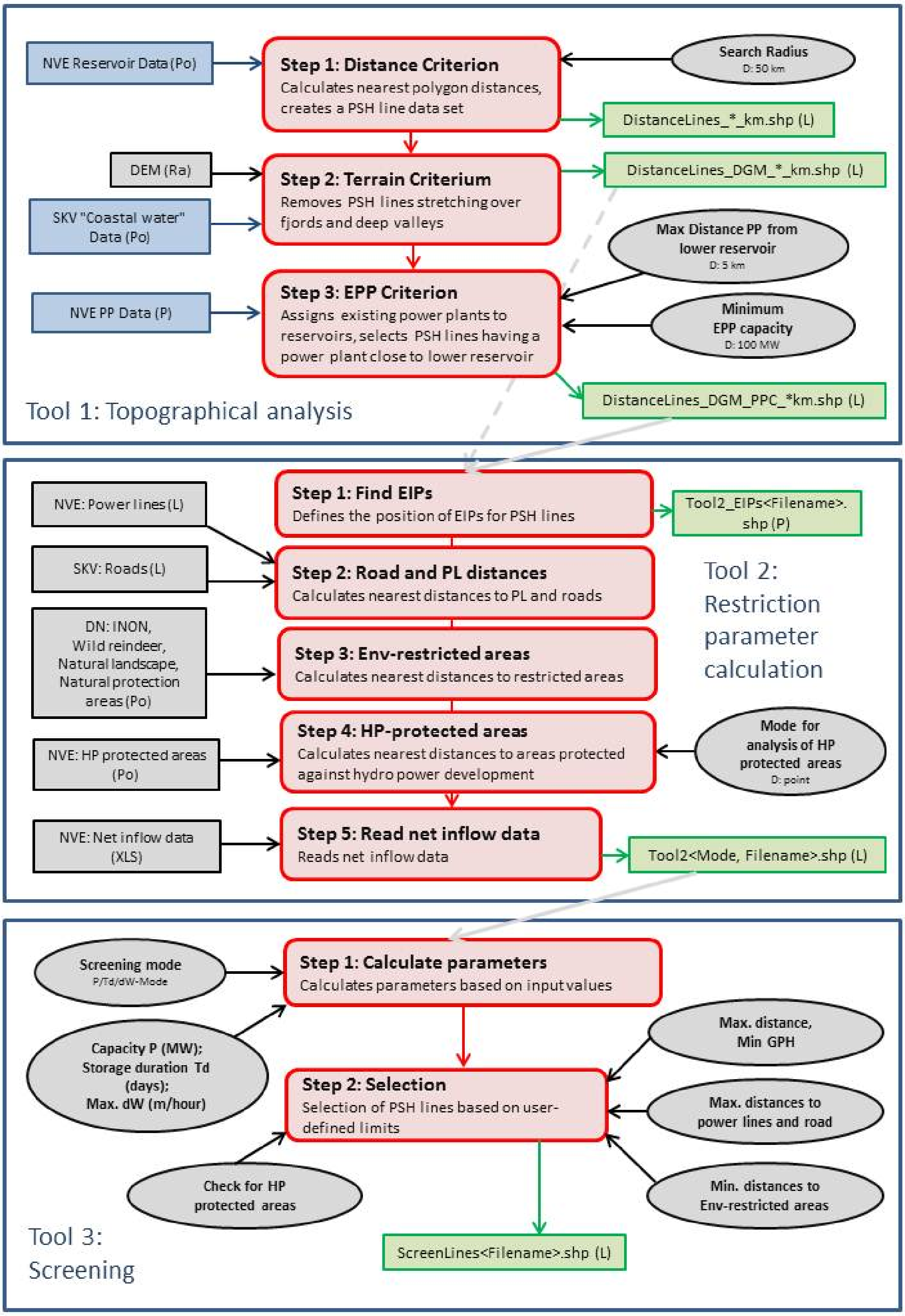


Figure 4: Flow chart of the Tool. Grey: user-defined parameters (ellipse) or input data sets (rectangle). Blue: Fast implemented input data sets. Green: Output data sets. Ra = Raster data. Vector data: Po = Polygon, P = point, L = Line.

2.3.2 Screening tool and modes

Tool 3 allows investigating the PSH potential for different parameter settings. Firstly, the user can define maximum distances from the EIP to power lines and roads and minimum distances to environmental restriction zones. He can decide whether he wants to include the environmental restrictions into the screening or not, and whether he wants to exclude reservoirs situated in zones that are protected against hydro power development.
Secondly, a choice has to be made between three screening modes: the P-Mode, Td-Mode and dW-Mode.
The differences between the three modes are explained in Table 6. The results are not identical.

Table 6: Description of the screening modes and the derived selection parameters

<table>
<tr><th>Mode</th><th>P-Mode</th><th>Td-Mode</th><th>dW-Mode</th></tr>
<tr><td>Start parameter</td><td>Power production P
(in MW)</td><td>Storage duration Td
(in days)</td><td>Water level change rate dW
(in m/hour)</td></tr>
<tr><td rowspan="4">Way of calculation</td><td>1. Calculates the maximum absorption capacity Q (m^3/s) from Eq. 1</td><td colspan="2">1. Calculates the absorption capacity Q with respect to both reservoirs and chooses the minimum value (Q_{min})</td></tr>
<tr><td>2. Calculates dW for both reservoirs</td><td colspan="2">2. Calculates power production P based on Q_{min} and Eq.1</td></tr>
<tr><td>3. Calculates Td (i.e. emptying or filling times) for both reservoirs</td><td>3. Calculates dW for both reservoirs, based on Q_{min}</td><td>3. Calculates Td for both reservoirs, based on Q_{min}</td></tr>
<tr><td>4. Calculates the maximum value for dW and the minimum value for Td</td><td>4. Calculates the maximum value for dW</td><td>4. Calculates the minimum value for Td</td></tr>
</table>

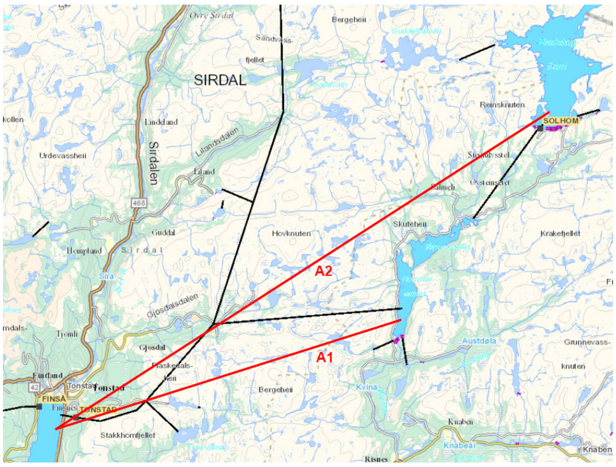
The P-Mode allows searching for PSH connections that can provide a defined power production P (in MW), hereby not exceeding the given maximum water level change rate for the reservoirs and not going below the given minimum storage duration. Power lines with alternating current have given ranges of transmission capacities (1-10 MVA for a voltage level of 22 kV; 500-2000 MVA for 420 kV (Solvang et al. 2012)). New power generation installations should have a capacity of 100 MW or more. International cable links have a capacity of 700 MW. Thus, the possibilities for installations with the following capacities are of special interest: 100 MW, 700 MW and 1400 MW.
The Td-Mode allows searching for PSH connections that can guarantee a defined storage duration (in days), hereby not exceeding the given maximum water level change rate for the reservoirs and not going below the given minimum power production. The storage duration equals the emptying time of the upper reservoir or the filling time of the lower reservoir, depending on which of the two values is lower.
The dW-Mode can be used to select PSH connections with a defined water level change rate (in m/hours), where the storage duration and power production do not fall below the defined minimum values.
The result of the screening is a selection of PSH lines (i.e. connections between reservoir pairs) fulfilling the user-defined criteria. It is possible to obtain many PSH connections from one reservoir. They can be graphically classified according to their capacity or storage duration, such that the user can identify the most suitable PSH connections. The interaction between multiple PSH connections (in particular the effect on the net inflow rates of the reservoirs) is not included into the GIS-tool and has to be investigated separately on a smaller scale.

2.4 Performance test of the tool for selected cases

The plausibility of the GIS-analysis-results was tested using selected potential PSH connections out of the 19 cases described by Solvang et al. 2012. The goal was to check whether the GIS-tool would lead to similar selection results and confirm the expert assessment.
However, only few PSH connections could be directly compared. Seven of the 19 cases describe hydro storage power stations with outflow into a fjord, which was not in the focus of the GIS-study. Most of the pumped storage power stations in Solvang et al. (2012) were designed as part of complex hydro power systems, with case-specific assumptions about the in- and outflows into the reservoirs and their changes due to the newly established PSH cases.
The results for selected cases, which were based on similar assumptions, are presented below. For these cases, the topographical analysis was done using a maximum reservoir distance of 50 km without power plant criterion.
A first GIS-screening was performed using the P-Mode for 400, 700 and 1400 MW together with a maximum water level change rate of 0.13 m/hour and a minimum storage duration of 1 day, with and without the environmental restrictions (based on the default values) included. The upper limit for distances to power lines and roads was set to 20 km and 10 km, respectively. Potential PSH connections between reservoirs situated in areas that are protected against hydropower development were excluded.
A second screening was conducted using the W-Mode for the same parameters. This allowed estimating the maximum power production and storage duration for a fixed water level change rate of 0.13 m/hour.

2.4.1 Tonstad (A1, A2)

Figure 5 shows the PSH connections suggested by Solvang et al. (2012) and the results of the GIS-screening for the "Tonstad" region.
Case A1 between Holmstølvatn and Sirdalsvatn did not appear in the results of the GIS-screening. This can be explained with a water level change rate >0.13 m/hour occurring already at a power production of less than 400 MW, see Tab. 2.1 in Solvang et al. (2012).



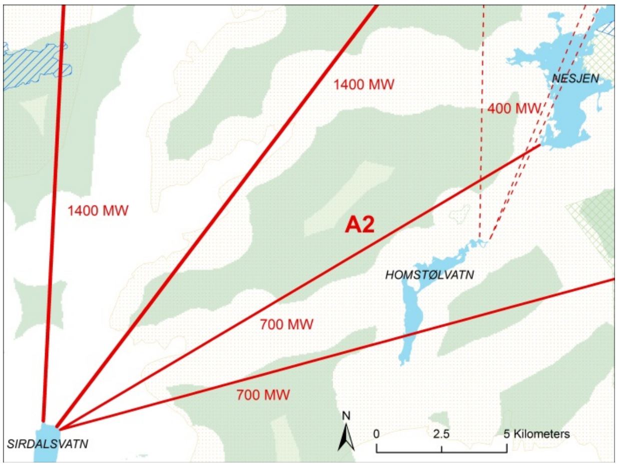


Figure 5: The Tonstad Case from Solvang et al. (2012, left) and results of the GIS-screening for 400, 700 and 1400 MW (P-Mode). Dashed lines: PSH lines which are in conflict with the environmental restriction zones.

Table 7: Net inflow from the reservoirs for Case A2. *From NVE database with special assumptions.

		Upper Reservoir: Nesjen		Lower Reservoir: Sirdalsvatn	
		Solvang et al. (2012)	Arnesen (2013)	Solvang et al. (2012)	Arnesen (2013)
Other inflow	m^3/s	76.9		254.0	
Other discharge	m^3/s	109.8		362.0	
Net inflow	m^3/s	**-32.9**	**-33.1**	-108.0	**-122.1***

For PSH connection A2 between Nesjen and Sirdalsvatn, a power production potential of at least 700 MW (W-Mode: max. 1258 MW at dW = 0.13 m/hour) was identified for the given boundary conditions. Solvang et al. (2012) investigated a power production up to 2000 MW for A2. In their study, the water level change rate of 0.13 m/hour was reached at a power production of 1200-1300 MW, which is in good agreement with the results of the GIS-tool.

2.4.2 Tinnsjø (C1)

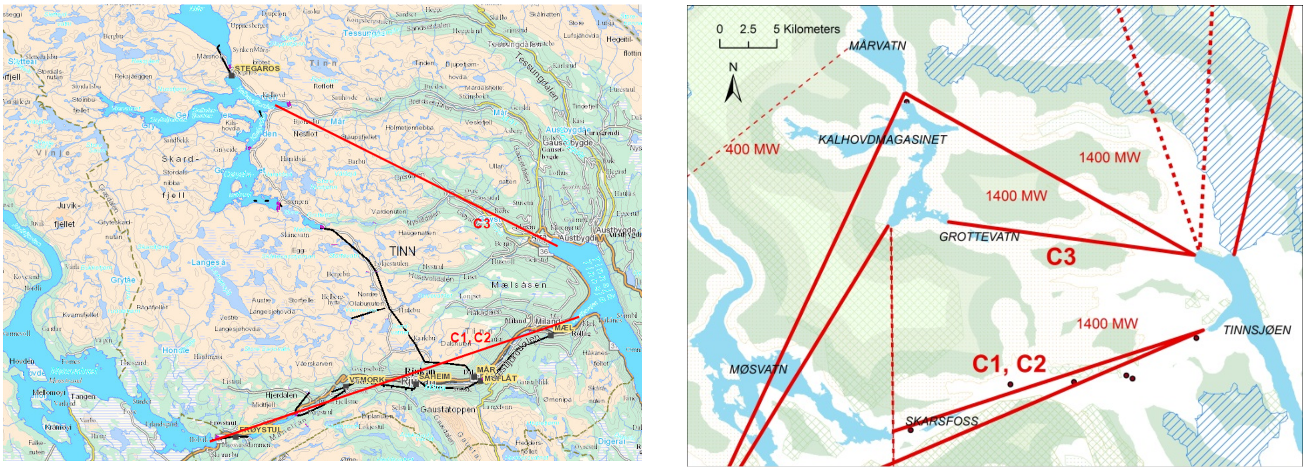


Figure 6: The Møsvatn-Tinnsjø-Kallhovd/Mår area with the PSH cases suggested by Solvang et al. (2012, left) and the GIS-screening results obtained using the P-Mode for 400, 700 and 1400 MW. Dashed lines: PSH lines which are in conflict with the environmental restriction zones.

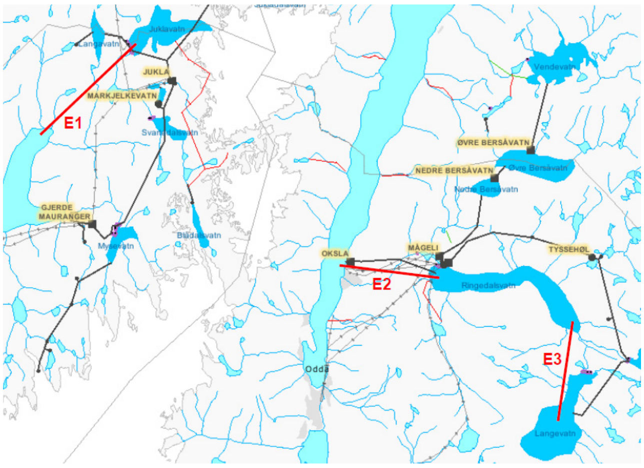
Figure 6 shows the results for the "Møsvatn-Tinnsjø-Kallhovd/Mår" region. The GIS-screening using the P-Mode for 400, 700 and 1400 MW reproduced the PSH lines suggested by Solvang et al. (2012) as lines with a PSH potential of 1400 MW.

Case C1 is the only case which can be directly compared with Solvang et al. (2012), because it does not include assumptions about additional PSH-related inflows into Lake Tinnsjø. The calculated water level change rates for the 1400 MW power production are comparable (about 0.02 m/hour). The filling time of the lower reservoir (Tinnsjø) was limiting for the PSH duration. For 1400 MW, it was calculated with about 7 days in Solvang et al. (2012) and 12 days using the GIS. This deviation reflects the differences or uncertainties about the inflow- and outflow data for the existing power plants (Tab. 8), since the other assumptions for the calculation were the same.

Table 8: Net inflow from the reservoirs for Case C1

		Upper Reservoir: Møsvatn		Lower Reservoir: Tinnsjø	
		Solvang et al. (2012)	Arnesen (2013)	Solvang et al. (2012)	Arnesen (2013)
Other inflow	m^3/s			99.7	
Other discharge	m^3/s	87.1		150.2	
Net inflow	m^3/s	**-87.1**	**-90.5**	**-50.5**	**-130.6**

2.4.3 Tysso (E3)



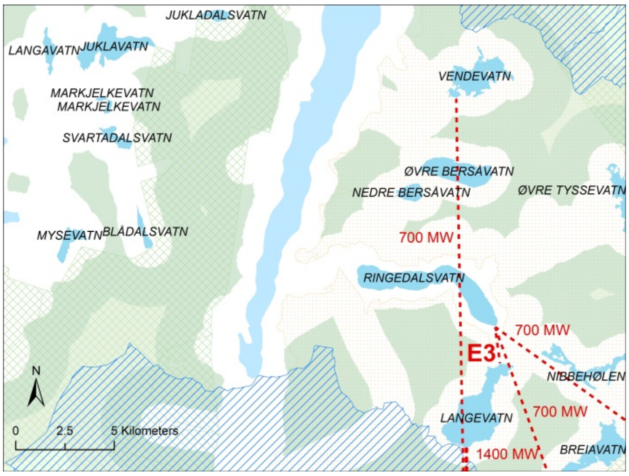


Figure 7: Mauranger-Okslø-Tysso area with the PSH cases suggested by Solvang et al. (2012, left) and the GIS-screening results obtained using the P-Mode for 700 and 1400 MW. Dashed lines: PSH lines which are in conflict with in conflict with the environmental restriction zones.

Figure 7 shows the results for the "Mauranger-Okslø-Tysso" region. The cases E1 and E2 suggested by Solvang et al. (2012) have outflows into the fjord and were not investigated.

For the PSH connection E3 between Langevatn and Ringedalsvatn, the GIS-screening using the P-Mode for 700 and 1400 MW revealed the potential for 700 MW power generation with a maximum water level change rate of 0.08 m/hour and a minimum storage duration of 13 days, the latter limited by the upper reservoir. This is similar to the values given in Solvang et al. (2012) for 700 MW, despite to some differences in the net outflows also in this case (Tab. 9). The GIS-screening using the W-Mode showed the potential for a 1125 MW power generation with a storage duration of 8 days for a water level change rate of 0.13 m/hour. There are some differences in the length and position of the tunnel.

The dashed lines in Figure 7 indicate potential environmental conflicts with respect to the installations that would be necessary at Ringedalsvatn, because this lake is surrounded by a wild reindeer area.

Table 9: Net inflow from the reservoirs for Case E3

		Upper Reservoir: Langevatn		Lower Reservoir: Ringedalsvatn	
		Solvang et al. (2012)	Arnesen (2013)	Solvang et al. (2012)	Arnesen (2013)
Other inflow	m^3/s			30.0	
Other discharge	m^3/s	30.0		52.0	
Net inflow	$\mathbf{m^3/s}$	**-30.0**	**-16.0**	**-22.0**	**-16.2**

2.4.4 Assessment of the performance test

The GIS-tool was developed for the mapping of potential pump storage sites on the national scope, including all regulated water reservoirs of Norway.
The comparison with the results of the study by Solvang et al. (2012) leads to the following conclusions, having in mind that the reservoir data base and assumptions used for the calculation of the gross pressure height, power generation, water level change rate and storage duration were basically the same:

- The GIS-screening allowed identifying the PSH connections suggested by experts, as long as the screening criteria and inflow/outflow rates were the same.

- The results of the screening were highly influenced by the net inflow rates due to existing power plants which were used. Differences are most likely related to differing assumptions about the calculation of inflow and outflow in cases where a power plant uses water from several reservoirs.

- The automatized distance calculation between reservoirs (nearest distance between polygons) does not exactly reproduce the reservoir connections suggested by Solvang et al. (2012), but it can be used for a first cost estimation.

3 Results: PSH potential in Norway

3.1 Results of the topographical analysis

Figure 8 shows the PSH lines identified for a maximum distance of 50 km, after application of the distance criterion, terrain criterion and power plant criterion. By far the most lines are concentrated in the southern and south-western part of Norway. The number of PSH connections on the Norwegian west coast is limited because of the deep fjords in that region.

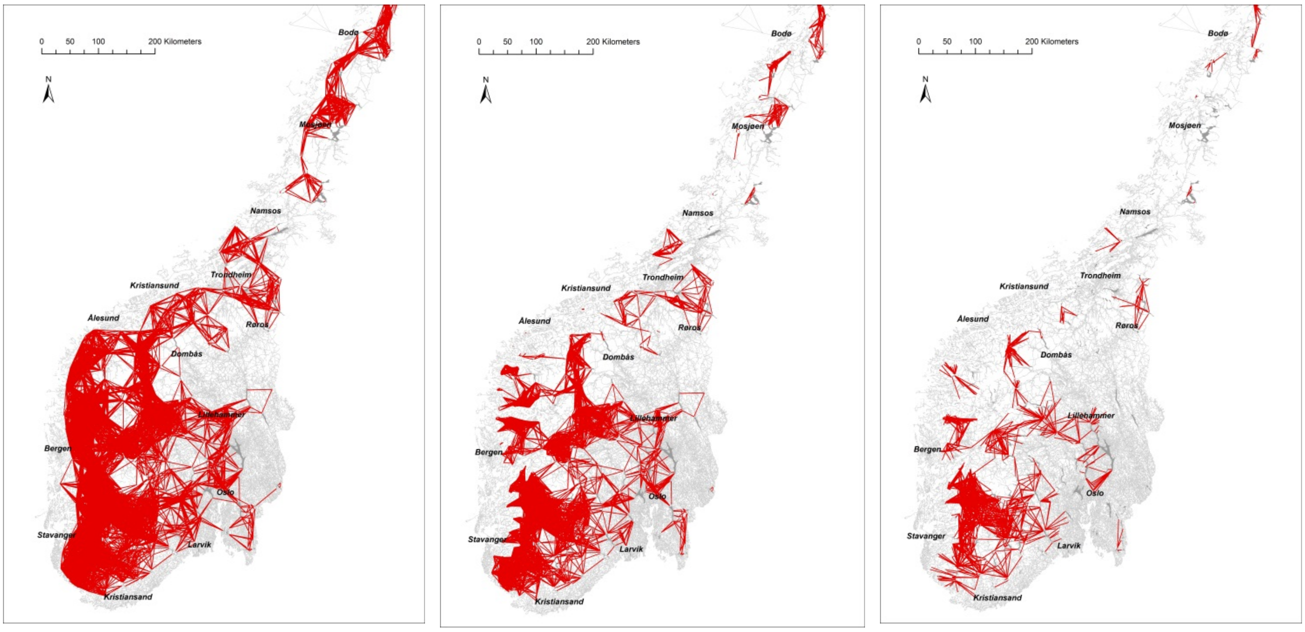


Figure 8: PSH Lines for a maximum distance of 50 km, after application of the distance criterion (left), terrain criterion (middle), and power plant criterion (right).

3.2 Selection based on restrictions

The results presented in this study were calculated using the following settings:

- maximum distance between reservoirs of 50 km without power plant criterion,
- maximum distance from EIP to suitable grid connection of 20 km
- maximum distance from EIP to roads of 10 km
- maximum water level change rate in reservoirs 0.13 m/hour

Potential PSH connections between reservoirs situated in areas that are protected against hydropower development were excluded. The net inflow from reservoirs due to existing hydro power plants was included based on NVE's list in the updated version from January 2013 (Arnesen 2013). In all cases, the screening was done with and without the environmental restrictions (ENV-R) included, hereby using the default values for minimum distances between the EIP and environmental restriction zones.

A first GIS-screening was performed using the P-Mode for 400, 700 and 1400 MW together with minimum storage duration of 1 day (Figure 9). A second screening was conducted using the Td-Mode for storage durations of three, seven and 30 days with a minimum power production of 100 MW (Figures 10-12).

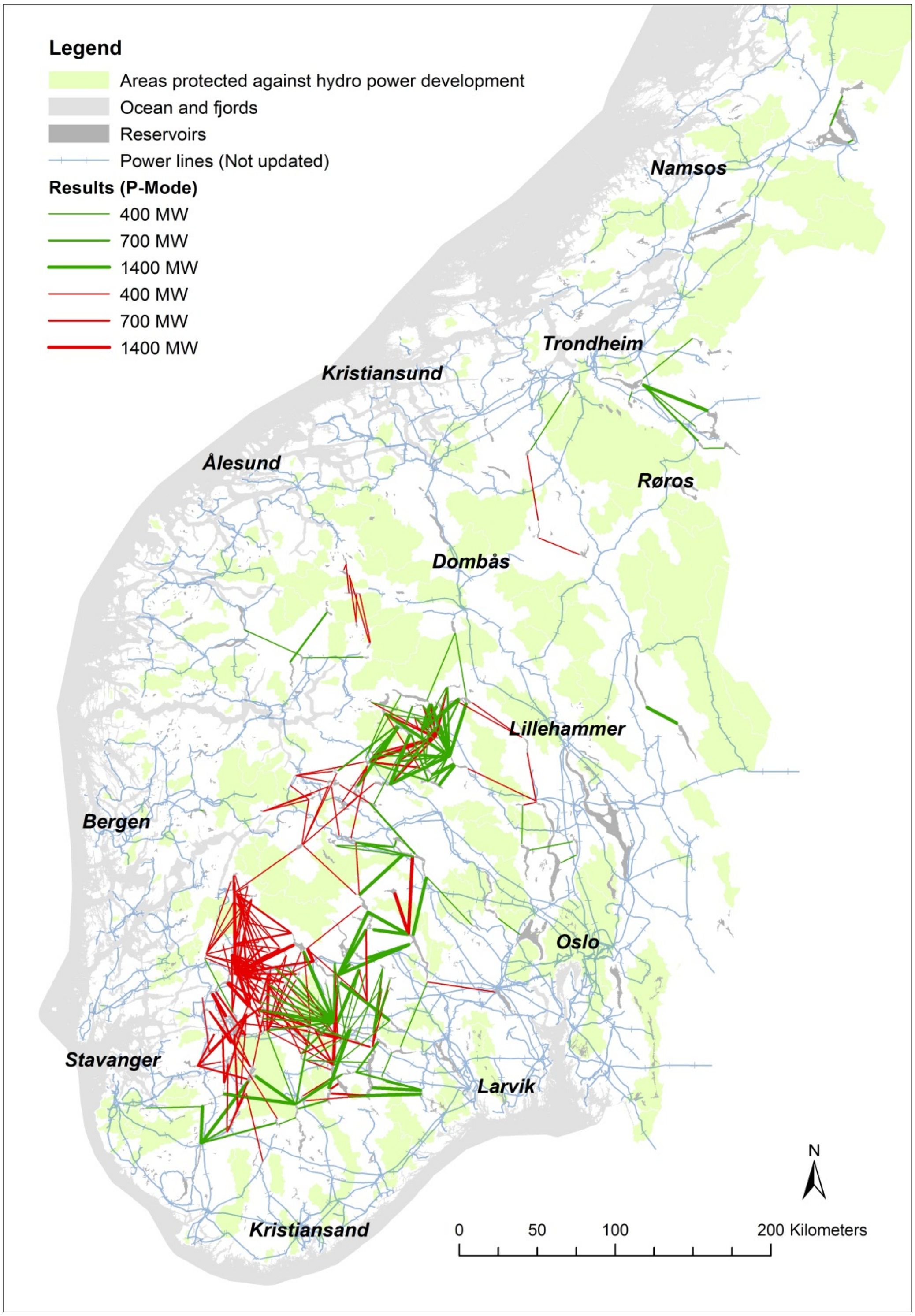


Figure 9: PSH potential for power production of 400, 700 and 1400 MW and minimum storage duration of one day, calculated using the P-Mode. Green lines indicate no conflicts with environmental restrictions. Red lines stand for PSH connections where these restrictions are violated.

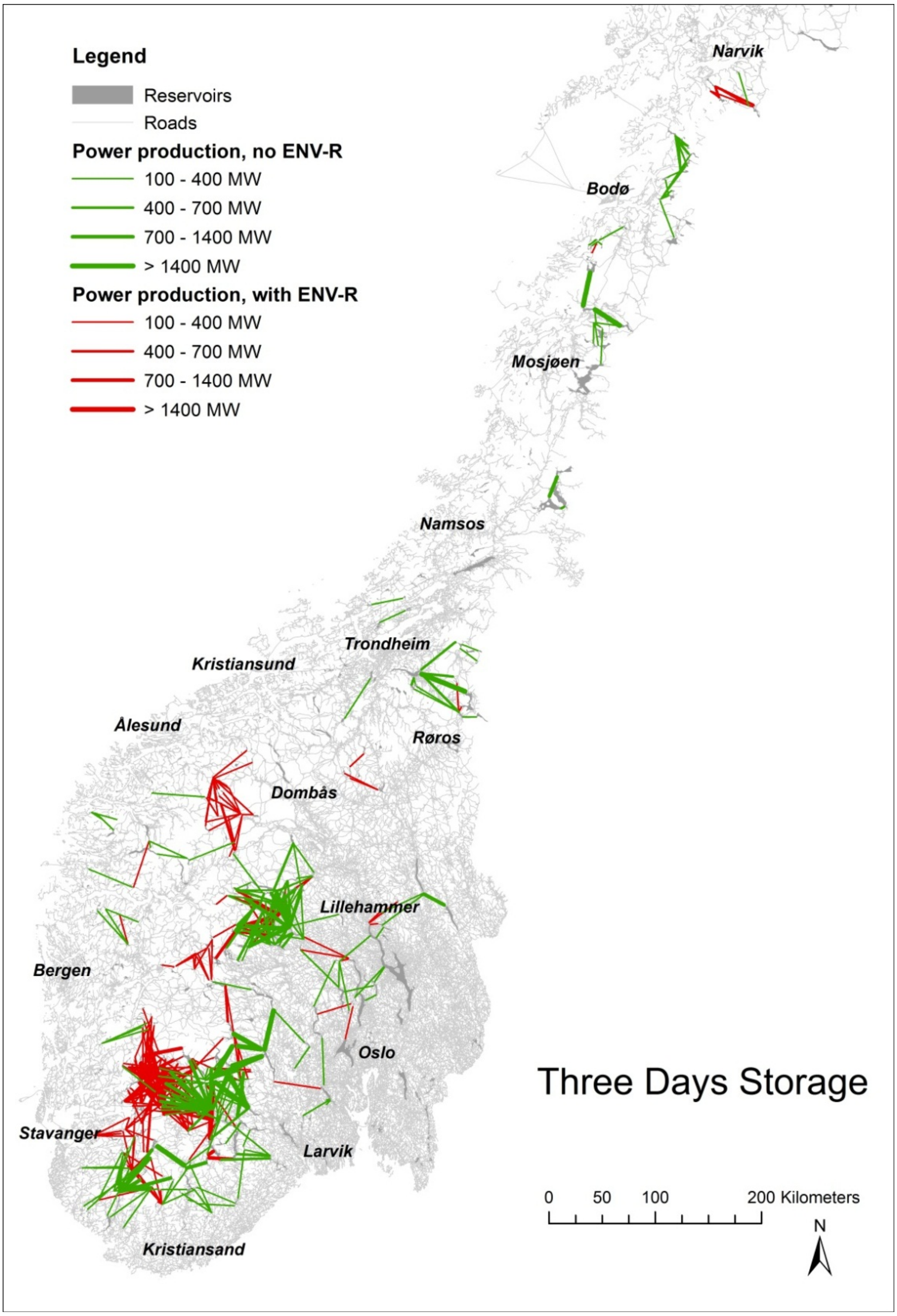


Figure 10: PSH potential for three days storage duration and minimum power production of 100 MW, calculated using the T-Mode. Green lines indicate no conflicts with environmental restrictions. Red lines stand for PSH connections where these restrictions are violated.

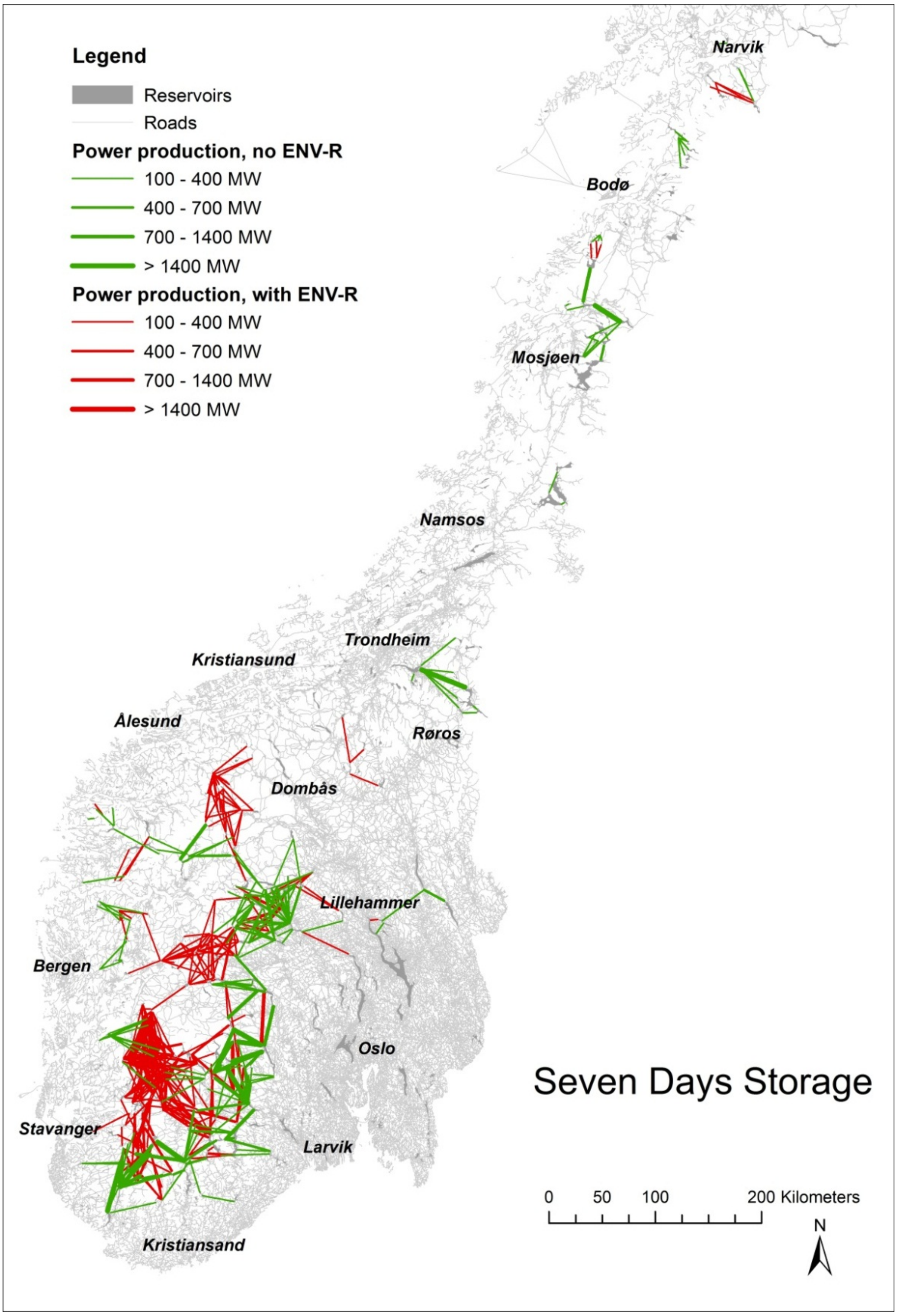


Figure 11: PSH potential for seven days storage duration and minimum power production of 100 MW, calculated using the T-Mode. Green lines indicate no conflicts with environmental restrictions. Red lines stand for PSH connections where these restrictions are violated.

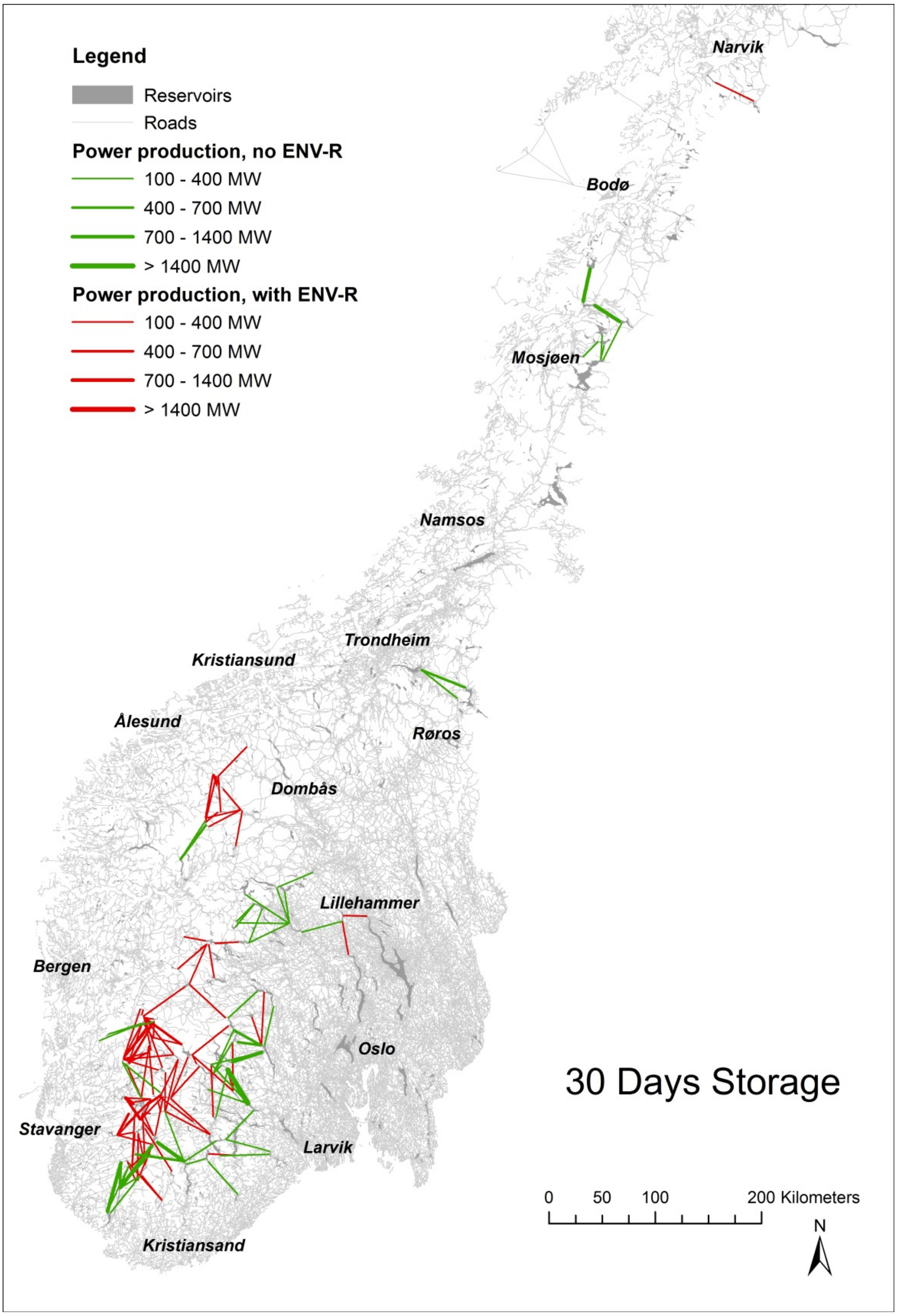


Figure 12: PSH potential for 30 days storage duration and minimum power production of 100 MW, calculated using the T-Mode. Green lines indicate no conflicts with environmental restrictions. Red lines stand for PSH connections where these restrictions are violated.

The screening results showed that the reservoirs in the mountains in the southern part of Norway have the highest PSH potential. Other regions with a relevant amount of PSH sites are situated in Mid-Norway and in North-Norway west of Mosjøen and Bodø.
The figures highlight that about 50 % of the potential PSH connections are in conflict with environmental restrictions, in particular in the areas South and North of the Hardangervidda. Figure 3 illustrates that these zones are covered by various and partly overlapping restriction areas, such as wild reindeer areas and natural protection areas.

4 Conclusions and outlook

The GIS-screening tool based on ArcGIS 10 and Python script tools was successfully applied to get a first overview of the PSH potential in Norway. The presented maps show potential pump storage sites in Norway for a few defined capacities and storage durations.
The reliability of the implemented assumptions and the plausibility of the model results have to be investigated more deeply. In addition, it is recommended to apply the tool with a variety of different parameter combinations and to perform a sensitivity analysis.

The study highlighted the importance of environmental restrictions for the estimation of the PSH potential sites in Norway. There is a need to further investigate these issues in cooperation with environmental experts and to find answers in particular to the following questions:

- Are the chosen default values for minimum distances between EIP and restriction zones acceptable, or should they be changed?
- What are the specific requirements in wild reindeer areas, natural protection zones, cultural landscape areas and other restriction zones with respect to hydro power regulation and infrastructure? For example: Are wild reindeer populations in addition to direct effects (e.g. cut-off movement tracks due to lack of ice cover) indirectly (e.g. via vegetation changes or erosion) affected by changes by the water level regulation regime of the reservoirs or not?
- Would it be acceptable to have new PSH sites in some environmental restriction zones when specific rules are observed?

The GIS-tool was created for the screening with the scope of the entire country Norway. This implicated some simplifications, such as the use of straight lines for potential reservoir connections. The next step will be regional or site-specific investigations in the areas where a high PSH potential was identified, including cost estimations. The present version of the GIS-tool provides the following parameters for each PSH connection line which can be used for a first cost estimation:

- Tunnel length (TUL)
- Penstock length (PSL)
- Cross-sectional area of the tunnel (A_TU) for a flow velocity of 2 m/s
- Cross-sectional area of the penstock (A_PSL) for a flow velocity of 3 m/s
- Distances from EIP to nearest road and power line (DIST_ROAD, DIST_PL)
- Absorption capacity (Q)
- Gross pressure height (GPH)
- Power production (P)

The further development of the GIS-tool for more detailed screenings should include an implementation and assessment of the additional parameters and aspects, such as (cp. Thomassen et al. 2012):

- Geology
- Inundation and landslide aspects
- Distance and visibility from tourist paths and cabins
- Distances from buildings and constructions (with special attention to cultural heritage)
- Reindeer husbandry (Areas cover 40 % of Norwegian land area, see RF(2013).)

The identification and planning of optimal PSH connections (in particular in reservoirs with several alternatives) could be supported by least-cost path methods and fuzzy logic tools. This includes a dialog process involving numerous formal and informal stakeholders representing ecological, economical, technological and societal perspectives (Thomassen et al. 2012).

5 Acknowledgements

This study was carried out as part of CEDREN in close cooperation between SINTEF Energy Research and NVE. Fredrik Arnesen (NVE) contributed with many ideas to the development of the GIS-tool and provided the net inflow data for the reservoirs.
Special thanks to Eivind Solvang, Atle Harby, Ånund Killingtveit and Bruno Capron for contributions during the work meetings and to my colleague Yisak S. Abdella for the friendly Python support.

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Appendix - Documentation of the GIS-Tool

A.1 Overview of model variables and field parameters

Table A.1 provides an overview of field parameters and their data sources or calculation routines. The relationships which were used for the calculation of selected parameters are shown below.

Table A.1: Field parameters and their data sources. * = "U" (Upper reservoir) or "L" (Lower reservoir). **= "PI" (for P-Mode) , "TdI" (for Td-Mode) or "WhI" (for W-Mode)

Field name	Content	Source	Parameter/Operation	Note
Xpl_*	E coordinate, UTM Zone 33N	Calculated	GIS, X-Y for UTM33	T1-Step1
Ypl_*	N coordinate, UTM Zone 33N	Calculated	GIS, X-Y for UTM33	T1-Step1
RNR_*	Reservoir Number	NVE Atlas, Magasin_P201111	Magnr	T1-Step1
RNA_*	Reservoir Name, UR	NVE Atlas, Magasin_P201111	Magnavn	T1-Step1
HRW_*	Highest regulated water level (m a.s.l.)	NVE Atlas, Magasin_P201111	LRV	T1-Step1
LRW_*	Lowest regulated water level (m a.s.l.)	NVE Atlas, Magasin_P201111	HRV	T1-Step1
AH_*	Reservoir area at HRW (m^2)	NVE Atlas, Magasin_P201111	ArealHRV	T1-Step1
RV_*	Reservoir volume (Mill. m^3)	NVE Atlas, Magasin_P201111	MagVolmm3	T1-Step1
PNR_*	No of the associated hydro power plant	NVE Atlas, Magasin_P201111	Vannkvnr	T1-Step1
PNA_*	Name of the associated hydro power plant	NVE Atlas, Magasin_P201111	Vannkvnavn	T1-Step1
dQG_*	Net outflow due to existing power plants	NVE	Table, Arnesen (2013)	T1-Step1
SL_*	Start water level (%)	Assumption	75 % U, 50 % L	T1-Step1
GM_*	Duration of max. power generation (hours/d)	Assumption	Default: 24 h/d	T1-Step1
PM_*	Duration of pumping (hours/d)	Assumption	Default: 0 h/d	T1-Step1
DISTpl	Nearest distance between reservoir polygons (km)	Calculated	GIS, Near table	T1-Step1
DGM_DIFF	Elevation difference	Calculated	DGM_MIN-LRW_L	T1-Step2

Field name	Content	Source	Parameter/Operation	Note
DGM_MIN	Minimum elevation value (m a.s.l.)	Calculated	GIS, Zonal statistics	T1-Step2
GPH	Gross Pressure height (m)	Calculated	Eq. (A.1)	T1-Step1
DIST_ROAD	Nearest distance from EIP to road (m)	Calculated	GIS, Near analysis	T2-Step2
DIST_PL	Nearest distance from EIP to power line (m)	Calculated	GIS, Near analysis	T2-Step2
DIST_INON	Nearest distance from EIP to INON areas (m)	Calculated	GIS, Near analysis	T2-Step3
DIST_WREIN	Nearest distance from EIP to wild reindeer protection areas (m)	Calculated	GIS, Near analysis	T2-Step3
DIST_CULSC	Nearest distance from EIP to cultural landscape areas (m)	Calculated	GIS, Near analysis	T2-Step3
DIST_NPR_E	Nearest distance from EIP to existing nature protection areas (m)	Calculated	GIS, Near analysis	T2-Step3
DIST_NPR_P	Nearest distance from EIP to suggested nature protection areas (m)	Calculated	GIS, Near analysis	T2-Step3
DIST_HPr*	Nearest distance from reservoir to NVE HP-protection area (m)	Calculated	GIS, Near analysis	T2-Step5
PSL	Penstock length (m)	Calculated	Eq. (A.2)	T2-Step4
TUL	Length of a/d tunnel (m)	Calculated	Eq. (A.3)	T2-Step4
P_**	Power generated (MW)	Input or calculated	If calculated: Min (P_U; P_L)	T3_Step1
A_PS	Cross-sectional area of penstock (m^2)	Calculated	Q_** / (3 m/s)	T3-Step1
A_TU	Cross-sectional area of a/d tunnel (m^2)	Calculated	Q_** / (2 m/s)	T3-Step1
Q_*_**	Discharge (m^3/s)	Calculated	Eq. (1)	T3_Step1
Q_**	Max. absorption capacity (m^3/s)	Calculated	If calculated: Min (Q_U; Q_L)	T3_Step1
WRh_U_**	Maximum rate of decrease for reservoir water level (m/hour)	Calculated	Eq. (A.4)	T3_Step1
WIh_L_**	Maximum rate of	Calculated	Eq. (A.5)	T3_Step1

Field name	Content	Source	Parameter/Operation	Note
	increase for reservoir water level (m/hour)			
Wh_**	Maximum rate of change for both reservoir water levels (m/hour)	Input or calculated	If calculated: Max (WRh_U; WIh_L)	T3_Step1
Td_U_**	Time for emptying of upper reservoir (days)	Calculated	Eq. (A.6)	T3_Step1
Td_L_**	Time for filling of lower reservoir (days)	Calculated	Eq. (A.7)	T3_Step1
Td_**	Minimum time for emptying/filling, from both reservoirs (days)	Input or calculated	If calculated: Min (Td_U; Td_L)	T3_Step1

$$GPH = \left[\frac{2}{3}(HRW\_U - LRW\_U) + LRW\_U\right] - \left[\frac{2}{3}(HRW\_L - LRW\_L) + LRW\_L\right] \quad \text{(A.1)}$$

$$PSL = \frac{(LRW\_U - LRW\_L)}{\sin 45°} \quad \text{(A.2)}$$

$$TUL = DISTpl - (PSL \cdot \cos 45°) \quad \text{(A.3)}$$

$$WRh\_U = \frac{3.6 \cdot (HRW\_U - LRW\_U) \cdot (Q + dQG\_U)}{RV\_U \cdot 1000} \quad \text{(A.4)}$$

$$WIh\_L = \frac{3.6 \cdot (HRW\_L - LRW\_L) \cdot (Q - dQG\_L)}{RV\_L \cdot 1000} \quad \text{(A.5)}$$

$$Td\_U = \frac{SL\_U \cdot (HRW\_U - LRW\_U)}{WRh\_U \cdot (GM\_U - 0.8 * PM\_U)} \quad \text{(A.6)}$$

$$Td\_L = \frac{(1 - SL\_L) \cdot (HRW\_L - LRW\_L)}{WIh\_L \cdot (GM\_L - 0.8 * PM\_L)} \quad \text{(A.7)}$$

A.2 User manual for the GIS-tool

Software and folder structure

The user needs a valid license of ArcGIS 10.0 including the Spatial Analyst and 3D Analyst extensions. The pre-defined folder structure has to be used, in order to run the shared Python scripts without problems. Note that the python script tools are subject to change due to further development. This documentation may contain errors and/or omissions which may therefore not reflect the exact condition of the software and/or documentation.

The structure of the folder is similar to the ToolShare folder structure recommended by ESRI (2012). The structure has to be maintained in order to run the GIS tool without problems. The main folder for the PSH analysis is organized in the following way:

C:/<….>/<Project name>

- **Data** (input and output files of the project)
- **Doc** (Project documentation)
- **Scripts** (Python scripts)
- **PumpStorageNorway.gdb** (geodatabase of the project, contains some processing files)
- **Scratch.gdb** (scratch geodatabase, for intermediate geo-processing files)
- PumpStorageNorway.mxd (ArcMap project)

The content of the sub-folders is structured as shown below:

C:/<….>/<Project name> / Data

- **Prepared_Data** (prepared input-shape-files and tables)
- **Raw_Data** (input-shape-files which were used without any changes/adjustments)
- **Result_Data** (output-shape-files of the project)

C:/<….>/<Project name> / Data / Raw_Data

- **DEM** (digital elevation model as raster file)
- **DN Norge** (with subfolders **INON** and **Others**)
- **NVE data** (with subfolders **Power_Lines**, **Reservoir_Polygons** and **NVE_Atlas_Feb2012**)

C:/<….>/<Project name> / Data / Prepared_Data

- **Tables** (with net inflow table as Excel-file)
- **UTM33** (with fy_vann_f_coast_merge_utm33.shp*, fy_vei_merge_utm33.shp, DistanceLines_50km_PreparedJan2013.shp*, VannKrvP_ekstern.shp*)

C:/<….>/<Project name> / Data / Result_Data

- **Tool_1** (with subolders **Step1_Distance_Criterion**, **Step2_Terrain_Criterion** and **Step3_EPP_Criterion**)
- **Tool_2** (with subfolders **EIP** and **PSH_Lines**)
- **Tool_3**
- **Lyr** (Files for legend symbols)

The catalog C:/<….>/<Project name> / Data / Raw_Data/Reservoir_polygons contains the file Magasiner_polygoner.shp with the magasin data. This file and the files marked with " * " in the list above are hard-coded and have to be stored in the defined folders. They can be replaced by new files having the same name and file structure.

The net inflow table (Excel) has to contain at least the following pre-defind fields, in order to work properly:

- MAGNR (reservoir number)
- MINUS_dQG (net inflow calculated from "inflow minus outflow", m^3/s)
- KV_NR (No. of the power plant)
- KV_NAVN (Name of the power plant)

Installation and Start

To start working with the ArcGIS-tool, do the following:

1) Copy the <PumpStorageNorway> project folder including its data sets into your project folder
2) Open ArcMap by clicking on the PumpStorageNorway.mxd
3) Open ArcToolbox (e.g. by clicking on the red toolbox-sign within ArcMap)
4) Open the PumpStorageNorway tool by clicking on the toolbox having this name.

Figure A3.1 shows the toolbox with the three script tools.

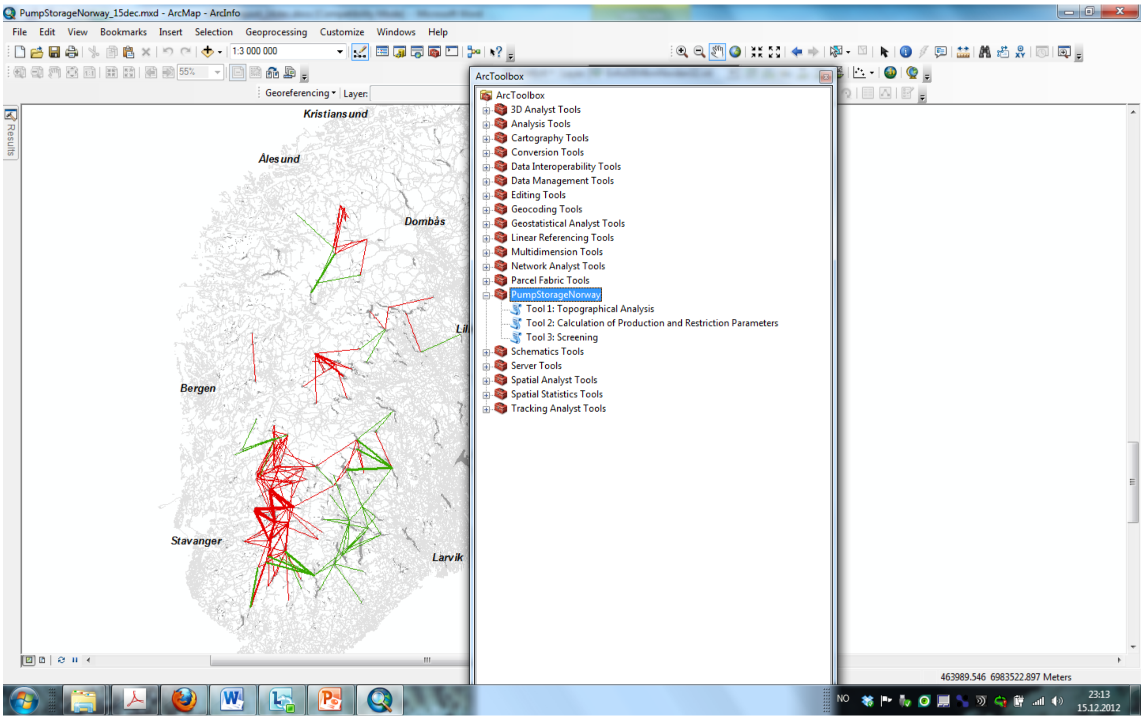

Figure A3.1: ArcToolbox with the PumpStorageNorway script tools.

Running the tools

The normal way for a GIS-screening is to start with Tool 1. A complete re-calculation of all reservoir connections is very time-consuming (5-6 hours on a 2.4 GHz Windows PC) and should only be performed when the input reservoir polygon file has changed. Otherwise, it is recommended to use the prepared file of a previous calculation which is delivered with the tool. The results of Tool 1 are the input data of Tool 2, which is run afterwards. The result line shape-files of Tool 2 are used as input data for Tool 3.

Once Tool 1 and 2 are run, these results can be used for many different GIS-screenings in Tool 3. Tool 1 and Tool 2 have to be run again only if the global input parameters and data sets (e.g. extension of wild reindeer areas) have changed. The data set that comes with the project includes some result files from all of the three tools, such that the user can test the different tools independently from each other.

Figures A3.2 to A3.3 show the ArcToolbox input windows of the three tools. They can be run from the model tool dialog box, using the following steps:

1. Double-click the model tool on the Catalog window or the ArcToolbox window.
2. Fill in any model tool parameters, or use the default values.
3. Click OK. The model tool is executed, and the result shape files are stored for each tool in the folder /<...>/<Project name>/Data/Result_Data.

The user-defined input variables and their units are explained in the tool. In Tool 1, the performance of the topographical analysis depends on the resolution of the DEM and the density of PSH lines in a given area.
The result shape files of the tool can be loaded into the ArcMap project using the Add Data function**.** The symbology of the newly created layers can be defined using prepared legends which are stored here:

/<...>/<Project name>/Data/Result_Data/Lyr.

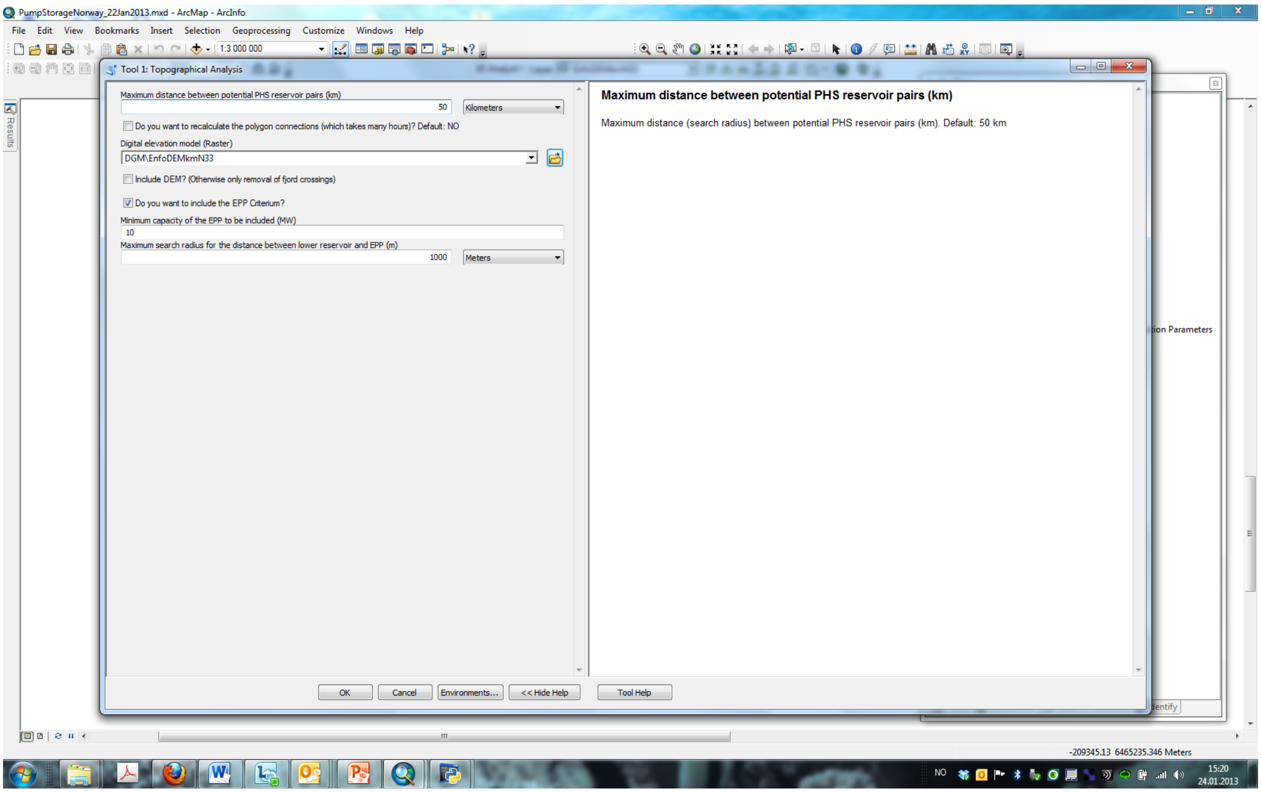

Fig. A.1: ArcToolbox input window for the Topographical Analysis (Tool 1)

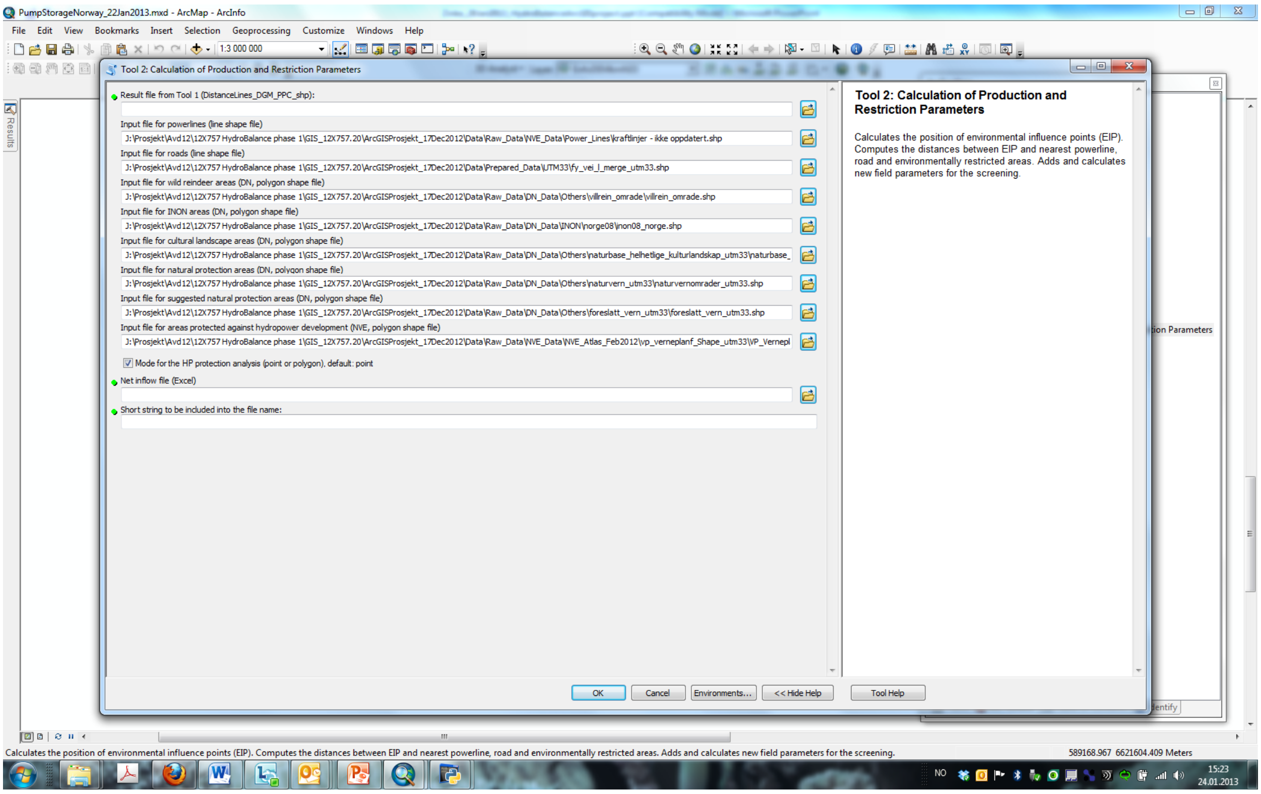

Fig. A.2: ArcToolbox window for the Restriction Parameter Calculation (Tool 2)

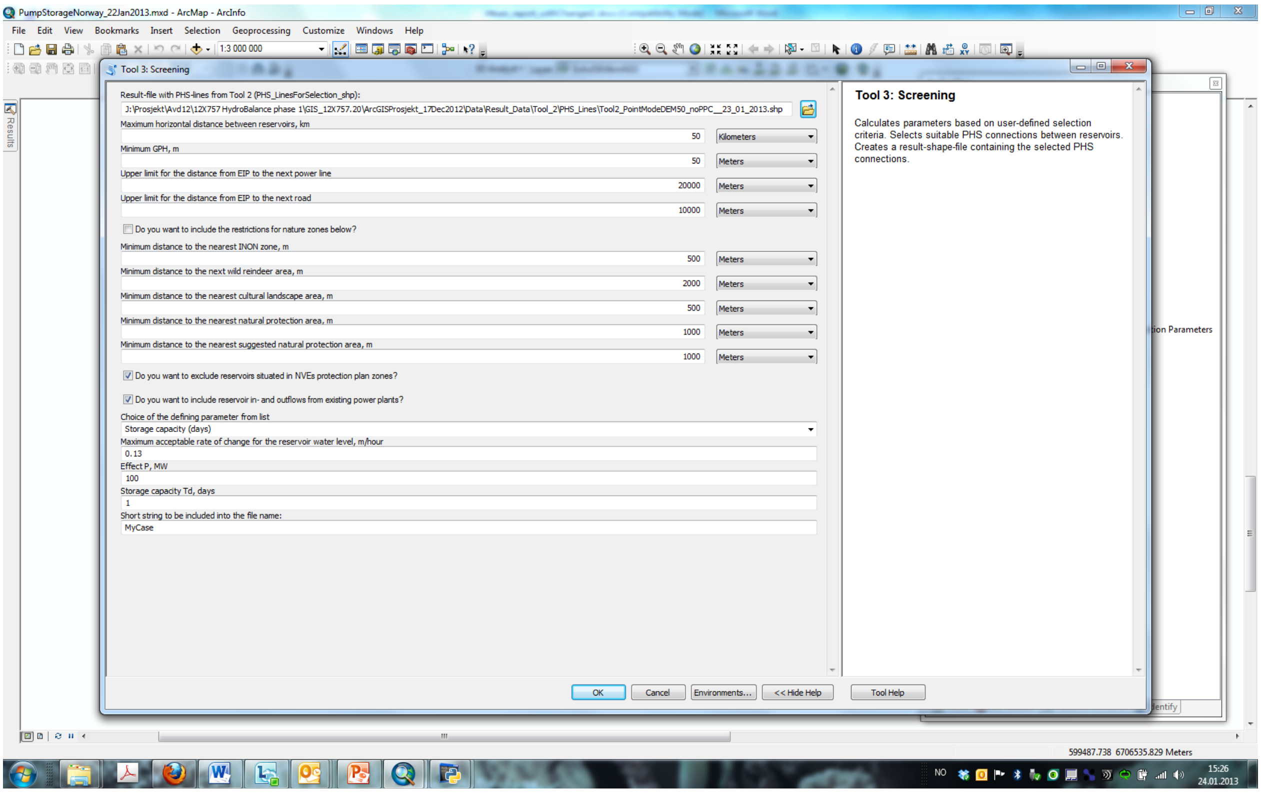

Fig. A.3: ArcToolbox window for the Screening (Tool 3)