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Report

Outlining a hydromorphological classification system for lakes

Data availability, modelling tools and comparable assessment approaches

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ABSTRACT

Abstract heading

This report outlines a hydromorphological classification system for lakes and reservoirs to support the implementation of the EU Water Framework Directive (WFD). The system is based upon the hydromorphological quality elements as defined by EU CIS Guidance document 13; i) Hydrological changes, ii) Changes in morphological conditions, and iii) Fragmentation and barriers hindering migration. The system describes a set of hydromorphological parameters, with a corresponding 3-class system. The classes are named 'Near-natural', 'Slightly to moderately modified' and 'Extensively to severely modified' status and refer to deviations from expected reference conditions (natural status). Three international systems were evaluated with respect to the suitability for Norway, i.e. Lake Habitat Survey, Lake MImAS - Morphological Impact Assessment Tool and GLAHF - Great Lakes Aquatic Habitat Framework. None of the systems can directly be adopted for the situation in Norway with a large number of lakes affected by river regulations. NVE hosts a set of databases that can provide very valuable data when hydromorphological classification is carried out. We would underline that the system should be tested and evaluated before applied for management purpose.

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Acknowledgement

The project was kick-started with a workshop at SINTEF in the Fall 2017 where state-of-the-art were presented, and the direction of the project discussed. The following scientists participated: Antti Eloranta and Ingeborg Palm Helland (NINA), Markus Lindholm (NIVA), Peggy Zinke (NTNU) and Lennart Hagen Schönfelder, Atle Harby and Tor Haakon Bakken (SINTEF), in addition to Steinar Sandøy from Miljødirektoratet (Norwegian Environment Agency). We would like to thank you all for your contributions during this workshop that gave valuable input to and direction to the project, and those of you for providing useful feedback on early versions of the report.

In addition to this report, the project has also produced two conference publications, i.e. contributions to the 5th IAHR Europe Congress (2018) in Trento, Italy, and to the 12th International Symposium on EcoHydraulics (2018) in Tokyo, Japan. These publications can be obtained by request to the main author of this report.

Finally, we would like to thank Miljødirektoratet (Norwegian Environment Agency) for financing the project. We are grateful for very useful discussions during the project, in particular with the main client contact Steinar Sandøy, related to both WFD-specific topics and the development of the classification system.

Table of contents

APPENDICES

[List appendices here]

1 Introduction

1.1 The EU WFD and the needs for a hydromorphological classification system

Hydromorphological alterations are one of the main pressures in many countries in EU and one of the dominant factors why surface water bodies are not in high or good ecological status. In Norway, hydropower regulation is the single most important pressure, causing deviations from natural conditions in both rivers and lakes. Hydromorphology of lakes is used to establish a typology of European water bodies according to the requirements of the European Water Framework Directive (WFD) 2000/60/EC. Typology of lake ecosystems is based on altitude, surface area and average depth as mandatory typology descriptors. In Norway, the typology is based on the same factors, but additionally diversified with respect to alkalinity, humus concentration and turbidity. It should be underlined that lakes also include regulated lakes, often termed as reservoirs. In this report we do not differentiate between lakes that are regulated and those without any regulation, but indicate specifically where we refer to a regulation as a pressure.

It is a possible to derive hydromorphological characteristics of rivers and lakes from existing databases, measurement techniques and modelling tools covering larger areas. Some measurement techniques, such as remote sensing, also have the advantage that it is repeated frequently, providing continuous monitoring of large areas. Use of hydromorphological conditions as indicators is therefore an efficient method to assess the ecological status of a large number of rivers and lakes.

There is presently no hydromorphological classification system for lakes and reservoirs available to support the implementation of the EU WFD in Norway. The classification system proposed in Section 8 is a pioneer work, based on current state of knowledge about the relationships between hydromorphological pressures and ecological response, and statistics on the hydromorphological pressures observed in Norwegian lakes derived from national databases (Section 3). It should also be mentioned that there is on-going work to establish and test a hydromorphological classification system for rivers (Harby et al. 2018). The classification system outlined for lakes and reservoirs is to a large extent based on the structure of the classification system developed for rivers, which has undergone more extensive research than the equivalent system for lakes and reservoirs.

1.2 The relevance of hydromorphological parameters in describing ecological state

The hydromorphology of lakes and reservoirs is one of the most important factors controlling the trophic status, physical and chemical conditions, productivity and distribution of aquatic organisms. Lake area, lake volume, maximum and average depth are parameters affecting nutrient cycling, water chemistry and hence ecological status. Deeper lakes typically cool slower and freeze later during fall and have longer retention time, which affects nutrient cycling and productivity and the vertical distribution of organisms compared to shallower lakes (Fee et al. 1994, Wetzel 2001). Small and shallow lakes are more strongly affected by wind-induced sediment re-suspension, which can result in significant changes in water chemistry and biogeochemical cycling.

Lake morphometry, i.e. lake area, depth, shoreline development and bottom slope, determines several limnological processes, such as habitat availability and productivity, thermal stratification, cycling of organic and inorganic matter, and sensitivity to anthropogenic disturbance (Wetzel 2001). Fee (1979) pointed out that mean depth is a factor controlling productivity while the size of the lake affects the establishment of the thermocline, while Håkanson (1977) states that the shape of the lake affects the bottom dynamic conditions.

The morphometry of lakes is a key factor for transport processes which influence abiotic variables such as water chemical variables and water clarity, which in turn regulate primary production (Håkanson 2005). Eloranta et al. (2017) showed that reservoir morphometry had a clear effect on how brown trout were affected by water level regulations (WLR) in Norwegian lakes. The slope of littoral zone has a great influence on the biomass and the distribution of submerged macrophyte communities (Duarte and Kalff 1986).

Upstream catchment area is also an important element for determining the water chemistry, as it affects inputs of allochthonous inorganic (e.g. nutrients and silt) and organic (e.g. dissolved and particulate organic carbon and living organisms) matter. There are several studies demonstrating the effects of land use in catchment area on water quality (e.g. Fraterrigo and Downing 2008) and the influence of catchment hydrology and geology on nutrient transport capacity (Kleinman et al. 2006).

The transformation of a natural lake into a hydropower reservoir changes the hydromorphological conditions (e.g. Hirsch et al. 2017, Zohary and Ostrovsky 2011, Strayer and Findlay 2010, Baxter 1977, Cott et al. 2008). The water level regulation will change the hydrological cycle of the lake, as well as the downstream areas, compared to the unregulated situation. The magnitude of the change will depend on the degree of regulation, regulation amplitude (i.e. the difference between the highest and lowest regulated water level), frequency, timing and rate of change. Extensive water level regulation and construction of dams can block access of fish to important spawning habitats, both due to dewatering of shallow areas within the lake, as well as reduced access to tributaries. Therefore, the river-lake connectivity is a relevant parameter to assess when hydromorphological alterations are investigated. Water level regulations can also induce shore erosion, siltation and de-coupling of lake littoral and riparian zones. The actual operation of the power plant will affect the physical conditions in both the reservoirs as well as the downstream recipients, and might lead to changes in circulation patterns, water temperatures and ice-cover.

As a part of the CEDREN EnviPEAK-project, the effect of hydro-peaking operations on the physical conditions in two regulated systems/reservoirs were investigated with use of modelling tools (Charmasson 2012, Tjomsland and Bakken 2012). EnviPEAK was followed by CEDREN HydroBalance where the environmental impacts of water level regulations were investigated using data from Norwegian hydropower reservoirs. The studies in HydroBalance concluded that the impacts of water level regulations are complex and highly case-specific, and that it is difficult to find consistent cause-effect relationships (Hirsch et al. 2017, Eloranta et al. 2018). These findings also demonstrate that it is difficult to develop a classification system based on known and scientifically-documented relationships between changes in hydromorphological conditions and ecological status. In other words, the outlined classification system presented in Section 8 can hardly be defended based on empirical scientific evidence alone. Hirsch et al. 2017 and Eloranta et al. (2018) suggest avenues for future research, which ultimately could lead to a more solid ecological basis for a classification system of hydropower impacts in reservoir ecosystems.

1.3 The aim and structure of this report

The primary objective of the project is to identify and develop a set of hydromorphological parameters that describe the human pressures on lakes due to regulations, and the effects on ecological state, landscape qualities and user interests. Secondary objectives are to:

1. Identify and link existing data sources/databases describing hydromorphological conditions in lakes and reservoirs. This is done by analysing data from existing data sources such as the NVE Lake database, Vann-Nett, ICOLD-database, GRanD-database.
2. Review and evaluate the applicability of existing methods such as Lake Habitat Survey, Lake MImAS and GLAHF for the assessment of ecological state, landscape features and user interests in Norwegian lakes and reservoirs.
3. Outline a hydromorphological characterization and classification system for lakes and reservoirs to support implementation of the EU Water Framework Directive. There is presently a hydromorphological classification system for rivers under development (Harby et al. 2018), and an identified need to develop a similar system for lakes and reservoirs. This project represents a first step in the way forward to develop an effective and applicable system for lakes.
4. Evaluate new measurement techniques for hydromorphological conditions in lakes, such as using multi-beam sonars combined with existing terrestrial elevation data, laser scanners and remote sensing.
5. Arrange a seminar/workshop on measurement techniques, where also external experts and companies are invited.

The findings from the evaluation of new measurement techniques (point 3 above) and the external seminar and the workshop (point 5 above) are reported separately and thus not in this report. The program and the workshop presentations (link at the very lower end) can be found via the following link:

https://hydrocen.blog/2017/12/08/seminar-on-measurement-and-data-processing-techniques-for-hydro-morphological-assessment-of-regulated-rivers-lakes-and-reservoirs/

Several other related research activities are going on in parallel to the work reported here, which might be of interest to the reader.

Hydromorphological classification of rivers (HYMO River): A hydromorphological classification system of rivers is now under development (Harby et al. 2018), equivalent to the classification system presented in Section 7 of this report.

HYMO River Test: The system developed for rivers (HYMO River) will be demonstrated and tested in 2018 by regional managers, under the supervision of researchers.

HYMO Ecology (river): This project aims at testing the class divisions proposed in the HYMO River project with respect to ecological response from hydromorphological changes. This project will together with HYMO River Test provide valuable input into a refined hydromorphological classification system on river.

HydroCEN Work package 4: A substantial part of the planned work is related to hydromorphology and the use of various measurement techniques to provide data/information of the hydromorphological state of rivers, and possibly also lakes. The majority of this work is carried out as part of a PhD, under the supervision of scientific personnel at NTNU, and in co-operation with researchers at SINTEF and NINA.

No-HYPE: This project demonstrated the applicability of the hydrological model HYPE in the provision of hydrological data relevant for the implementation EU WFD in Norway. The model is capable to produce time-series of runoff for defined sub-catchments with acceptable precision, which forms the basis for calculation of a set of hydrological indices. The results from this project are reported in Schönfelder et al. (2017).

SusWater: SusWater focuses on water management in regulated rivers, and will examine different paths towards a more unified water management policy that will be accepted at both local, regional and national levels, while meeting our international obligations. Key questions addressed in SusWater relevant to this report are i) how much water is sufficient to meet given environmental objectives, ii) how can different benefits and costs be better measured and operationalised, and in particular iii) how to characterise hydrological and morphological changes in rivers due to hydropower. Development of indicators describing the water needs of the various user interests are very central related to the last question addressed.

EU REFORM: REFORM was an EU-funded project with the overall aim to provide a framework for improving the success of hydromorphological restoration measures to reach, in a cost-effective manner, target ecological status or potential of rivers. One of the key finding of REFORM was that hydromorphological assessment should consider physical processes and appropriate temporal and spatial aspects beyond river restoration project boundaries and project life span. For this, REFORM developed an open-ended hydromorphological framework incorporating multi-scale spatial and temporal aspects. It aids users in developing understanding of the morphology and dynamics of river reaches and their causes. The Morphological Quality Index (MQI) (Rinaldi et al. 2016) is the method recommended by REFORM for assessing river condition. More information about REFORM can be found here: www.reformrivers.eu

EU FitHydro: FITHydro is an EU-funded project and stands for 'Fish friendly Innovative Technologies for Hydropower'. FIThydro addresses the decision support in commissioning and operating hydropower plants by use of existing and innovative technologies. The project concentrates on mitigation measures and strategies to develop cost-efficient environmental solutions and on strategies to avoid individual fish damage and enhancing fish population developments. Hydropower plants across four different regions in Europe are used as test sites and SINTEF has a central scientific role in FitHydro. More information about FITHydro can be found here: https://www.fithydro.eu/

Figure 1.1. Regulated waters and variations in water level can also pose a risk to humans (photo: Tor Haakon Bakken).

2 Description of existing national data sources

Norges vassdrags- og energidirektorat (NVE) (Norwegian Water Resources and Energy Directorate in English) maintains a large range of map-based services relevant for the assessment of hydromorphological status and changes of lakes and reservoirs. An overview and short description of many of these services are available from: https://www.nve.no/map-services/map-tools/. In the following those products and services that are considered most relevant in describing hydromorphological conditions in lakes and reservoirs are described, presented and processed for the purpose of this project.

NVE's geospatial data are open to the public. Many of the products can be downloaded for further processing with use of desktop tools, or can be accessed by using Web Map Services (WMS).

2.1 Relevant hydromorphological terms and parameters

In this section, central parameters and terms that are used to describe lake and reservoir properties are presented. Most of these parameters are suitable as classification parameters directly, and could potentially be used as proxy for other parameters that are relevant for classification purposes (Håkanson 2005). The presented parameters can be used as the basis to calculate more sophisticated hydromorphological parameters.

Lake surface area (A)

Lake surface area is the horizontal spatial extent of a lake at a given time. It changes dynamically with water level.

Volume

Lake volume is the space that is occupied by water. This information is necessary to calculate the mean depth of a lake and to describe water quantity dynamics. In practice, it can be calculated from bathymetric maps or be estimated from volume-area scaling functions (Cael et al. 2017).

Mean depth

Mean depth is the volume to area ratio: $D_m = V/A$. It determines the amount of energy necessary to have a full vertical mixing and influences stratification respectively (Rowan et al. 2012). It is related to the renewal process (recycling) of nutrients in the reservoir. Mean depth also partly determines e.g. habitat availability and lake productivity (the relative proportion of littoral and pelagic area to the total lake area etc.).

Maximum depth

Maximum depth is the distance from the water surface to the deepest point in the lake.

Altitude

Altitude is the lake elevation in meters above sea level. It can be linked to the trophic status of the lake and to its temperature: high altitude lakes tend to be oligotrophic, with low concentrations of dissolved nutrients and organic carbon limiting primary and secondary production.

Shoreline development

The shoreline development of a lake is its shore length divided by the perimeter of a circle of the same area as the lake.

$$Shoreline\ development = \frac{Shore\ length}{Perimeter\ of\ circle\ of\ equivalent\ area}$$

The shoreline development is a dimensionless number that can be used to compare the shape of a lake and potentially indicate the littoral area relative to lake surface area. High values indicate complex shorelines and reticulate lake shapes, whereas low values indicate near-circular lakes.

Fetch length

Fetch length can be calculated for the whole lake or for points/parts of the lake. As a descriptor for the whole lake, fetch can be defined as the longest unobstructed straight line within the lake area boundaries over which the wind can reach a point on the shoreline. For an individual point, the fetch length is the distance to the furthest point on the opposite shoreline. Fetch length can be calculated using GIS tools. The fetch length can be used as an indicator for the occurrence and intensity of waves. Waves play a fundamental role in mixing and stratification dynamics of lakes.

Average annual inflow (Q)

The average annual inflow is the volume of water entering the reservoir during a year, averaged over several years.

Residence time (T)

Residence time is the ratio of total reservoir volume V to the annual inflow $T = V/Q$. Residence time is the time necessary for all water contained in the reservoir to be renewed when assuming complete mixing of the lake. Residence time quantifies to what extent lake hydrodynamics are conditioned by river flow. It is an indicator to characterize water quality and to evaluate lake response to accidental spill of pollutants.

Degree of regulation (%)

The degree of regulation is given by the storage capacity of a reservoir, which is the volume between highest regulated water and lowest regulated water level, divided by the mean annual inflow. The percentage then indicates the reservoirs capacity of storing generated runoff, i.e. if the degree of regulation is 100%, the reservoir can store the inflow of an average year (Arheimer et al. 2017).

Regulation height

The regulation height is the difference between the highest regulated water level (HRWL) and the lowest regulated water level (LRWL), in meters. HRWL and LRWL are given by the concessions agreement of the hydropower project. A reservoir is not always regulated to its maximum limits, which means that actual regulation height can be less than the difference of HRWL and LRWL.

2.2 Important databases containing information about lakes

A wide range of data can be relevant in order to assess the hydromorphological status of lakes. This includes biological data, water chemistry data, data on physical conditions, human-induced pressures and more. These data are hosted by different directorates and sectors authorities, or research institutes carrying out monitoring on behalf of authorities. Data can be stored in well-organised databases made available for instance via a map-based user interface, or only available in printed reports.

In this section, those databases we consider being most important and relevant for carrying out a hydromorphological classification are described. These are databases mainly maintained and updated by Norges Vassdrags- og Energidirektorat (NVE) (Norwegian Water Resources and Energy Directorate).

2.2.1 NVE - Innsjø

The Innsjø database provides a georeferenced inventory of all lakes larger than 2500 m^2 in Norway. The evaluated shapefiles consist of lake polygons, which can be further processed to extract other relevant hydromorphological information.

Table 2.1. Overview of content in the NVE-Innsjø database.

Category	Number
Reservoirs	2053
Natural lakes > 50 ha	3349
Natural lakes > 5 km^2	147

Table 2.2. Derivable lake parameters in NVE-Innsjø database and their relevance for typology and classification purposes.

Parameter	Relevance	Availability
Lake surface area	Fundamental property	all
Altitude	Fundamental property	all
Position	Fundamental property	all
Perimeter	Fundamental property	all
Shoreline development	Littoral zone	GIS calculation (all)
Effective fetch length	Susceptibility to wind	GIS-tool necessary

2.2.2 NVE - Magasin

NVE provides a georeferenced database of all reservoirs in Norway. Generally, all parameters listed for natural lakes in Table 2.2 can also be calculated for reservoirs in NVE-Magasin database. The additional information provided by NVE-Magasin is tabulated in Table 2.3.

Table 2.3. NVE-Magasin database with available number of descriptive parameters for reservoirs.

Selection	**No of records**	**Regulation height: lowest level**	**Storage volume**	**Regulation height: highest level**	**Start Year of operation**	**Concession status**	**Type of use**	**Name of hydropower plant**
Number	2287	1358	1153	1546	1557	423	1989	1256

2.2.3 NVE - Dybdekart

The NVE-Dybdekart database is based on bathymetric map surveys. Lake depth measurements in this dataset were taken from 1906 until 2001, with use of handheld cables and echo sounders. Table 2.4 shows an overview of the available variables for the surveyed lakes. This dataset contains derived variables from bathymetric maps, but does not contain detailed bathymetric maps.

Table 2.4. Overview over NVE-Dybdekart with available number of descriptive parameters.

Selection	**No of records**	**Mean depth**	**Maximum depth**	**Mean inflow**	**Volume**	**Residence time**
Number	688	386	596	461	395	333

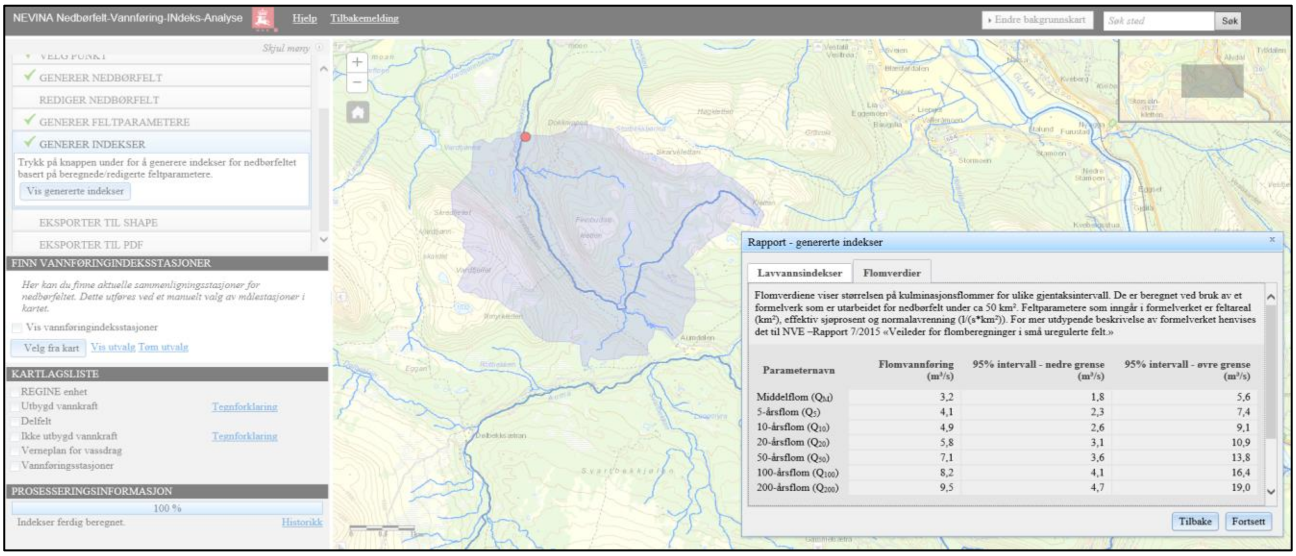
2.2.4 NVE - Bathymetric maps

The unpublished depth maps database from NVE was obtained via personal communication. The dataset consists of georeferenced contour lines of 360 lakes. These lakes are a sub-selection of the NVE-Dybdekart database with the additional bathymetric map information. The contour lines have height differences within individual lakes ranging from 2 m to 50 m, with the majority having 2 m and 10 m, depending on depth and size of the lake.

The depth values are defined relative to the water level; the filling level of the moment when the measurements were made are not given and may be inconsistent within the dataset. Also, the original measurements might be made many decades ago, so conditions in some reservoirs may have changed, e.g. due to transformation of a natural lake into a hydropower reservoir, landslides, sedimentation and erosion processes. The importance of bathymetric maps and the derivable hydromorphological parameters are explained in detail in Chapter 3.

2.2.5 NVE - NEVINA

NEVINA is a newly developed data service by NVE for the calculation of catchment characteristics, high and low flow indices. Based on the selection of a random point on the map, the system will calculate the size of the upstream area and land use characteristics, including percentage of surface waters. NEVINA also calculate low flow indices and high-flow values of certain return periods, based on methodology developed for catchments smaller than 50 km2. NEVINA can be accessed via nevina.nve.no.



Trykk på knappen under for å generere indekser for nedbørfeltet basert på beregnede/redigerte feltparametere.

Her kan du finne aktuelle sammenligningsstasjoner for nedbørfeltet. Dette utføres ved et manuelt valg av målestasjoner i kartet.

Indekser ferdig beregnet.

Flomverdiene viser størrelsen på kulminasjonsflommer for ulike gjentaksintervall. De er beregnet ved bruk av et formelverk som er utarbeidet for nedbørfelt under ca 50 km². Feltparametere som inngår i formelverket er feltareal (km²), effektiv sjøprosent og normalavrenning (l/(s*km²)). For mer utdypende beskrivelse av formelverket henvises det til NVE –Rapport 7/2015 «Veileder for flomberegninger i små uregulerte felt.»

Parameternavn	Flomvannføring (m^3/s)	95% intervall - nedre grense (m^3/s)	95% intervall - øvre grense (m^3/s)
Middelflom (Q_M)	3,2	1,8	5,6
5-årsflom (Q_5)	4,1	2,3	7,4
10-årsflom (Q_{10})	4,9	2,6	9,1
20-årsflom (Q_{20})	5,8	3,1	10,9
50-årsflom (Q_{50})	7,1	3,6	13,8
100-årsflom (Q_{100})	8,2	4,1	16,4
200-årsflom (Q_{200})	9,5	4,7	19,0

Figure 2.1. Screendump from NEVINA.

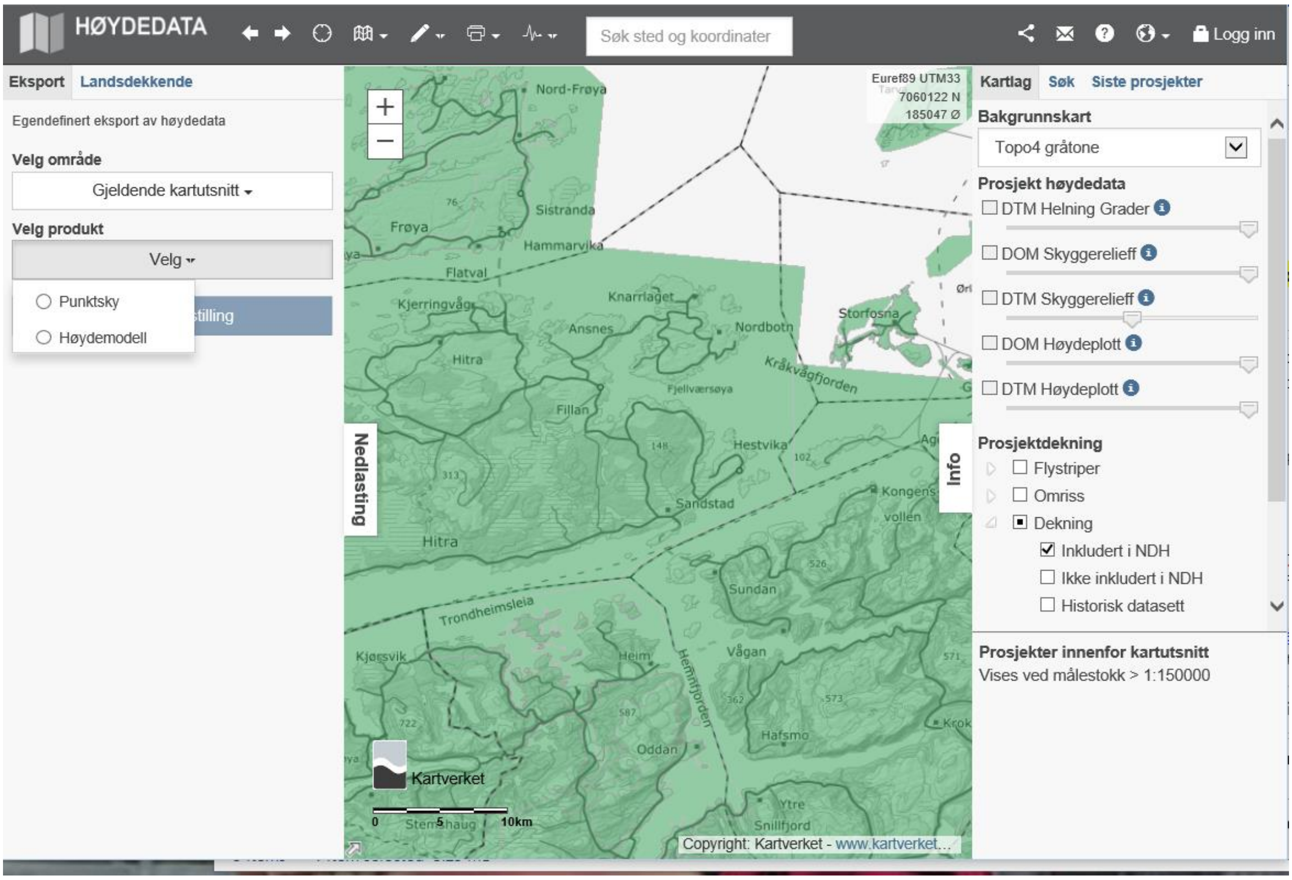
2.2.6 NVE - HYDRA II

Hydra II is the main database containing timeseries of discharge and water level in Norway. These data can be the basis for calculating for instance hydrological indices and the alterations in these due to river regulations. Data from Hydra II can be directly accessed and downloaded if the user has an abonnement. Data can also be accessed by contacting NVE by e-mail.

2.2.7 Map-based products from other national providers

The Norwegian Mapping Authority offers a wide selection of maps and data for use. Data can be downloaded for further processing locally, or services can be developed via standardised application programming interface (API). Digital elevation models (DEM) are available for the purpose of hydromorphological classification, which are freely available via hoydedata.no. The data available are included in the project National Detailed Height Model running in the period 2016-2021, collected by air plane or helicopter mounted laser scanners. The data sets have a point density of 2 points per square meter, and in some places even higher point density, and the target is a national coverage model with resolution 1x1 meter.

The Norwegian Mapping Authority has also started mapping Norway with green laser from the air plane, and has started with five coastal regions in South Sunnmøre. Data from this campaign will 'fill in' data in those shallow, coastal areas that are difficult to cover from boat and on-shore areas. On individual basis, some hydropower companies have also started detailed mapping on the topography in rivers basins they regulate.



Egendefinert eksport av høydedata

Velg område: Gjeldende kartutsnitt

Velg produkt: Velg

○ Punktsky
○ Høydemodell

Bakgrunnskart: Topo4 gråtone

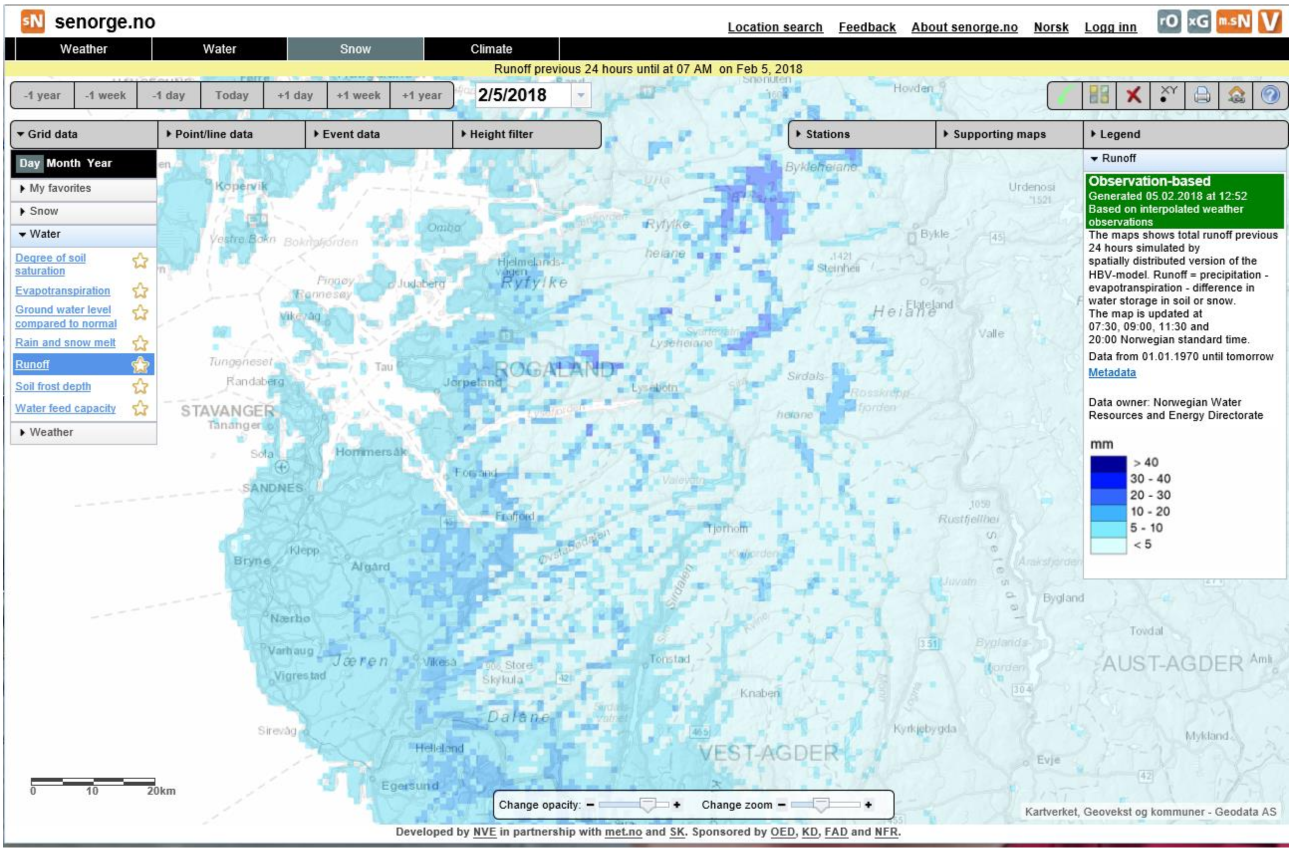
Prosjekt høydedata
☐ DTM Helning Grader
☐ DOM Skyggerelieff
☐ DTM Skyggerelieff
☐ DOM Høydeplott
☐ DTM Høydeplott

Prosjektdekning
☐ Flystriper
☐ Omriss
■ Dekning
  ☑ Inkludert i NDH
  ☐ Ikke inkludert i NDH
  ☐ Historisk datasett

Prosjekter innenfor kartutsnitt
Vises ved målestokk > 1:150000

Figure 2.2. This screendump shows a dataset that has been prepared for download from hoydedata.no.

SeNorge is a Map-based service available from www.senorge.no provided by NVE, met.no (Meteorological Institute) and Kartverket (Norwegian Mapping Authority). SeNorge gives access to data and information about 'Snow', 'Water', 'Weather' and 'Climate'. It provides information about the present state in absolute values and percentage deviation from the 'normal' conditions. SeNorge also offers short-term statistics, such as changes in snow cover that last day, last week and compared to one year back. The data provided are based on a combination of monitoring and model simulations.



Runoff previous 24 hours until at 07 AM on Feb 5, 2018

Observation-based
Generated 05.02.2018 at 12:52
Based on interpolated weather observations

The maps shows total runoff previous 24 hours simulated by spatially distributed version of the HBV-model. Runoff = precipitation - evapotranspiration - difference in water storage in soil or snow. The map is updated at 07:30, 09:00, 11:30 and 20:00 Norwegian standard time.

Data from 01.01.1970 until tomorrow

Metadata

Data owner: Norwegian Water Resources and Energy Directorate

Developed by NVE in partnership with met.no and SK. Sponsored by OED, KD, FAD and NFR.

Figure 2.3. This map is a screendump from www.senorge.no, where runoff by February 5th, 2018, is shown.

Norge i bilder (www.nogeibilder.no) is a service provided by the Norwegian Mapping Authority, NIBIO and the Norwegian Public Roads Administration. At this site, historical orthophotos can be compared with photos taken very recently, and landscape changes can be identified. Some of the photos date back to 1935, so it is a potential to use these photos in the support of establishing reference conditions in those cases the hydromorphological changes have been introduced at a later stage.

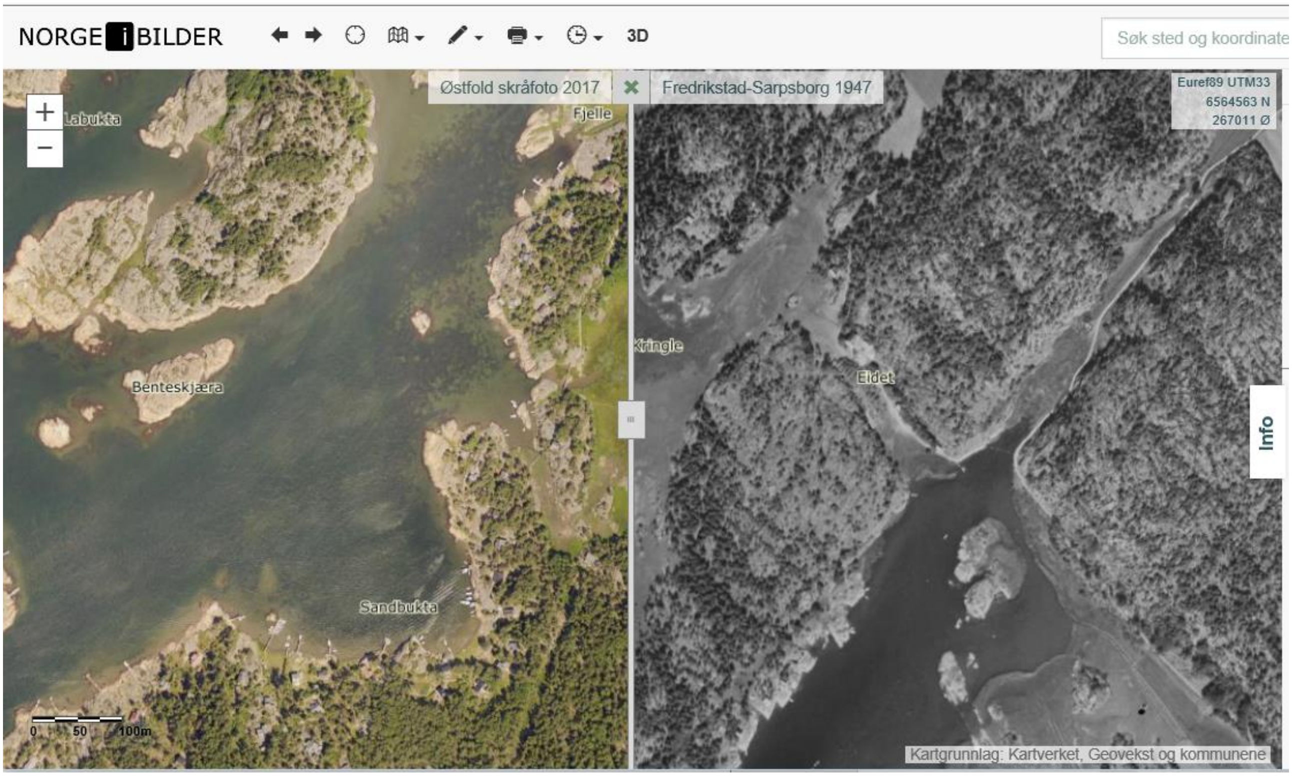


Figure 2.4. This combined image from Norge i bilder shows aerial photos taken in 2017 (left) and in 1947 (right) of a certain location outside Fredrikstad (www.norgeibilder.no).

2.2.8 Lake - catchment data set

The catchment upstream of a lake must be known in order to calculate the Schindler's ratio (ratio of catchment area and lake volume), which in turn correlates to the intensity of the catchment area's impact on the lake ecosystem (Kolada et al. 2005). Terrestrial vegetation cover in the lake catchments, expressed with normalized difference vegetation index, can be used as proxy for dissolved organic carbon in Norwegian lakes (Finstad et al. 2016).

A lake catchment data set for approximately 20 000 lakes in Norway was obtained from an unpublished work at NTNU (Anders Finstad, anders.finstad@ntnu.no). It contains the lake catchment shapes and derived data as shown in Table 2.5.

Table 2.5. Available data in lake catchments database.

Variable	Potential application
Area	Calculation of Schindler's ratio, annual inflow estimation
Land use	Proxy for nutrient concentrations
NDVI	Proxy for catchment vegetation (Finstad et al. 2016)

Flow accumulation	Annual inflow estimation
Altitude statistics	Precipitation distribution, snow melt and other hydrological properties
Slope statistics	Response time

The catchment delineation can further be used as input data and for verification purposes in catchment models such as HYPE and WEAP.

3 Characteristics and statistics on reservoirs in Norway

The following section provides an overview of the characteristics of the regulated lakes in Norway, data on altitude, surface area, regulation volume, degree of regulation and other relevant information was retrieved from a selection of Norwegian reservoirs. Three databases are used as a source for the statistics, namely NVE-magasin, NVE-innsjø, and NVE-dybdekart. The latter databases (NVE-innsjø and NVE-dybdekart) were combined to complete information about reservoirs available in NVE-magasin. In total, 2287 reservoirs were registered, but not all had parameters registered in each NVE database. For some parameters like altitude, area, and reservoir volume, data was available for the majority of the reservoirs, while for other parameters like maximum depth, data was available for less than 400 reservoirs.

In the following tables Min. and Max. stand for minimum and maximum values in the dataset, Mean and Median the mean and median values, SD stands for standard deviation and the percentages different percentiles.

3.1 Statistics based on combining NVE databases

Table 3.1. Altitude distribution of the regulated lakes in the database (m.a.s.l.).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
4.0	1477.0	471.4	394.0	342.1	86.0	185.0	694.0	978.4

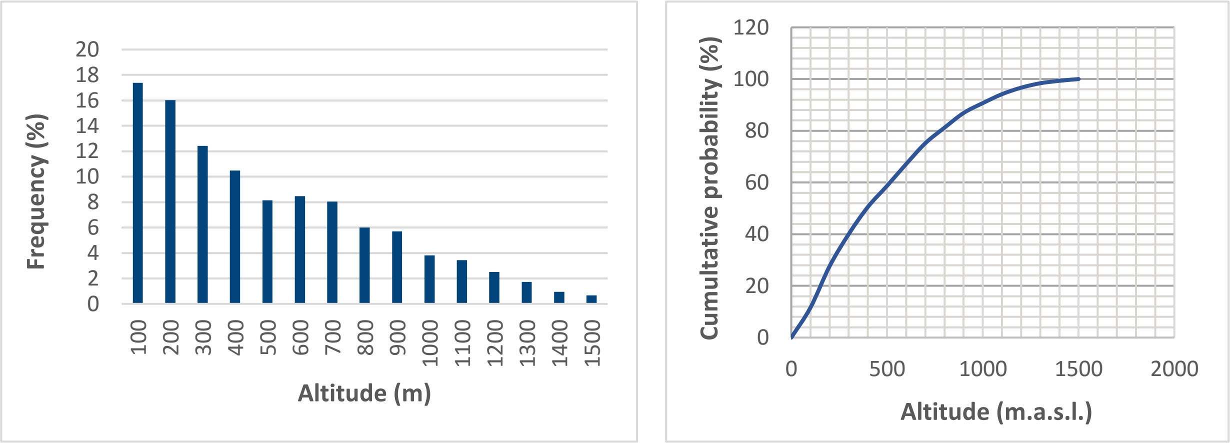


Figure 3.1. Altitude distribution of the reservoirs (n=1915).

Table 3.2. Maximum depth distribution of the reservoirs in the database (m).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
3.9	460.0	74.9	53.0	75.0	18.0	32.3	84.0	160.6

Information on the maximum depth was available for 213 reservoirs among 2286. The maximum depth refers to the greatest depth measured in the reservoir.

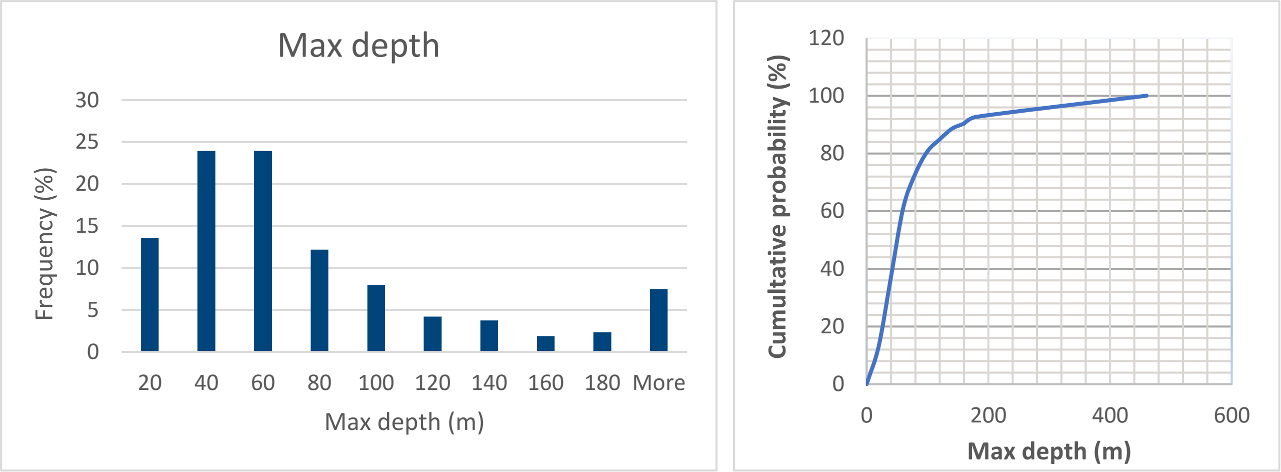


Figure 3.2. The figures show the max depth distribution of the reservoirs (n=213).

Table 3.3. Surface area distribution of the reservoirs in the database (km^2).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
0.01	376.00	2.98	0.50	12.61	0.04	0.14	1.81	5.90

Surface area was available for 2248 reservoirs among 2286. Surface area refers to the area of the reservoir when the reservoir is at the highest regulated water level (HRWL).

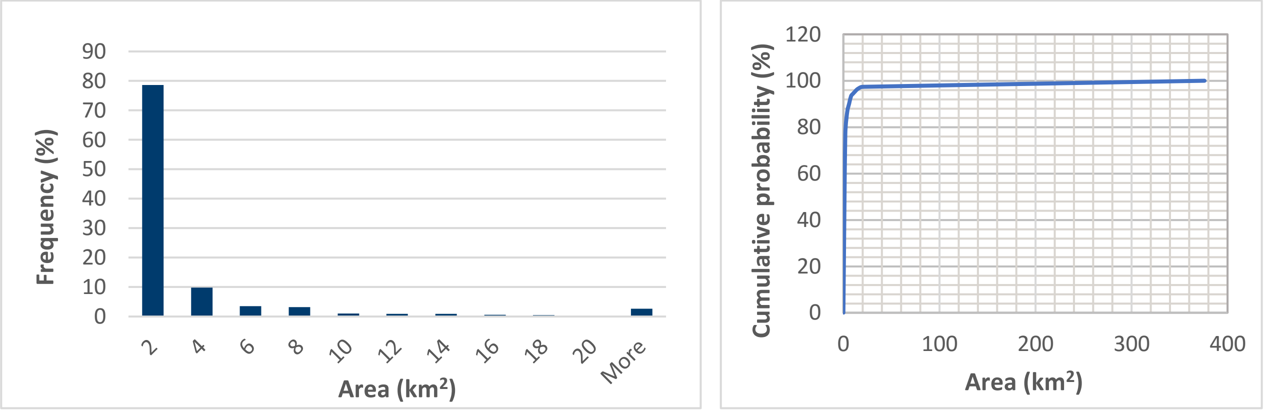


Figure 3.3. The figures show the surface area distribution of the reservoirs (n=2248).

Total water volume was available for 136 reservoirs among 2286. The total reservoir volume refers to whole reservoir volume when it is at the HRWL.

Table 3.4. Total reservoir volume distribution of the reservoirs in the database (mill. m^3).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
1.1	56244.0	1414.8	78.6	5294.8	4.5	18.6	586.4	4167.9

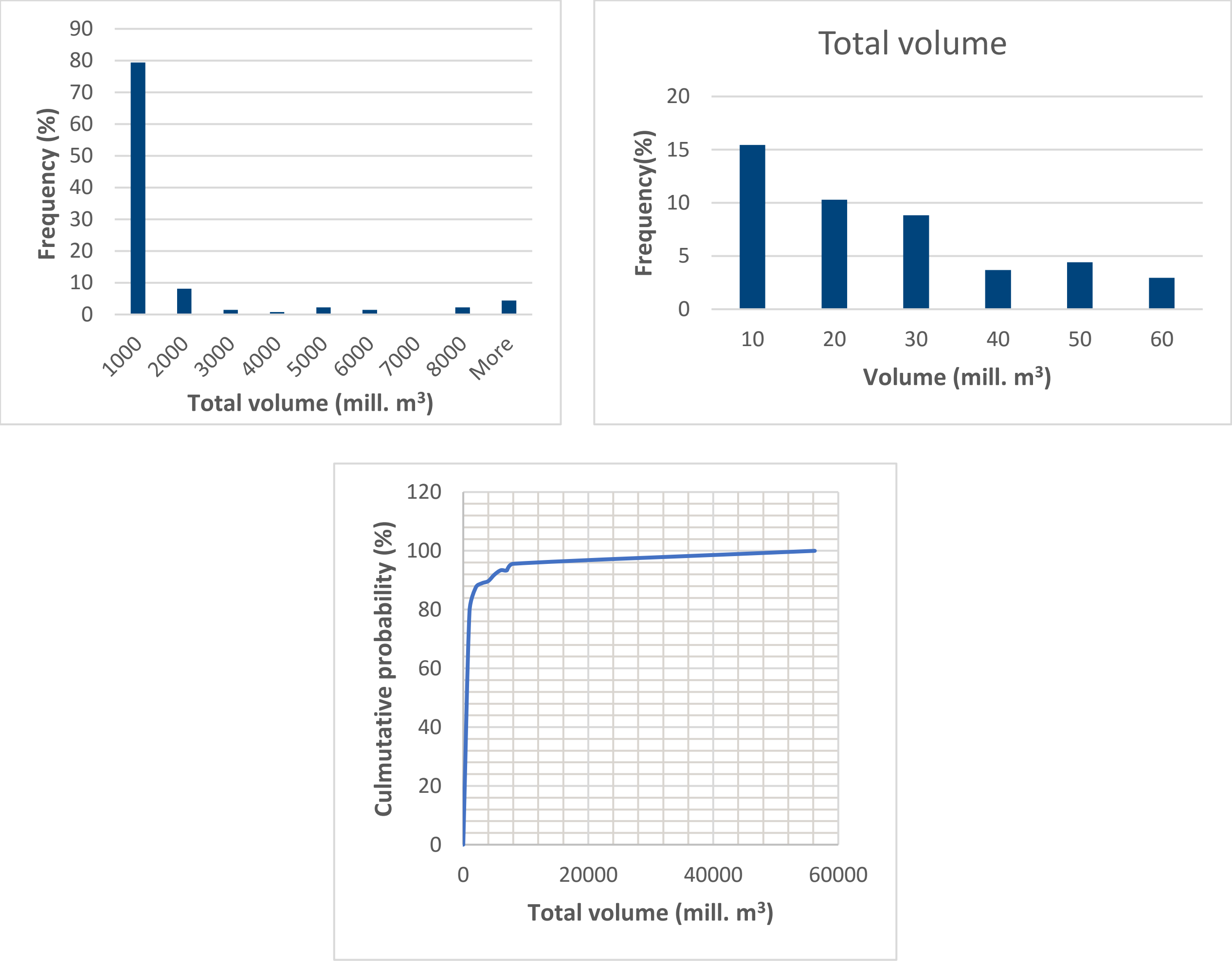


Figure 3.4. The figures show the total reservoir volume distribution of the reservoirs (n=136).

Table 3.5. Available reservoir volume distribution of the reservoirs in the database (mill. m^3).

Min.	Max	Mean	Median	SD	10 %	25%	75%	90%
0.01	3506.0	52.6	7.7	179.0	0.4	1.5	34.0	124.2

Available water volume was registered for 1150 reservoirs among 2286. The available reservoir volume refers to the water volume which is used for regulation, i.e. between HRWL and LRWL.

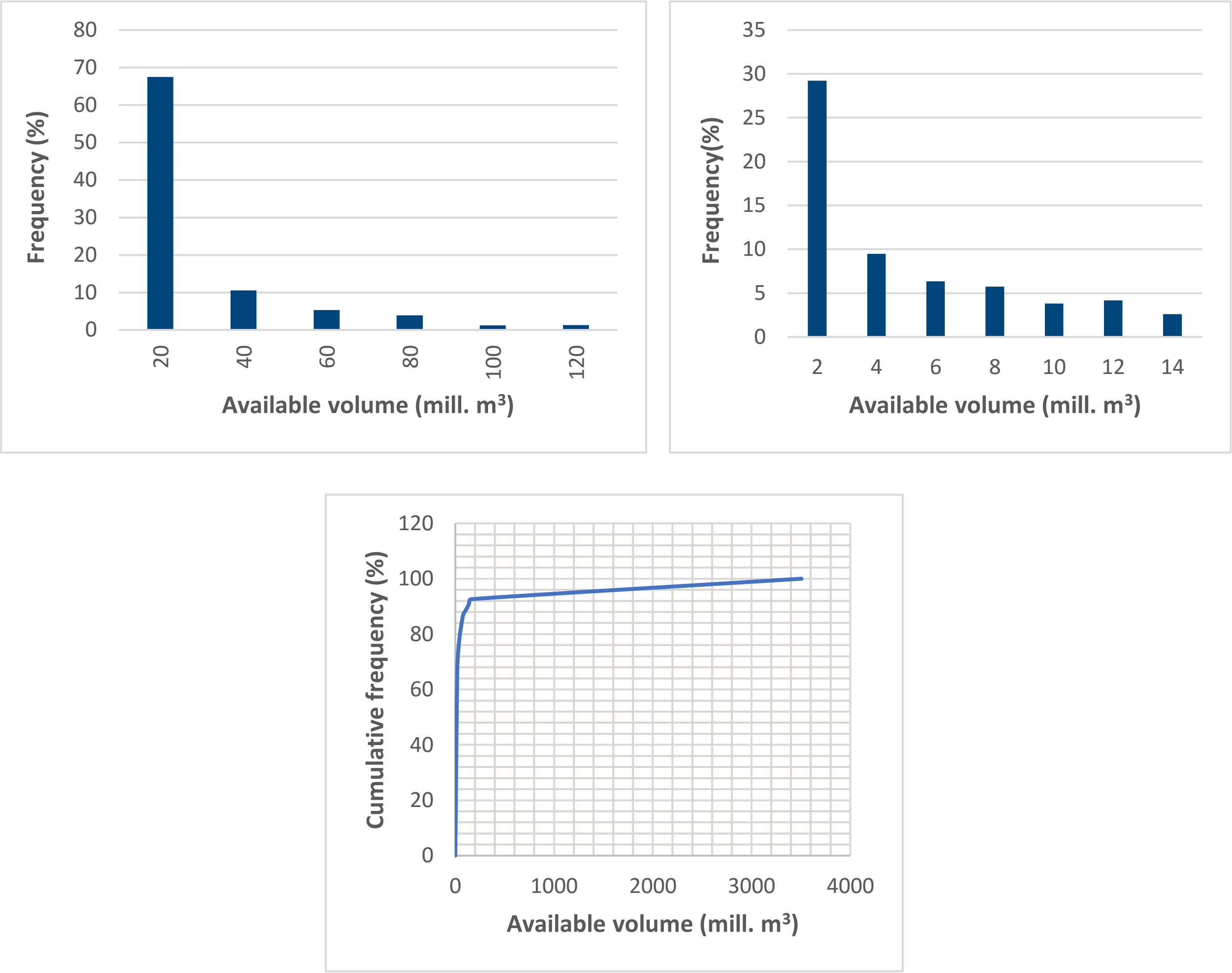


Figure 3.5. The figures show the available volume distribution of the reservoirs (n=1150).

Table 3.6. Water level fluctuations of the reservoirs in the database (m).

Min.	Max	Mean	Median	SD	10%	25%	75%	90%
0.1	140.0	12.4	6.0	16.4	1.5	3.0	15.3	32.0

Water level fluctuations were available for 1432 reservoirs among 2286. Water level fluctuation is computed as difference between the highest regulated water level (HRWL) and the lowest regulated water level (LRWL).

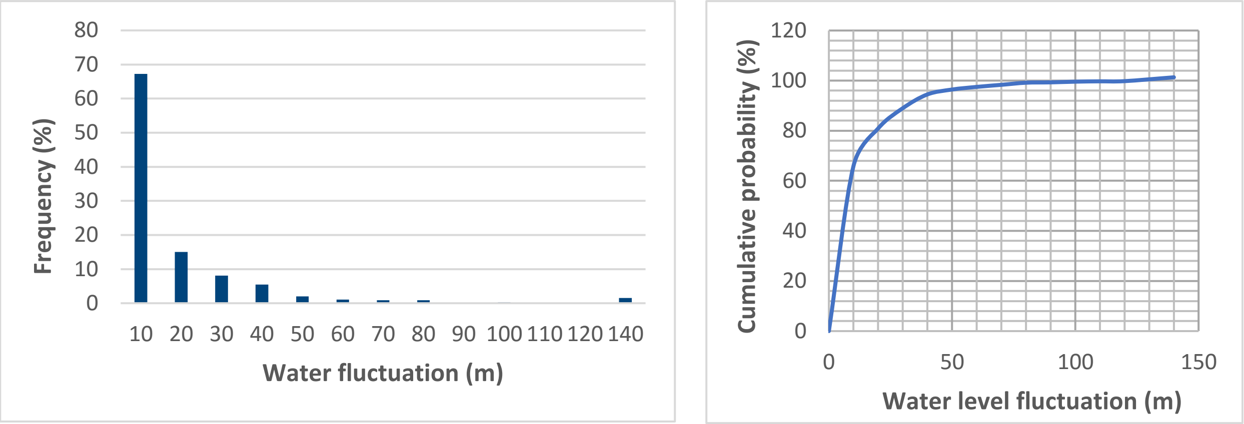


Figure 3.6. The figures show water level fluctuation distribution of the reservoirs (n=1432).

3.2 Statistics derived from data in NVE databases

The statistics presented in this section is based on the same data sources as presented in the previous section, but is derived based on calculations of the numbers given directly in the databases.

Mean depth:

Table 3.7. Mean depth of the reservoirs in the database (m).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
4.0	190.0	36.1	23.0	36.8	7.0	15.0	40.5	87.0

Mean depth was computed for 109 reservoirs among 2286.

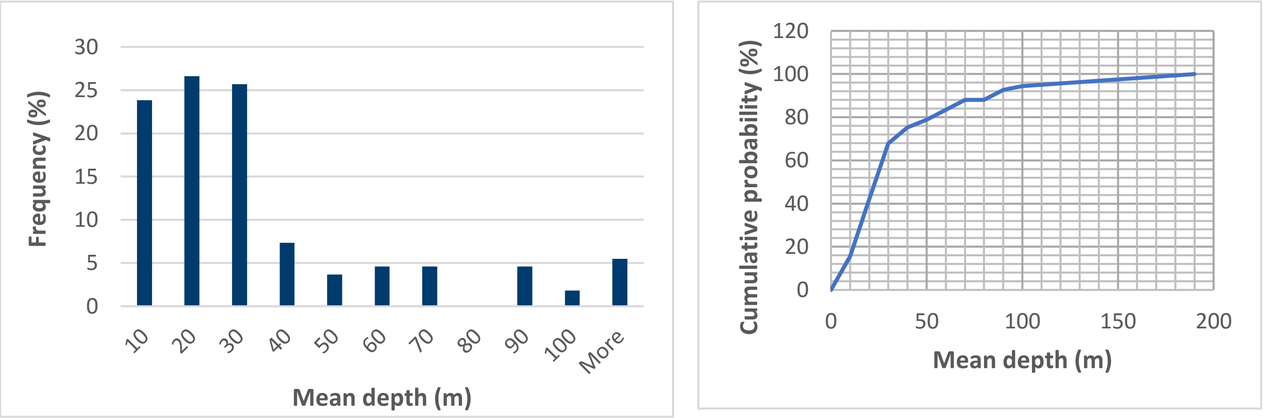


Figure 3.7. The figures show the mean depth distribution of the reservoirs (n=109).

Renewal time:

Renewal time was computed for 132 reservoirs among 2286.

Table 3.8. Renewal time distribution of the reservoirs (years).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
0.000431	52.47	2.28	0.67	5.40	0.05	0.35	2.41	5.13

Shoreline development:

Shoreline development was computed for 206 reservoirs among 2286.

Table 3.9. Shoreline development (dimensionless).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
0.24	14.40	4.80	4.48	2.07	2.58	3.26	6.19	7.72

Relative lake level fluctuation

Relative lake level fluctuation (RLLF) was computed for 84 reservoirs among 2062. RLLF has been introduced by Kolding (Kolding and van Zwieten 2012) to compare water fluctuations influence to the stability of a lake. It combines mean depth and water level fluctuation.

$$RLLF = \frac{mean\ reservoir\ level\ amplitude}{mean\ depth} x100$$

We adapted the RLLF to reservoir, the reservoir level amplitude being the water level difference between HRWL and LRWL.

Table 3.10. Relative lake level fluctuation (dimensionless).

Min.	Max.	Mean	Median	SD	10%	25%	75%	90%
0.96	263.16	58.01	35.42	63.43	2.63	8.15	90.53	155.00

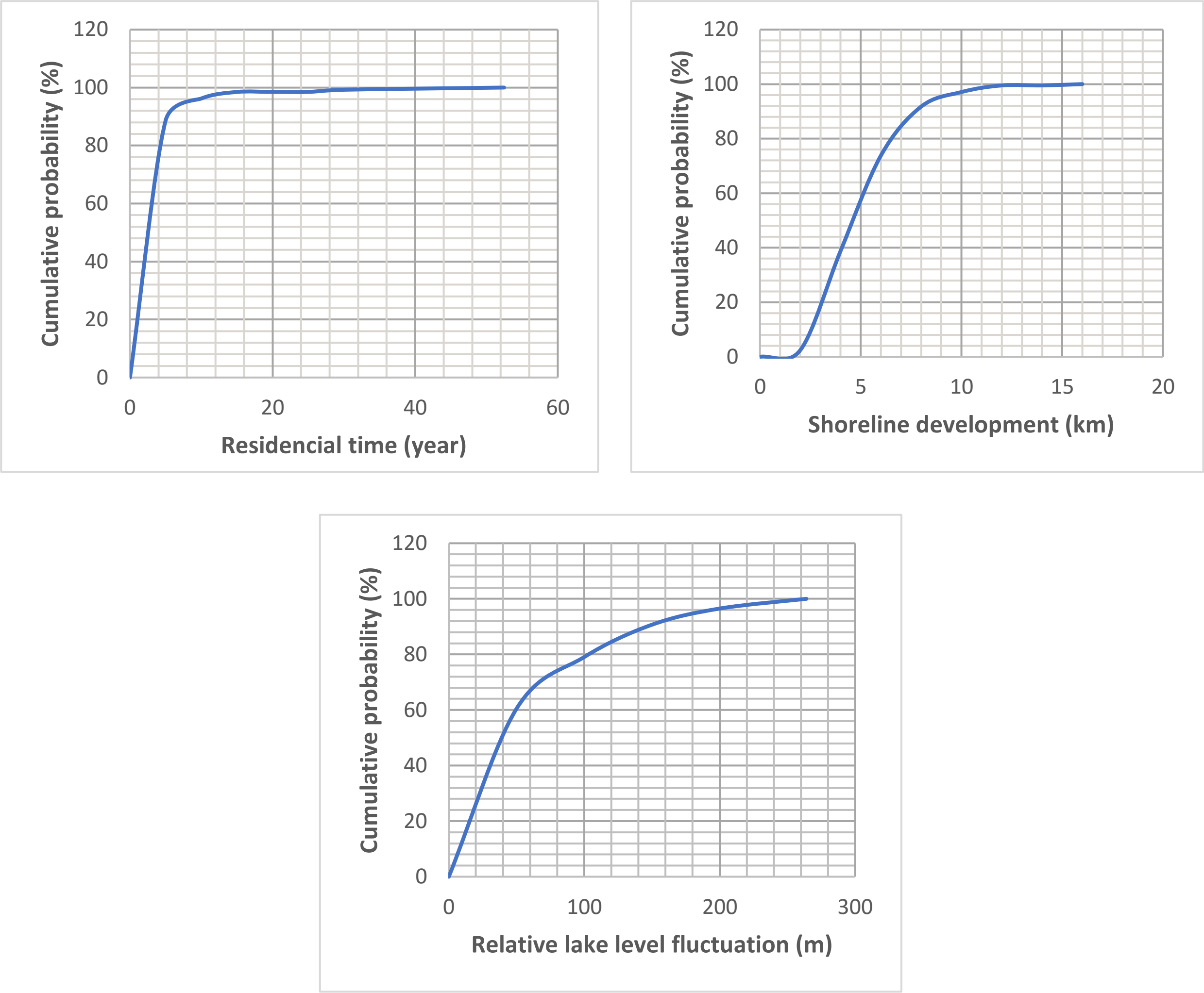


Figure 3.8. The figures show the renewal time, shoreline development and relative lake level fluctuation of the analysed data.

Table 3.11. Summary of the parameters analysed.

Parameter	Unit	Min.-Max.	Median
Altitude	m.a.s.l.	4-1477	394.0
Water level fluctuation	m	0.1-140	6.0
Surface area	km^2	0.01-1089	0.5
Available volume	Mill. m^3	0.01-3506	7.7
Total Volume	Mill. m^3	1.1-56244	78.6
Mean depth	M	4-190	23.0
Max. depth	m	3.9-460	53.0
Renewal time	Year	0.000431-52.47	0.67
Shoreline development	-	0.24-14.4	4.5
Relative lake level fluctuation (RLLF)	-	0.96-263.16	35.42

3.3 Relationship between area, volume and depth in reservoirs

A set of relationships have been calculated from a dataset generated by combining various NVE databases (as described early in Section 3). The relationships are based in information on depth, surface and volume of the regulated lakes.

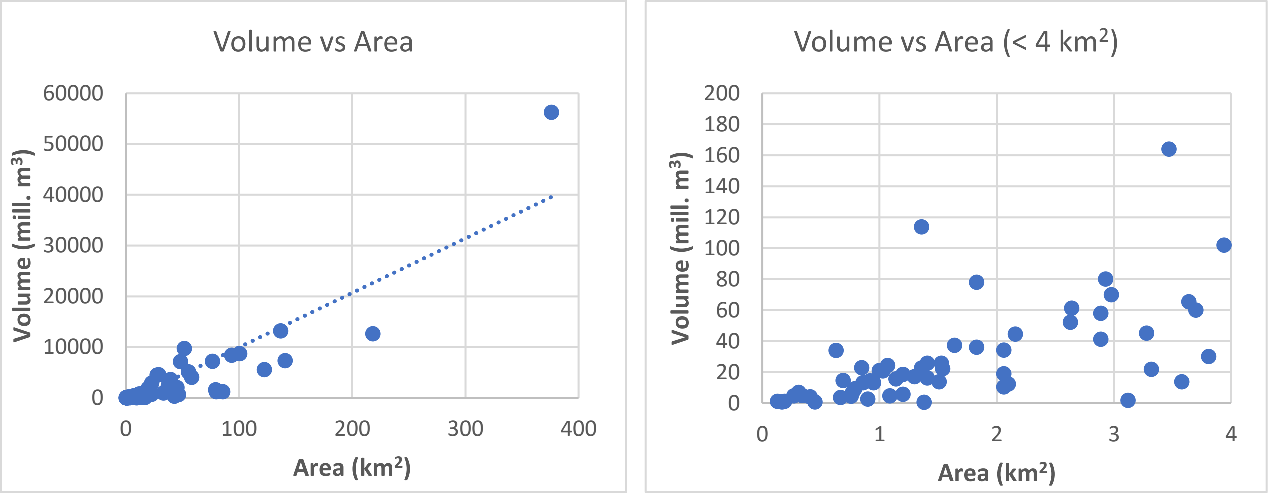


Figure 3.9. The figures show the relationships between reservoir volume (between HRWL and LRWL) and surface area. The figure to the left shows all reservoirs, while the figure to the right shows those with a surface area less than 4 km^2.

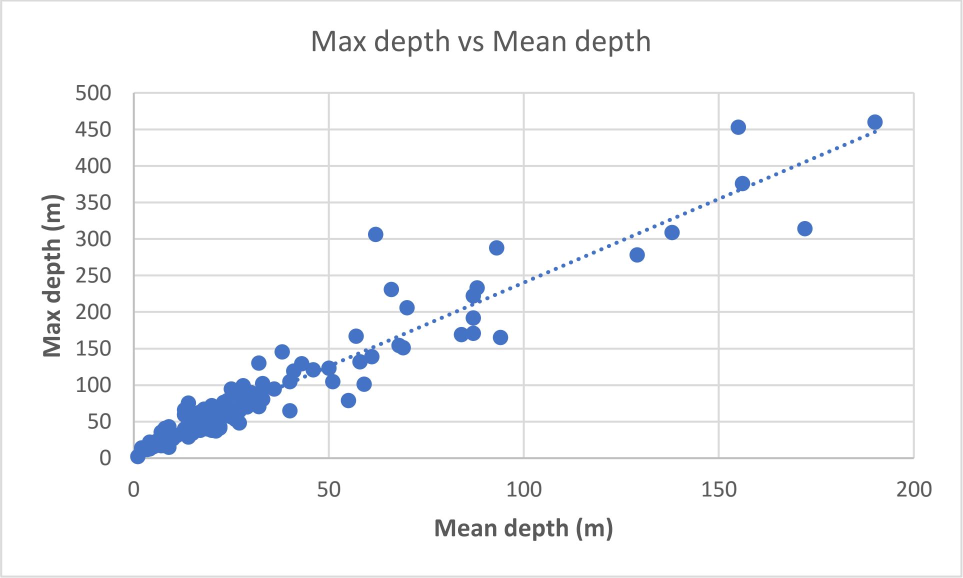


Figure 3.10. The figure shows the relationships between maximum depth and the mean depth.

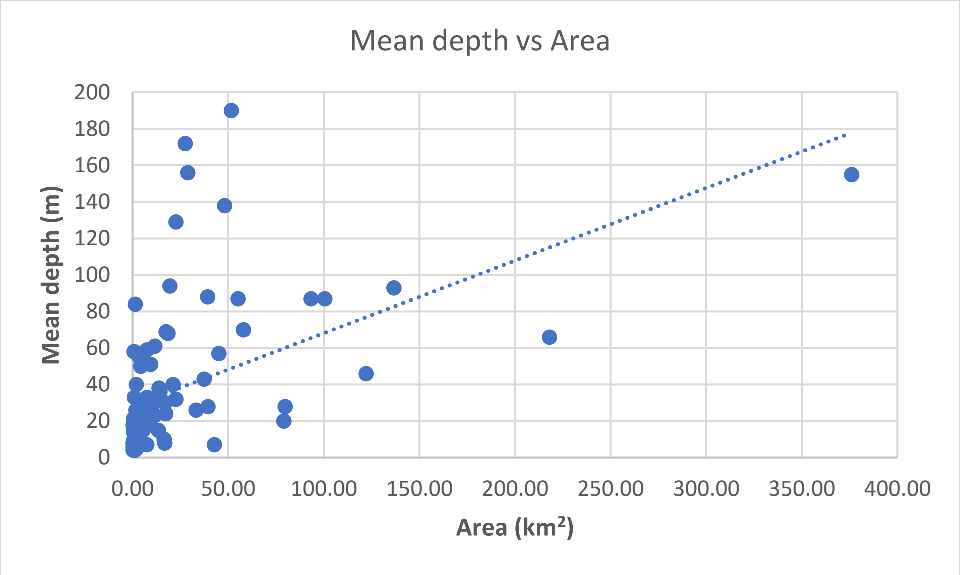


Figure 3.11. The figure shows the mean depth versus the surface reservoir area.

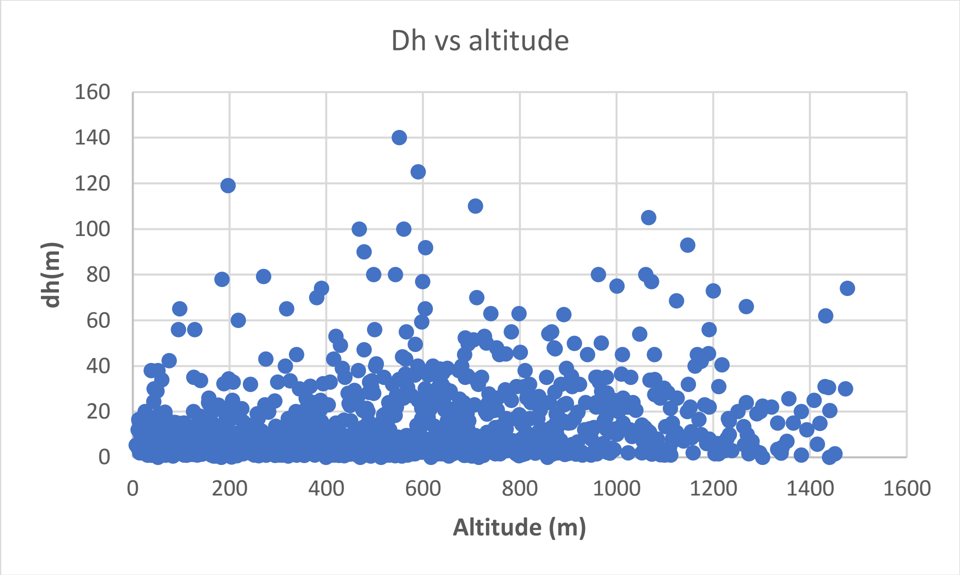


Figure 3.12. The figure shows water level fluctuations as a function of reservoir altitude.

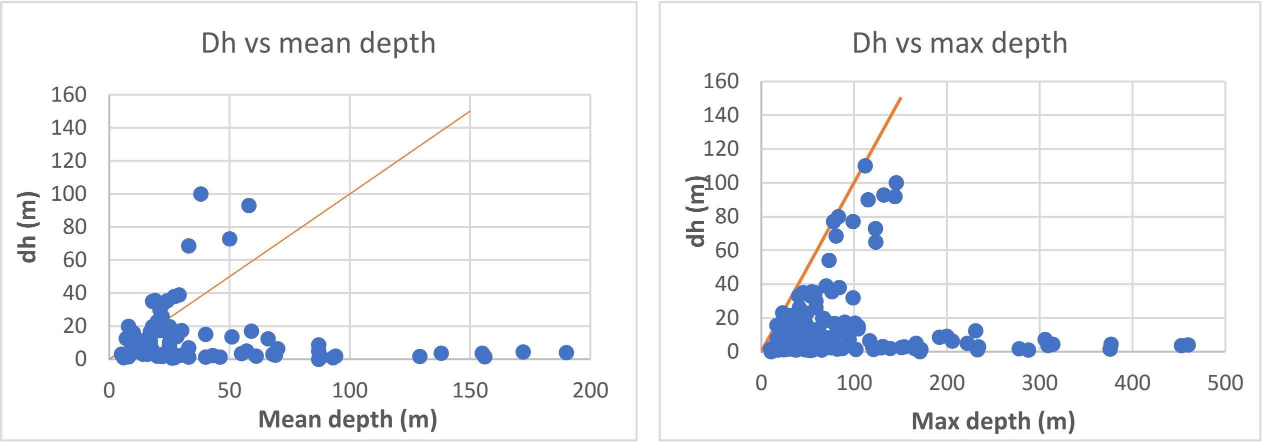


Figure 3.13. The figures show the relationships between mean depth and water fluctuations (left) and max depth and water level fluctuations (right).

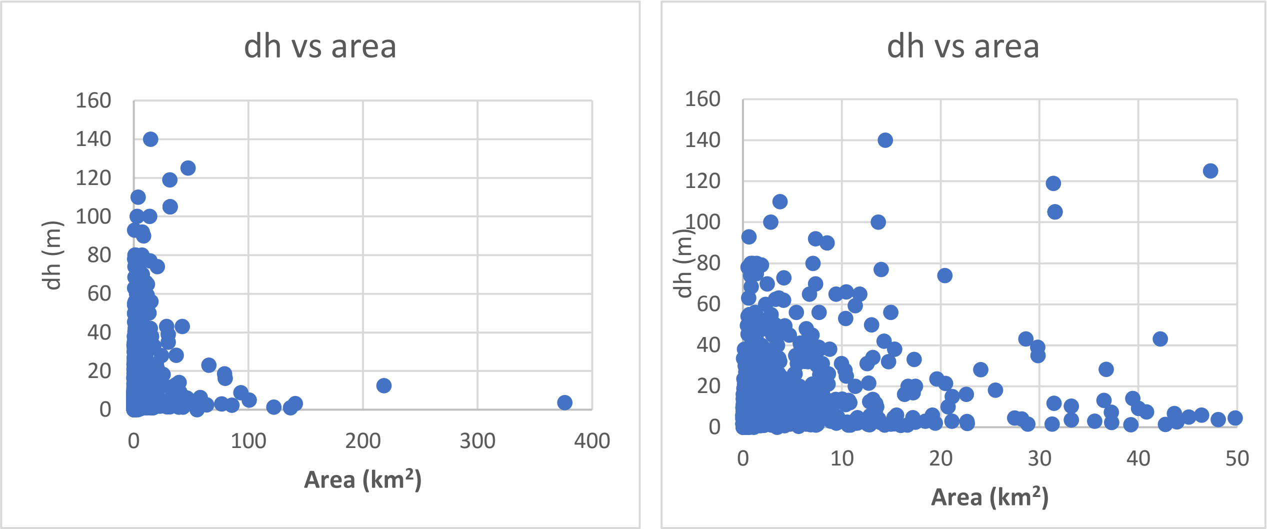


Figure 3.14. The figures show the relationships between water fluctuations and reservoir surface area, with all data plotted (to the left) and only those with surface areas less than 50 km^2 (to the right).

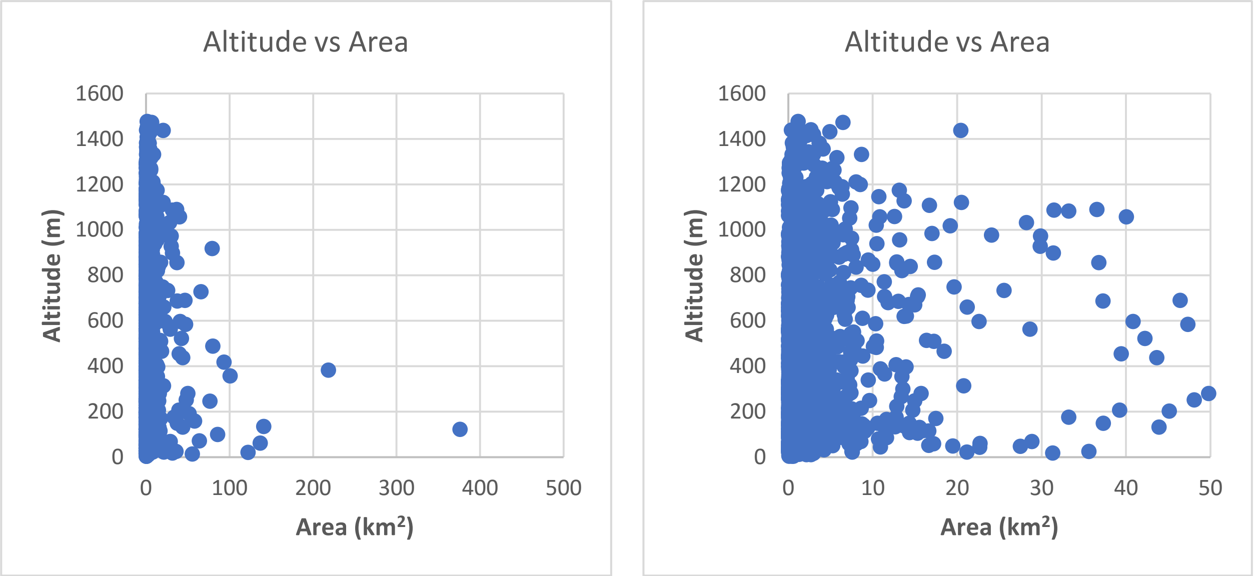


Figure 3.15. The figures show the relationships between altitude and reservoir surface area, with all data plotted (to the left) and only those with surface areas less than 50 km^2 (to the right).

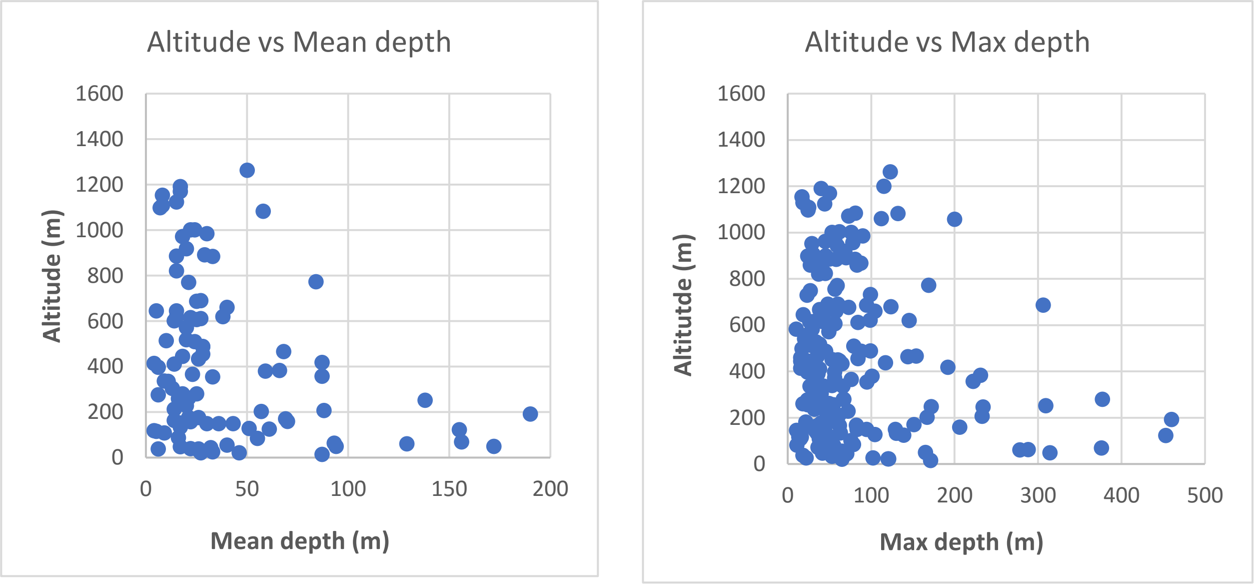


Figure 3.16. The figures show the relationships between altitude and mean depth (left) and max depth (right), respectively.

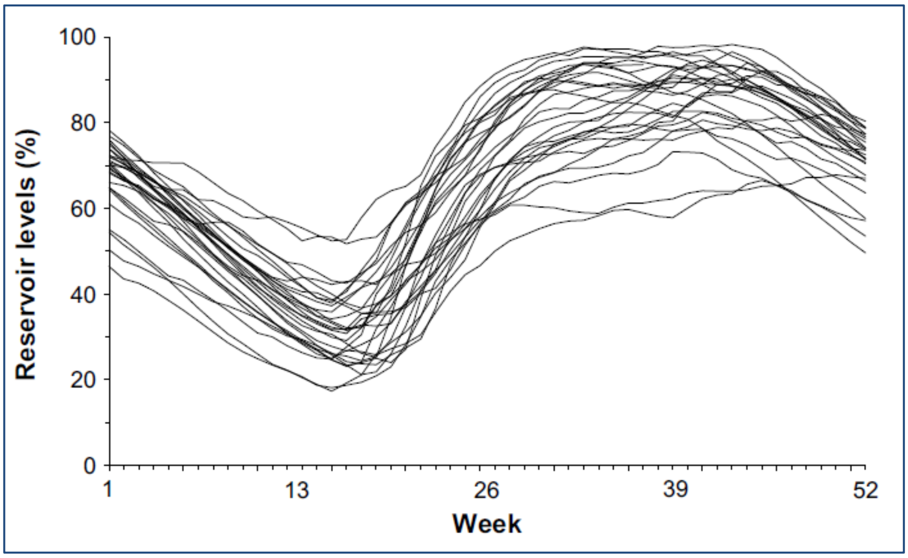


Figure 3.17. The reservoir filling varies extensively throughout the year, but follows a typical pattern. The figure shows observed reservoir levels throughout the year, aggregated for whole for Norway for different the years in the period 1980–2007 (Source: Wolfgang et al. 2009).

Figure 3.18. Reservoir drawdowns can cause large dewatered areas and block the access to tributaries (reduce connectivity) (Photo: Atle Harby).

4 International data sources

Some international databases hold information about Norwegian reservoirs that might be relevant for the hydromorphological assessments of these water bodies. These databases are presented in the following.

4.1 ICOLD database

The International Commission on Large Dams (ICOLD) is a non-governmental international organization, which provides a forum for the exchange of knowledge and experience in dam engineering. The World Register of Dams is a database ('ICOLD database') owned and hosted by ICOLD and includes more than 55 000 dams (by July, 2018). The Committee of the Register coordinates the data collection within the National Committees. 'A Large Dam' is defined as a dam with a height of 15 meters or greater from lowest foundation to crest, or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters of water. The ICOLD database is the most complete register of dams with respect to the number of dams included.

Table 4.1. Examples of data stored in the ICOLD database.

• Name of dam	• Dam Type
• Name of country located in	• Height of dam
• Name of reservoir	• Length of dam
• Year of completion	• Reservoir capacity
• Electric installed capacity	• Area of reservoir
• Mean annual energy	• Length of reservoir
• Volume flood protection	• Purpose of reservoir

335 of the Norwegian dams and reservoirs are registered in the ICOLD database. All relevant data about Norwegian dams and reservoirs registered in ICOLD are also available via NVE's map-based services (https://www.nve.no/map-services/map-tools/), most likely also better maintained. As such, we conclude that NVE's systems are the preferred source of data for the assessment of hydromorphological conditions in Norwegian lakes and reservoirs.

4.2 Global Reservoir and Dam Database (GRanD)

The Global Reservoir and Dam (GRanD) Database provides the location and main specifications of large global reservoirs and dams with a storage capacity of more than 0.1 km^3 both in point and polygon format. The current version 1.1 of GRanD contains close to 7000 records of reservoirs with a cumulative storage capacity of 6197 km^3 (by July, 2018).

There are in total 125 Norwegian dams and reservoirs registered in the GRanD database. All relevant data about Norwegian dams and reservoirs registered in GRanD are also available via NVE's map-based services, most likely also better maintained and more complete in terms of number of dams and reservoirs registered. As such, we conclude that NVE's systems are a preferred source of data for the assessment of hydromorphological conditions in Norwegian lakes and reservoirs.

The main difference between the GRandD-database and the ICOLD-database is the entries in GRanD are precisely geo-referenced, while dams/reservoirs in ICOLD are only given by their country (and possibly region) of their location. The ICOLD-database is more complete with respect to the number of dams and reservoirs, while GRanD holds more attributes on each of the entries registered. GRanD is freely accessible, while ICOLD requires purchase of a licence.

Table 4.2. Examples of data stored in the GRanD database.

• Name of reservoir or lake	• Storage capacities
• Name of dam structure	• Average discharge at reservoir location
• Name of impounded river	• Average depth
• Name of main basin	• Degree of regulation/retention time
• Name of sub-basin	• Elevation
• Height of dam in meters	• Area of upstream catchment
• Length of dam in meters	• Purpose of reservoir
• Maximum reported surface areas	• Based on existing lake or not
• Minimum reported surface areas	• Year of construction/completion/etc.

For studies outside Norway, where national databases are not developed or available, ICOLD and GRanD are considered being of relevance.

5 Hydromorphological features derived from bathymetric maps

5.1 The relevance of bathymetric data

Bathymetric maps are useful to derive lake properties such as volume, maximum and mean depth. These basic lake properties can then be used to define residence time, Schindler's ratio and other lake descriptors. The classification of lake zones into littoral and profundal is relevant for many classification systems. It can also be done using bathymetric data, when combined with information about light penetration.

Furthermore, volume curves (depth-volume relationships) and hypsographic curves (depth-area relationships) can be calculated from bathymetric maps. Hypsographic curves can quantify the dewatered areas when depth measurement time series are available. When the spatial extent of the water surface is known (e.g. by satellite data), the water depth, volume and dewatered areas can be calculated using a combination of hypsographic and volume curves.

Tributaries entering lakes are potentially important areas for spawning, juvenile habitats and refugee areas. Access to these areas can be of major importance in specific life stages or certain periods of the year, and access to these areas can vary with water level. Low water levels can act as barriers to these areas. Bathymetric maps combined with a digital elevation model (DEM) of sufficient precision will be able to investigate how access to tributaries is determined by water level. Similarly, areas within the lake can be cut off during periods of drawdown, causing periodic isolation, which can also be investigated with GIS tools and bathymetric maps. Another aspect related to the connectivity of lakes is boating, and the possibilities of launching boats on the lake. The timing of the filling is also essential, and this has been raised as a user interest to consider as part of the process of revision of hydropower licences, besides the ecological aspects.

Figure 5.1 shows the bathymetric map of Kjårdavatnet in Nordland, combined with data from satellites. It's surface area covers approximately 3 km^2. The differences in lake area when calculated from the bathymetric map and the satellite image in the background, can be explained by different times of data retrieval. The bathymetric measurements were taken in 1965 whereas the satellite image was taken some time during 2010.

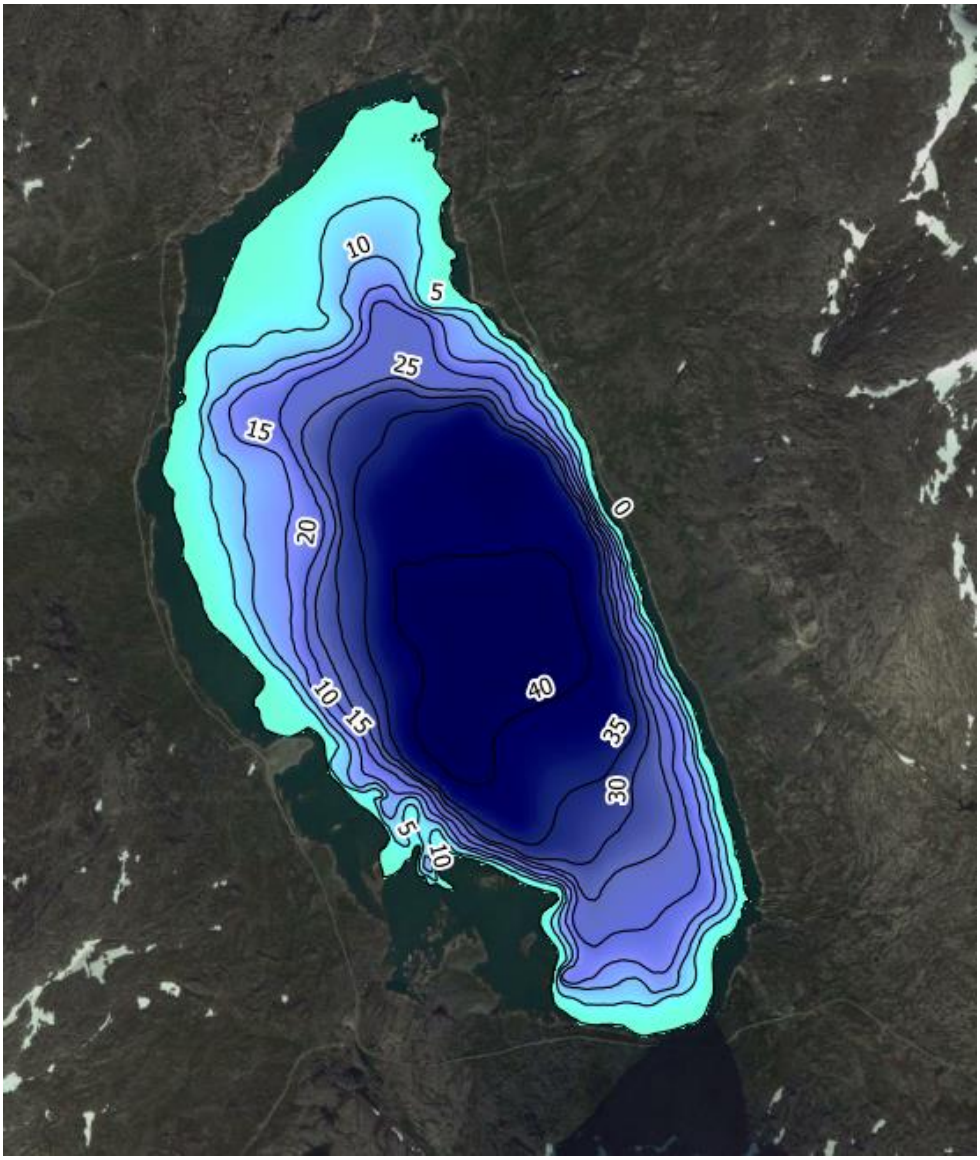


Figure 5.1. Example of a bathymetric map from Kjårdavatnet, combined with satellite data.

5.2 Derived properties based on bathymetric data

Based on the bathymetric map relations between volume, water level and surface area can be derived. A variant of such curves can be found in Figure 5.2 and Figure 5.3, where the volumes and water surfaces areas located within each water depth/elevation contour are plotted. Generally, the curves showing the relationship between water surface area and water level (or depth) can be used to identify at what water levels dewatered areas start to increase, or decrease, more rapidly. In some reservoirs, it might be possible to identify break points on this curve that can form the basis for ecological sound restrictions, based on the morphology of the lake.

As soon as the relationships between water surface area and water level is established, the actual water level can be found from satellite images, as such being a tool to monitor if restrictions in level of filling is followed.

If the relationships between volume and water level also are established, actual water volumes of the lakes can also be calculated based on satellite images giving the surface area. This can also be useful information for hydropower companies or other companies doing power trading, as the filling of the reservoir will provide information about the future availability of hydro-electric power in the market.

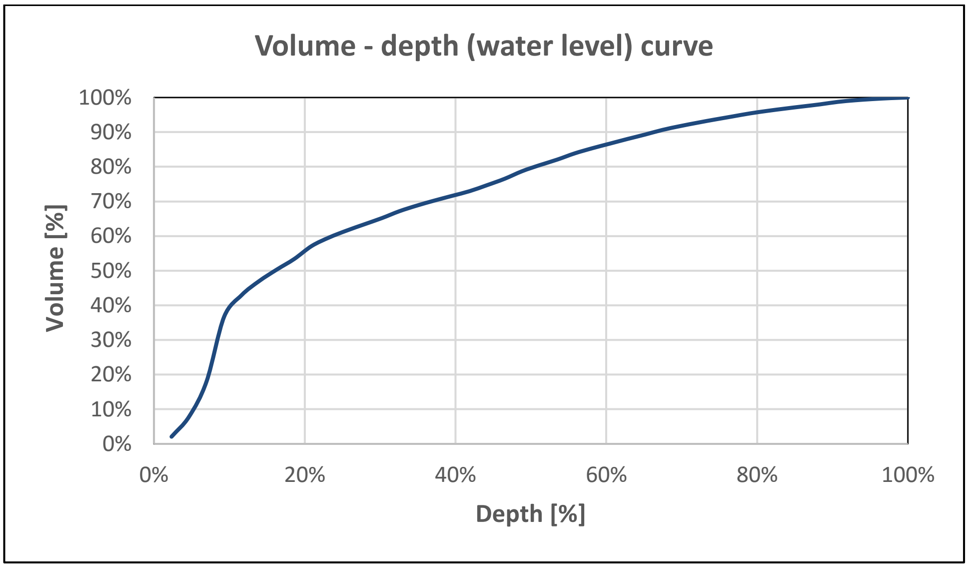


Figure 5.2. Volume – depth relationships from Kjårdavatnet. This variant of a volume – depth curve shows how large volumes of water are within each water level contour. The curve can be read as 'the 20 % deepest part of the lake stores approximately 55 % of the water', when the reservoir is filled.

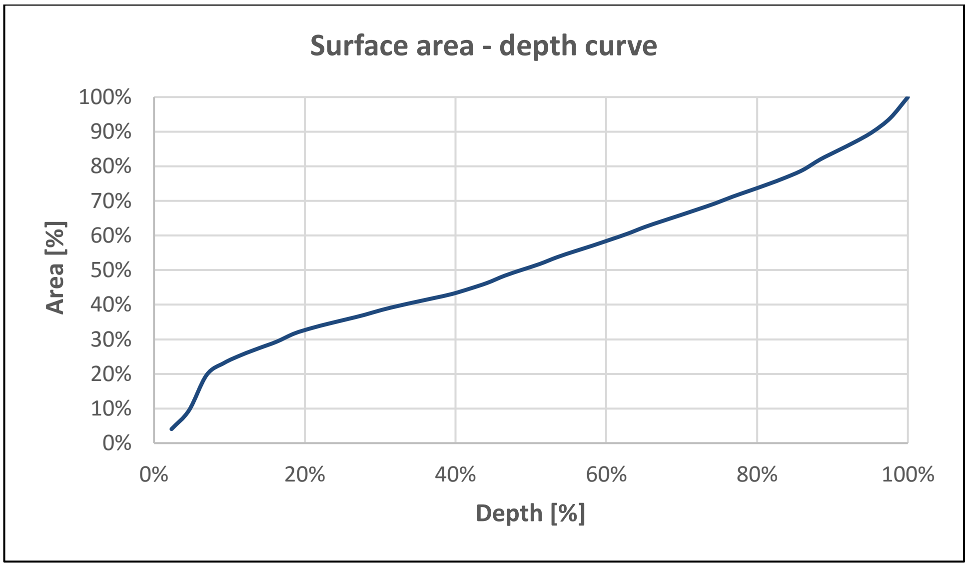


Figure 5.3. The surface area – depth relationships from Kjårdavatnet. This variant of a surface area – depth curve shows how large parts of the surface area are within each water level contour. The curve can be read as 'the 20 % deepest part of the holds approximately 33 % of the surface area', when the reservoir is filled.

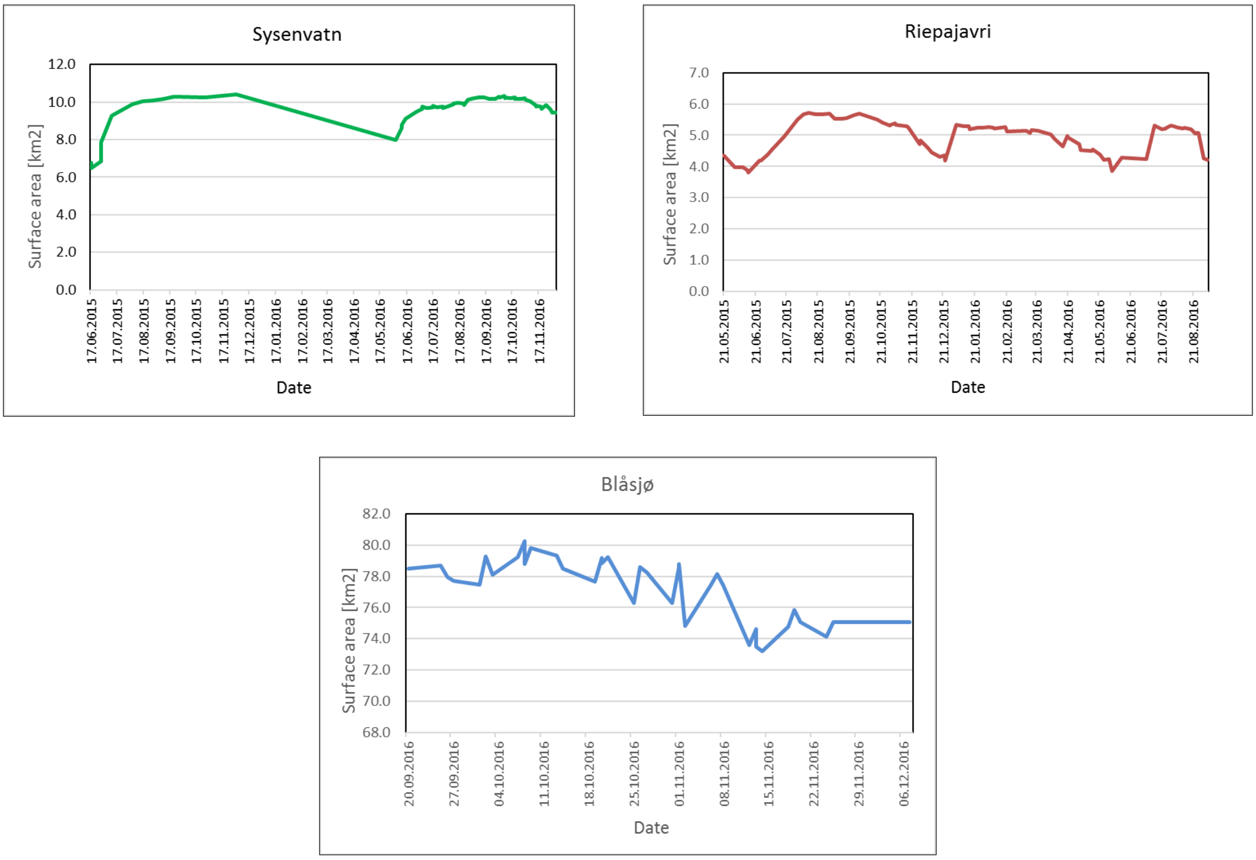


Figure 5.4. The graphs show variations in surface area over time of Sysenvatn (upper left), Riepajavri (upper right) and Blåsjø reservoirs (lower), derived from satellite images. Data is analysed and provided by Globesar.

As soon as the relationships between surface area and water level/depth are established satellite images can be used to frequently measure water surface areas. This will enable the establishment of timeseries of water level data (Figure 5.4) and would potentially be an efficient way of monitoring a large number of lakes and reservoirs. There are, however, methodological challenges related to monitoring water surface areas in periods of snow and ice as it is difficult during these conditions to differentiate between the lake and the surrounding areas, which might limit the use of this technology in periods of the year.

The water level of reservoirs used for hydropower production are in most cases already monitored by the hydropower company, as this is important information to know the available water for future power production. Monitoring of water level can also be requested by the authorities to prove that the filling restrictions are followed. This information is, however, exclusively to the operator of the reservoir in real-time, but can be released publicly after some weeks.

5.3 Derived hydromorphological data from bathymetric maps

We have evaluated the potential of deriving hydromorphological data based on high-resolution (spatial) bathymetric data. Previously surveyed bathymetric data of 5m resolution from Selbusjøen, measured by NTNU in collaboration with NVE and Statkraft was used for developing elevation – volume – area relationship curve (Belete and Alfredsen 2010). The ArcGIS 3D analyst extension tool was used to create Triangulated Irregular Networks (TINs) and the surface of the lake (polygon) was established using contour lines of different elevation levels. Thereafter, the surface area and TINs were combined to compute the volume and surface area of each polygon at every contour line was computed, as shown in Figures 5.5 and 5.6.

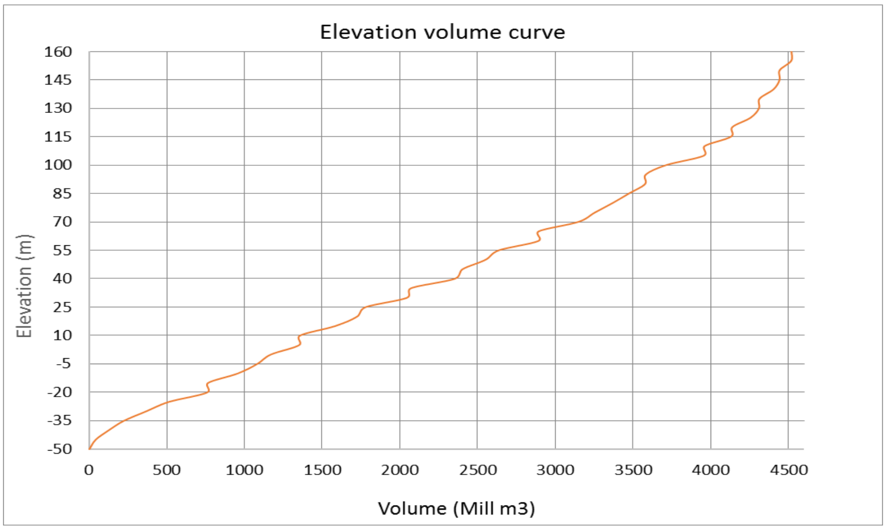


Figure 5.5. The graph shows the relationship between elevation and volume in Selbusjøen, based on data analysed in Belete and Alfredsen (2010). Negative elevation values refer to the fact that the deeper parts of the lake are lower than sea level. In general, the volume increases with elevation, but there are inaccuracies in the upper parts of the curve.

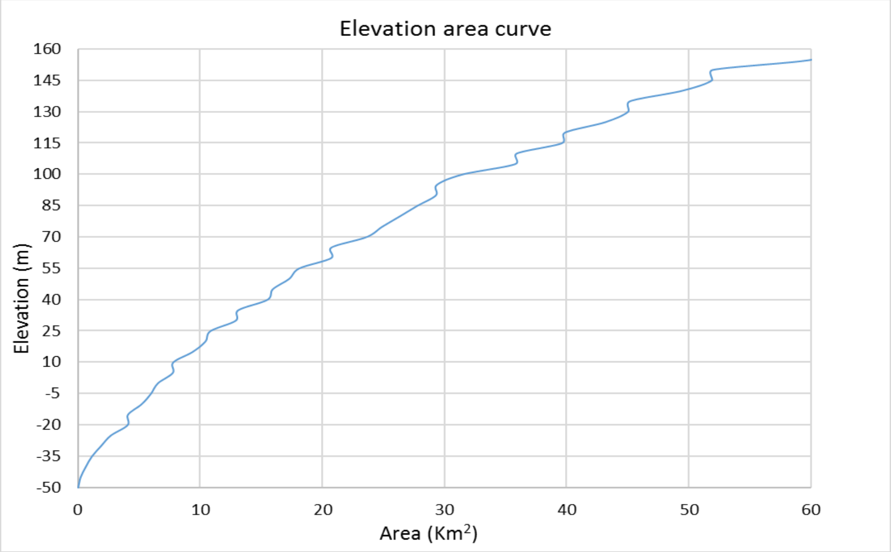


Figure 5.6. The graph shows the relationship between elevation and surface area in Selbusjøen, based on data from Belete and Alfredsen (2010). Negative elevation values refer to the fact that the deeper parts of the lake are lower than sea level.

From Figure 5.5 we can see that the gradient on the curve is less steep in the upper parts of the reservoir compared to the deeper parts, which means that larger volumes are lost per meter drop in water level than at lower elevations. This is confirmed in Figure 5.6 as it can be seen that the increase/decrease in surface area per meter is larger in the upper part of the lake than in the middle and lower parts. Phrased differently; one meter drop in water level will expose (dewater) larger areas when the lake is close to filled, than when the water level is at a lower level.

The curves presented in Figures 5.5 and 5.6 show some sort of 'curles'. These are explained due to technical inaccuracies in the generation of the Triangulated Irregular Network (TIN) and the raster needed to calculate the curves. In addition to that, there is also inaccuracies of interpolation technique used during processing the surveyed data.

The shoreline development index was computed as the ratio between the shoreline length to circumference of a circle that has the same area as the lake (see definition is Section 2.1). Similarly, the slopes were also computed for every 5 meters (contour), and shown in Figures 5.7 and 5.8.

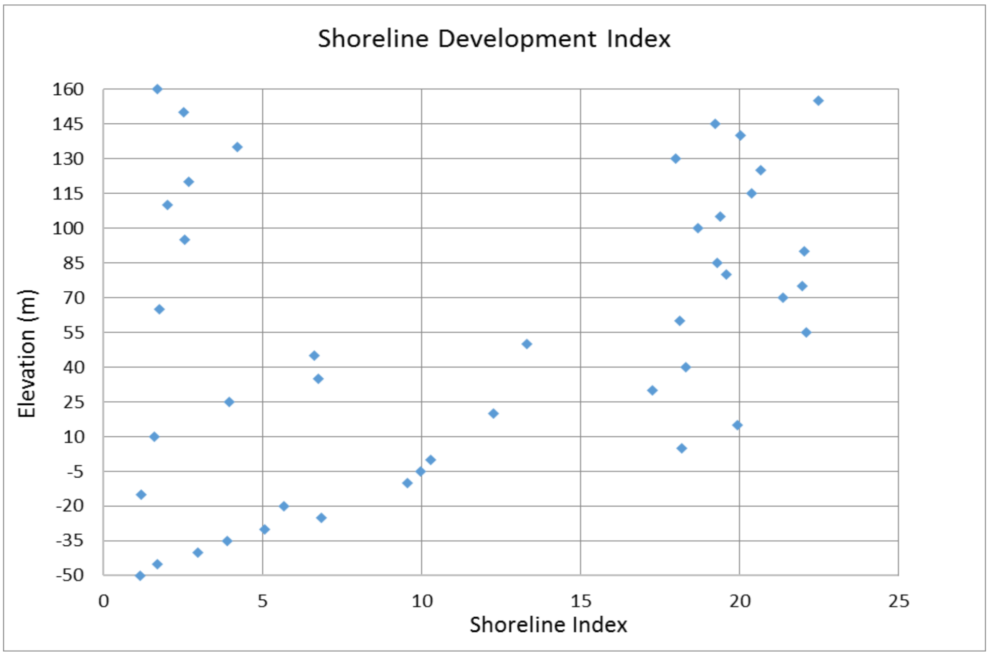


Figure 5.7. Shoreline development index for Selbusjøen at different elevations (every 5 meters). Negative elevation values refer to the fact that the deeper parts of the lake are lower than sea level.

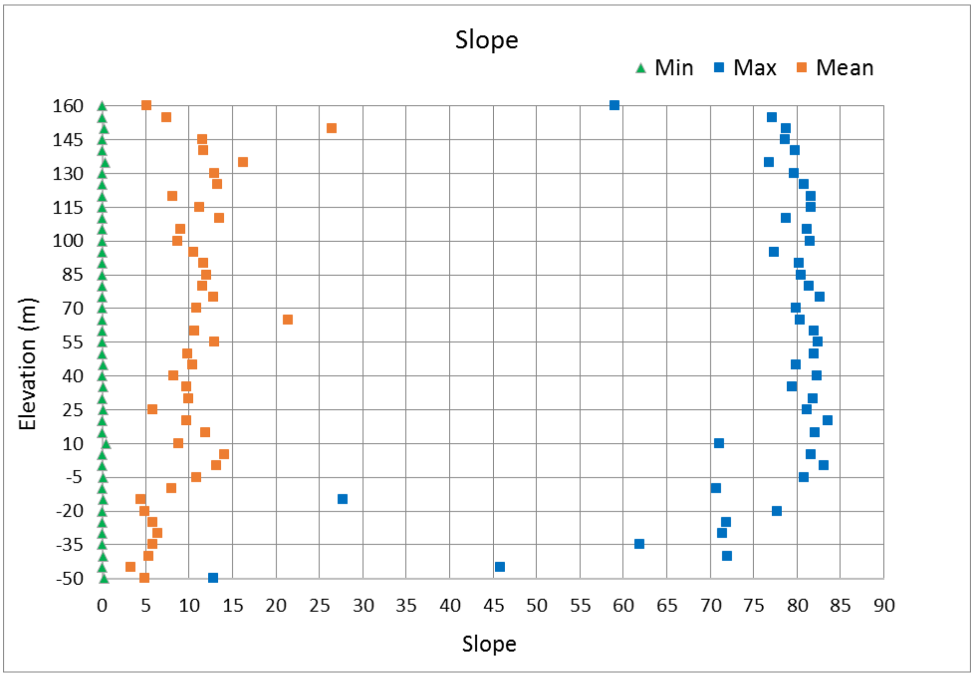


Figure 5.8. Slope (in degrees) of the bottom at every 5 meter contour for Selbusjøen. Negative elevation values refer to the fact that the deeper parts of the lake are lower than sea level.

In Figure 5.7 we can see that the highest shoreline indices are calculated down to an elevation around 0 m.a.s.l. There are, however, also small numbers in the upper parts of the lakes. From approximately 0 m.a.s.l. the numbers tend to decrease, which means that the shape of the (remaining) surface tends to gradually get more circular. The inaccuracy of the interpolation techniques used for making contour lines could possibly explain the large variation in shoreline index from one elevation level to the next, as seen in Figure 5.7. Our experiences would then conclude that use of this technique to calculate shoreline indices should be made with great care, and further testing of techniques is recommended before this is applied in a real management situation.

In Figure 5.8 we can see that the minimum slope at each elevation is always 0 degree, meaning that there is at all levels/contours flat areas. The maximum slope is at most elevations close to 90 degrees, i.e. there are at most elevations (except at some lower elevations) parts of the lake with a close to vertical bathymetry (vertical walls). The mean slope tends to be lower at the very lowest part of the lake (lowest 40 meters), and in the very upper parts (10 uppermost meters). It is difficult to assess the quality of the calculated hydromorphological features.

It should also be mentioned that the calculation of the numbers presented in Figures 5.5 – 5.9 was a time-consuming process due to inconsistencies in the bathymetric data. It appeared that the contour lines were not continuously, and breaks in the contour lines had to be repaired manually. Without proper checking and fixing of the dataset erroneous results would have been calculated.

5.4 Comparison of low and high resolution bathymetric data

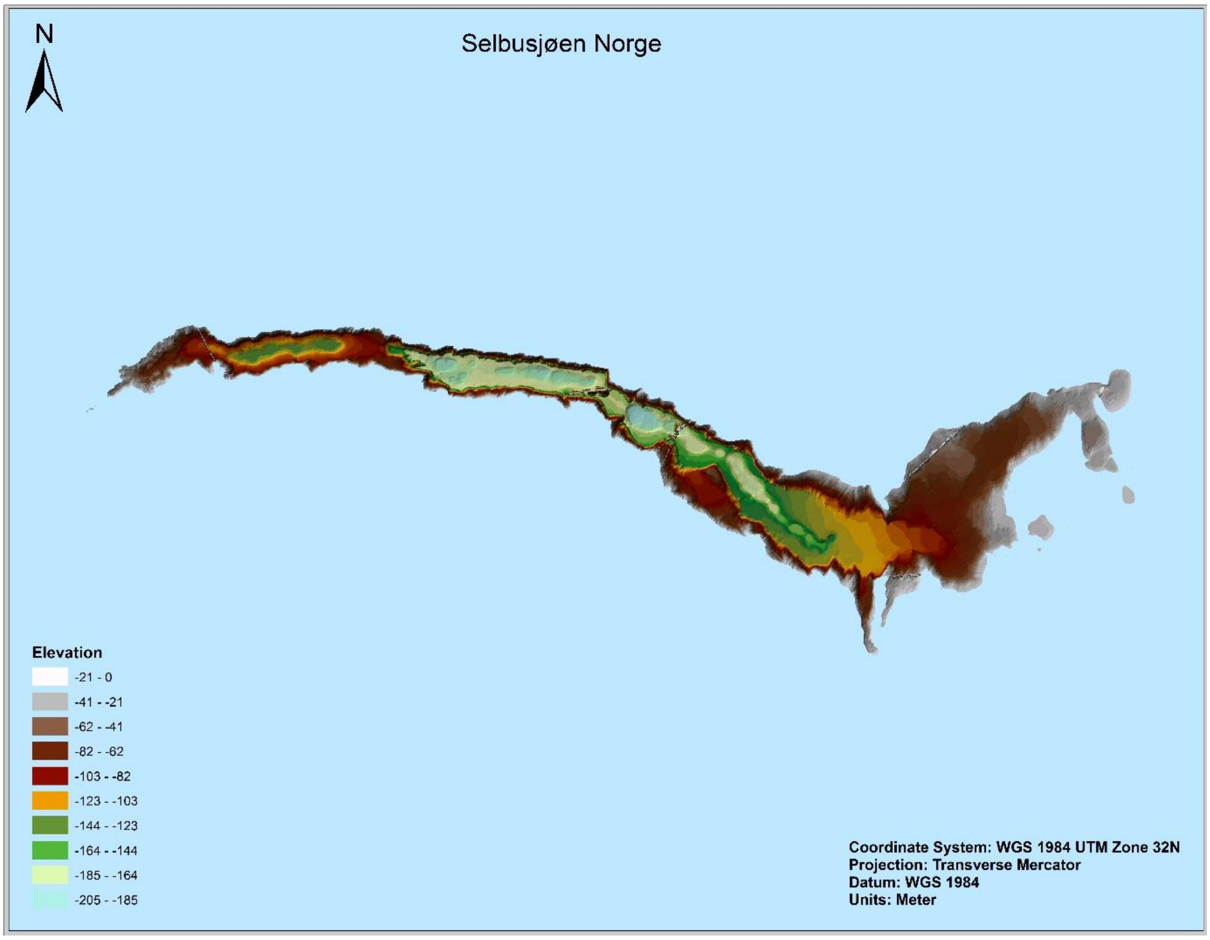


Figure 5.9. Bathymetry of Selbusjøen, located in Central Norway, based on measurements reported in Belete and Alfredsen (2010).

The volume calculated in ArcGIS based on data reported in Belete and Alfredsen (2010), and this dataset compared with data from the same lake given in the NVE database (Innsjø Dybdekart). The same numbers can also be calculated by using the 'standard' shapefiles of lake bathymetry provided by NVE (polygon of the lake surface). According to NVE, the volume is computed by multiplying the area with the average depth, and the calculated number is given in the property table of the given lake. The approximation of using the average depth and lake surface area is only correct for given shapes of the lake.

For Selbusjøen, the total area computed from GIS is 55.5 km^2, the maximum depth is 205 m and the total volume is 6046 million cubic meter, based on the dataset from Belete and Alfredsen (2010). The depth is equal to the data given in NVE Innsjø dybdekart/database, while there is some deviation with respect to surface area and volume as the computed numbers are higher than the numbers given in the NVE database (see Table 5.1). Various reasons can explain the deviations including differences in measurement approach, water level at the time of the measurement, methodology to compute area and volume and maybe some minor changes in actual area/volume over time.

Table 5.1. Hydromorphological data calculated based on high-resolution bathymetric data of Selbusjøen from Belete and Alfredsen (2010) dataset compared to the same hydromorphological features calculated based on data given in NVE Innsjø dybdekart database.

Parameter given/calculated	**Belete and Alfredsen (2010) dataset**	**NVE Innsjø dybdekart**
Maximum depth [m]	205	205
Surface area [km^2]	60.28	57.52
Volume [mill. m^3]	4520.5	4034.1

We believe that the measurement approach of dataset reported in Belete and Alfredsen (2010) potentially could provide a higher precision in the estimated area and volume, and our approach of calculating the area and volume is more accurate.

6 Simulation of hydromorphology with catchment and lake models

Numerical models can be used to provide information about the current state and characteristics of catchments, lakes and reservoirs, and assess the effect of changes introduced to the system. Models are useful tools to understand underlying physical, chemical and biological processes of the studied system. In addition, models allow estimates of the state of the systems for conditions that were not observed. Models can give information about vulnerability to climate change, analyse the impact of changes in the operational regime of a reservoir, and the effect of mitigation measures that cannot be deduced from observations.

The choice of the numerical model depends on the objective of the study, the availability of data and the prior experience of the modeller with the specific tool. The models presented in the following sub-sections within the same modelling domain (catchment versus lake/reservoir) have very much the same capabilities, but might have some differences in spatial and temporal resolution and extent, differences in process representation and hence which output they can generate.

6.1 Catchments models

6.1.1 HYPE

Model description

HYPE is a process-based semi-distributed rainfall-runoff model which has been developed at SMHI (Swedish Meteorological and Hydrological Institute) from 2005 to the present. Its code is written in FORTRAN and the software is open source under the Lesser GNU Public license (Free Software Foundation 2007). The open source availability was chosen to initiate and strengthen international collaboration in hydrological modelling. HYPE is based on HBV (Lindström et al. 1997) and has its main advantages in prediction of discharge in ungauged basins and water quality modelling. An up-to-date comprehensive description of the features, process modules and model structure can be found on the HYPE wiki (http://www.smhi.net/hype/wiki/doku.php). See Schönfelder (2017) for a complete methodology of the model set-up for central Norway.

HYPE was recently comprehensively tested with respect to supporting the implementation of the EU Water Framework Directive in Norway for central and southern Norway (Schönfelder et al. 2017, Adera et al. 2018), with positive results. The main objective of this study was to assess if HYPE can generate hydrological data on reference conditions, as well as hydrological indices based on simulation of hydrological conditions before and after regulation. The model was set-up for central and southern Norway.

Model structure, in- and output

The catchments are divided into sub-catchments that are linked in a horizontal flow network. In turn, the sub-basins are divided into classes, which are not coupled geographically within the sub-catchment. The classes consist of a land use and a soil type class (SLC – *"soil and land use class"*). Model parameters can be associated with land use, soil type, SLC or be general for the whole catchment or domain respectively. Many process modules in HYPE are similar to the processes in HBV.

The HYPE model setup with the simplest modules employed requires daily values of precipitation and temperature of all sub-catchments as input data. The model uses a linked network of spatially explicit sub-catchments for its flow routing. Runoff can be calculated for the outlet of the sub-catchments and can be linked to the waterbody delineation as defined by the EU WFD implementation. Evaporation, potential evaporation, snow water equivalent and groundwater level are averaged for the sub-catchments and can be generated as output text files.

Role of lakes and reservoirs in HYPE

Selected lakes can be considered as a sub-catchment in HYPE. A common approach for this selection is to implement all lakes above a threshold surface area. Lakes and reservoirs that are not part of the selection (usually lakes that are smaller than the chosen threshold size) are calculated as a special land use class.

The selected lakes are linked within the flow network as a sub-catchment with specific lake properties, the inflows into lakes are therefore calculated dynamically. The lakes' outflow may be calculated by either an individual or general rating curve. Lake volume and mean depth can be provided as input data, the lakes' bathymetry are simplified in the way that they have vertical sides and a flat bottom.

The implementation of relevant reservoirs can be done in analogue to the implementation of lakes. Additionally, HYPE offers several modules to simulate their water management. The two most relevant modules for the simulation of regulated lakes and water diversion are the bifurcation module and the management module. The Bifurcation module enables water transfer to a downstream sub-catchment based on a provided discharge time series, a fraction of the outflow of the source sub-catchment, a maximum or a minimum flow. Both donating and receiving sub-catchment can be of any type. This module can be used for flow transfer within the same catchment.

The Management function of HYPE can use discharge time series to transfer water from a reservoir to any other sub-catchment, hence it can simulate inter-catchment water diversion. It is defined as a demand-sided transfer, but water is only transferred if it is available in the source sub-catchment. Only one transfer per donor catchment is possible when time series are used, the function includes a delay of one timestep for the water to arrive in the destination sub-catchment.

Relevant model output for lakes and reservoirs are therefore time series of the following variables: water-level, inflow, residual flow (reservoirs), outflow, evaporation and air temperature. HYPE can therefore also simulate water-level fluctuations in natural lakes when a rating curve is known or assumed. It may be useful to model reference conditions and to compare the water level fluctuations with those of a regulated lake with similar characteristics.

6.1.2 WEAP – Water Evaluation and Planning Tool

The WEAP software (Water Evaluation and Planning Tool) is a computer-based tool for integrated water resources planning and management, aimed at supporting policy-setting and decision-making (Yates et al. 2005). WEAP supports multi-scenario based planning for hydrologic basins and associated water systems that fully integrate aspects related to water supply, water demand, and multiple management objectives. The tool holds built-in models for rainfall runoff and infiltration, evapotranspiration, crop requirements and yields, surface water/groundwater interaction, and instream water quality. WEAP has a simplified GIS-based interface, standard Windows dialogues and is equipped with powerful model-building capabilities allowing user-defined process descriptions to be incorporated. The software is applied in almost all countries in the world and has a user group of several thousand water experts. WEAP has recently been technically linked with the LEAP system to support integrated water-energy system analysis.

WEAP has been used by SINTEF/NTNU in international water studies with complex interactions between various water users with potentially conflicting interests. This Spring (2018) the tool was applied in Orkla river basin to simulate the effect of hydropower reservoirs to reduce the flood risks (Hansen 2018), and produced results of acceptable quality.

The soil-moisture method is one of the hydrological methods implemented calculating rainfall-runoff processes. This method is a one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme based on empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation for a watershed unit. The method allows for the characterization of land use and/or soil type impacts to these processes. The deep percolation within the watershed unit can be transmitted to a surface water body as baseflow or directly to groundwater storage if the appropriate link is made between the watershed unit node and a groundwater node.

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and the water balance is computed for each fractional area. A set of meteorological stations can be assigned to the model area, but climate is assumed uniform over each sub-catchment.

6.1.3 Other catchment-based simulation tools

Several other tools have also been applied in modelling hydrological conditions in Norway, and many of them variants developed on the basis of the HBV-model (Bergström 1976).

NVE-tools: NVE performs analysis of meteorological and hydrological data with use models based on statistical and deterministic descriptions of the hydrological cycle. The most commonly used model for the simulation and predictions of runoff is variants of the Swedish HBV-model, originally developed by the Swedish Meteorological and Hydrological Institute (Bergström 1976). This model has proven to perform well for Nordic conditions when compared to other international hydrological models.

The HBV model belongs to a group of models with a structure based on a simplified mathematical representation of the hydrological elements and processes in nature. It can be perceived as an advanced water balance calculation, where water transport between the various hydrological trays in the model structure is determined by the volume of water in the trays. The model has three main components, i.e. snow, groundwater zone and drainage section, each of which accounts for important hydrological elements in the catchment. A further description is available at www.nve.no.

Enki: Enki is developed by SINTEF and is a framework for implementing process models in time and space. It is motivated by, but not limited to hydrological models. The basic function of Enki is to build a model from a library of subroutines, and to run this model for a geographical region containing all process data. The Enki framework itself contains only the administrative functions and interfaces. All process data are GIS data; in raster form, as point-vector data, or as discrete variables (scalars). For each time step, the framework reads a new time slice from the input database into the region, calls the model to operate on the region’s variables, and writes a time slice from the region to the output database.

The model is composed from several subroutines, which for each time step are called in the user-specified order. A subroutine is an instance of a method, which implements the simulation equations. The methods are separately coded and compiled as dynamic-link libraries (dlls). Each dll implements a class inheriting from a parent class defined in the Enki core. The operator builds a model by selecting the desired dlls, and linking their variable interfaces to the region's data. Hence, the subroutines in a model do not access each other, only the region's data.

SHYFT: SHYFT is Statkraft's internal hydrological modelling system for the prediction of inflow to their reservoirs. SHYFT is a tailor-made platform for the needs of Statkraft, but makes use of core hydrological routines developed by SINTEF and originating from the development of the Enki platform.

6.2 Lake models

Lake models are used to assess the internal conditions in lakes and reservoirs and they can simulate physical, chemical and biological conditions in 1, 2 or 3 spatial dimensions (1D, 2D and 3D models, respectively). 1D models are typically easier to set-up and less time consuming with regards to computation than 2D or 3D models, and 1D-models can be used to simulate a large number of lakes over long periods (decades). More complex models are more adapted to study particular lakes, and suit better for analysing and understanding of processes occurring in specific lakes, or investigation of local mitigation measures.

6.2.1 MyLake

MyLake (Multi-year simulation model for Lake thermo- and phytoplankton dynamics) is a one-dimensional model (Saloranta and Andersen 2007). It can simulate daily vertical distribution of lake water temperature and thus stratification, evolution of seasonal lake ice and snow cover, and phosphorus-phytoplankton dynamics. MyLake is well suitable for making predictions and scenarios, like in climate change studies where a high number of lakes are modelled. It can be used for a screening of geographical areas in order to assess vulnerability to climate changes.

6.2.2 GEMSS/CE-QUAL2 model

CE-QUAL-W2® is a two-dimensional (longitudinal-vertical), hydrodynamic and water quality model for lakes and reservoirs, in addition to rivers, estuaries, and river basin systems developed by U.S. Army Corps of Engineers in 1975, and is under continuous development. As the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients. This model can provide information about lake's hydrodynamics, such as temperature and stratification, mixing, surface and deep currents, internal waves, and water quality components including oxygen conditions and nutrients load, and occurrence of eutrophication.

GEMSS® is a general-purpose modelling package for simulating 3-D flow, transport, sediments and biological processes in water systems such as rivers, lakes, reservoirs, estuaries, wetlands and coastal regions. The GEMSS® model is developed by ERM's Surface water Modelling Group in Exton, Pennsylvania (http://www.ermsmg.com). This model provides the similar information as CE-QUAL2, but it has the advantage of taking into account also the horizontal variations of lakes. It is therefore adapted to lakes that are non- longitudinal. However, it has longer computational time as it models lake/reservoir processes in 3 dimensions. GEMSS® was applied in EnviPEAK project to simulate the effects of pumping in two regulated systems (Charmasson 2012, Tjomsland and Bakken 2012).

7 Direct assessment of hydromorphological habitat qualities

Lake Habitat Survey (LHS), Morphological Impact Assessment Tool (Lake MImAS) and Great Lakes Aquatic Habitat Framework (GLAHF) are three different methods to characterize physical habitats in lakes, reservoirs and ponds. Lake Habitat Survey is developed in UK and used as a support to the implementation of the EU WFD. Applying the method requires compilation of hydromorphological features of the lakes/reservoirs from maps and databases supplemented with data monitored on site, such as secchi depth, oxygen level and water temperature.

Lake MImAS (Morphological Impact Assessment Tool) is a decision-support tool for managing hydromorphological alterations in lakes. It is developed based on the concept that physical characters of lakes, including the hydrological regime, strongly influence the structure and function of its associated ecosystems. A selected set of hydromorphological features, given by the lake typology, describe the possible deviation from natural conditions.

GLAHF is a third method and stands for Great Lakes Aquatic Habitat Framework. This method depends extensively on the availability of spatial data which is processed in GIS. Based on the compilation and processing of physical, chemical and ecological data, a classification of aquatic ecology is done. The tool is still under development, and the classification routine not finalized (July, 2018).

In this chapter, these different tools to assess the hydromorphology are presented and the suitability of the tools for Norwegian lakes and reservoirs is discussed.

7.1 Lake Habitat Survey and its derived metrics

The Lake Habitat Survey (LHS) was developed to create a standard characterization of physical habitat of lakes in Europe (Rowan et al. 2006). It was tested and applied in the UK for both lakes and reservoirs. The survey combines both existing data from databases (e.g. depth, surface area, catchment area) and measurements made on-site, which are usually taken within a single site visit in the summer months. LHS includes not only hydromorphological features, but also occurrence of littoral species. It is designed in a way that it can be carried out by local authorities and organisations. The recorded datasets from a variety of surveyors were evaluated for consistency and it was proven statistically that measurements done by different teams throughout the UK yielded repeatable and consistent results. The application of remote sensing only played a marginal role.

Two different types of complexity for the lake assessment can be employed: LHS_{core} and the full LHS version LHS_{full}. LHS_{full} includes ten habitat plots, whereas LHS_{core} includes only four Habitat-Plots and omits the index site. Habitat plots can be described as samples of sub-units of a lake, that collectively can be used to describe the lake as a whole.

The index site is the deepest location of the lake, where for instance Secchi depth and temperature profiles are measured. The employment of LHS_{core} was discontinued during the development. It is however addressed in this report, because reduction of measurement effort is perceived as relevant due to the large number of lakes in Norway.

7.1.1 Lake Habitat Survey (LHS)

LHS and its results are divided into five parts which are explained step-wise in the following:

Part 1 - Lake information and survey details: This part of the LHS is a desk-top study which includes collecting information about the lakes prior to the site visit. Information to collect is data that can be accessed from databases, such as maximum depth and catchment characteristics. It furthermore shows the Hab-Plots' location and coordinates.

Part 2 - Hab-Plot attributes: The second part is the core element of the survey. The in-situ measurements are characterized by Habitat plots (Hab-Plots) and can be carried out either by foot or by boat, but by boat is preferred due to improved access to all the different zones of the lakes. Hab-Plots are taken at locations on the lake shoreline. A Hab-Plot is georeferenced via GPS and includes photographs. It yields extensive information about riparian zone, bank edge, exposed shore and littoral zone under water (see Figure 7.1). Information can be given within a numerical classification system, as category (e.g. substrate) or as numerical estimation. It also includes human pressures on the lake such as the existence of structures or anthropogenic use of the riparian zone in a detailed manner.

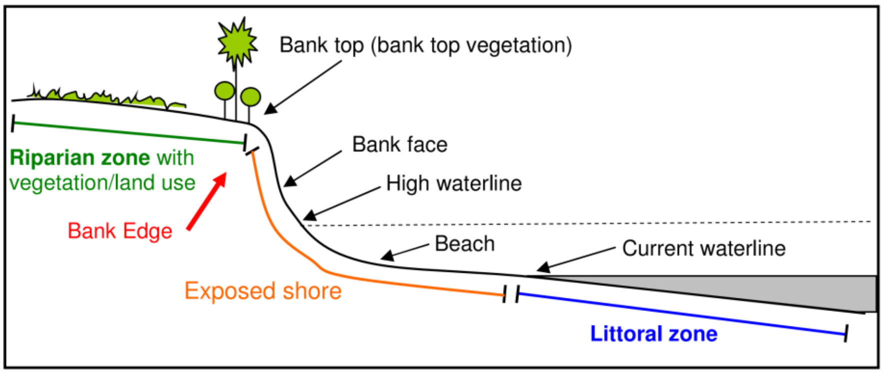


Figure 7.1. Cross section of a Hab-Plot.

Part 3 - Whole lake assessment: This part of the survey yields information on the lake perimeter characteristics, lake site activities (e.g. fishing, infrastructure development, etc.), landform features and the lake's outlet. The lake perimeter is divided into stretches divided by the Hab-Plots. Extensive information about shore/littoral zone pressures, riparian land use pressures, wetland and other habitats is reported.

The whole lake assessment also considers different type of lake site activities and pressures, such as recreational, educational and boating pressures and additionally reports their intensity. The extent of different landform features such as vegetated islands or gravel deposits is recorded as percentage of lake surface area. The lake's outlet is characterized by its geometry, classified into trapezoidal, V-shaped, rectangular or parabolic.

Part 4 - Hydrology: The hydrology section of the survey categorizes the lakes by principal uses, hydrological regime classes (e.g. unmodified, raised water level) and the presence of hydraulic structures such as dams, weirs and sluices. All information in this section is gained qualitatively upon visual inspection and estimation in a single site visit. A single site visit cannot fully assess key aspects of the regime such as seasonal or daily water level fluctuations. However, gathered estimations can be vital if there is no information given from other data sources.

Part 5 - Lake profile information at index site: The index site is located at the deepest point of the lake. The LHS field guide recommends a brief sonar survey if the location is not known. Surface films (e.g. algal mats, scum or oily films) and odours are recorded and the maximum depth is measured.

Furthermore, the secchi depth is measured using a secchi disc. Dissolved oxygen and a temperature profile is measured along a depth gradient. The last element of the index site measurements is a bed sediment sample. The predominant substrate texture and the presence of macrophytes is recorded. The field survey guide recommends a Van Veen grab sampler, which functionality is basically a simple excavator bucket.

7.1.2 Lake Habitat Modification Score (LHMS)

The Lake Habitat Modification Score (LHMS) is a summary metric based on LHS survey and formulates an index of morphological alteration. LHMS evaluates the pressures in Table 7.1 based on a score system, both $\mathrm{LHS}_{\mathrm{core}}$ and $\mathrm{LHS}_{\mathrm{full}}$ can be employed to generate the scores. The score of a lake can reach values between zero and 48, where low values indicate near-natural conditions and high values indicate severe anthropogenic modifications. The sum of the scores of the pressures tabulated in Table 7.1 define the overall lake score (Rowan et al. 2006). The scores of individual pressures are quantitatively assessed based on information given in the LHS, often combining percentage changes of key aspects and ordinal occurrences of structures or hab-plots.

Table 7.1. Pressures and their score generation principles for LHMS (from Rowan et al. 2006).

Pressure	Elements of score system approach	Score
Shore zone modification	• Percentage of shoreline affected by hard engineering • Shore reinforcement recorded at number of habitat plots • Poaching recorded at number of habitat plots	0-8
Shore zone intensive use	• Percentage of non-natural shoreline land cover • Non-natural landcover recorded at Hab-Plots	0-8
In-lake use	• Number of in-lake pressures	0-8
Hydrology	• Number of hydrological/hydraulic structures • Occurrence of specific principal uses • Occurrence of specific structures • Yearly water level fluctuation thresholds (only for score 8) • Water level raised/lowered (only for score 6)	0-8
Sediment regime	• Percentage of shoreline affected by erosion	0-6
Nuisance species	• Number of recordings of invasive species	0-4

McGoff et al. (2013) tested LHS metrics as predictor of littoral macroinvertebrate communities across 42 lakes in Europe. The 42 lakes were divided by region, the northern region consisted of nine Swedish and two Finnish lakes with areas ranging from 0.6 - 63.5 km^2 and maximum depths 2.2 - 32.0 m. In this study, no relationship between littoral macroinvertebrates and the LHMS metrics were found. Their results indicated that the riparian variables accounted for the majority of variance in community composition.

7.1.3 Lake Habitat Quality Assessment (LHQA)

The Lake Habitat Quality Assessment (LHQA) is a summary metric based on LHS to indicate naturalness and diversity of a lake. The scoring system is similar to LMHS in the way that scores of several aspects are summed to the total score, and points are gained for extent and diversity of natural habitat features. For a detailed description of the LHQA and its scoring system, see Rowan et al. (2004).

McGoff and Irvine (2009) used a customized version of the LHQA as an indicator for abundance and for aquatic taxa richness in a single lake. They showed potential limitations of using LHQA as metric for natural status in lakes where macrophytes are naturally sparse and therefore suggested a lake typology approach, with different habitat feature scores dependent on lake type. In another study, LHQA metrics were related to littoral macroinvertebrate community composition in Swedish and Finnish lakes and reasonably strong relationships were found, especially with variables of the riparian zone (McGoff et al. 2013). The component scores separated by location of LHQA (littoral, riparian, shore and whole lake) were correlated with eight macroinvertebrate metrics (e.g. number of taxa) and no correlation were found.

7.1.4 Discussion of LHS, LHMS and LHQA

The LHS campaign-like field study yields detailed information about lake conditions. However, it relies on extensive field observations. Sampling a large number of lakes is assumed to be cost prohibitive (Wehrly et al. 2012), especially for Norway with thousands of lakes. An economic and practical advantage of LHS is that it can be carried out by different teams, e.g. in combination with other surveys. Most of the measured data by LHS is dependent on the timing of the survey, which can be crucial for the assessment of reservoirs, since its characteristics vary heavily within the range of water-level regulation.

The original LHS protocol and its resulting LHMS may not be optimal for Norwegian reservoirs due to the imprecise description of the pressure of water-level fluctuations. Water-level fluctuations are only affecting the modification score if they are smaller than 0.5 m or exceed 5 m. Moreover, the according Hydrology score of the LHMS does not consider the relativity of the water-level fluctuation to the absolute depth of the lake and there is no metric that takes frequency of water-level fluctuations into account. Dalu et al. (2016) tested LHS in a tropical reservoir and criticized the insufficient attention of LHS to natural extreme water level regimes.

7.2 Lake MImAS - Morphological Impact Assessment Tool

Lake MImAS was developed and finalized in 2007 by the Scotland and Northern Ireland Forum for Environmental Research. MImAS is a risk assessment tool for lakes based on the concept that a water body has a type-specific robustness and reaction towards hydromorphological stress. It builds on the original MImAS scheme developed for rivers in the UK and captures most large lakes in Great Britain and Ireland (Armstrong and Johns 2008). In order to apply the MImAS tool, information surveyed with the LHS (Section 7.1) or high-resolution aerial survey data may be needed. 95 lakes in the United Kingdom were used for the development and testing of the MImAS tool, all of which had LHS data readily available.

Morphological Condition Limits (MCL) were developed using expert knowledge and experience from the river MImAS scheme to define the threshold limits for hydromorphological alteration. MCL are defined as percentage of 'system capacity' used, where the system capacity is the lakes capacity to assimilate hydromorphological alterations without changing its ecological status. The underlying assumption is that there is a correlation between the risk of ecosystem deterioration and the share of used lake capacity.

MCL were defined for the sub-systems 'pelagic-profundal' and 'shore zone'. The MCL threshold of 5 % is critical, because it is employed as the boundary between high and good ecological status. For statuses below good ecological status, hydromorphological conditions may be used in absence of biological data, but otherwise have an informing character.

7.2.1 MImAS' module structure

MImAS uses an interdependent step-wise modular scheme shown in Figure 7.2, and the modules can be updated when new information becomes available.

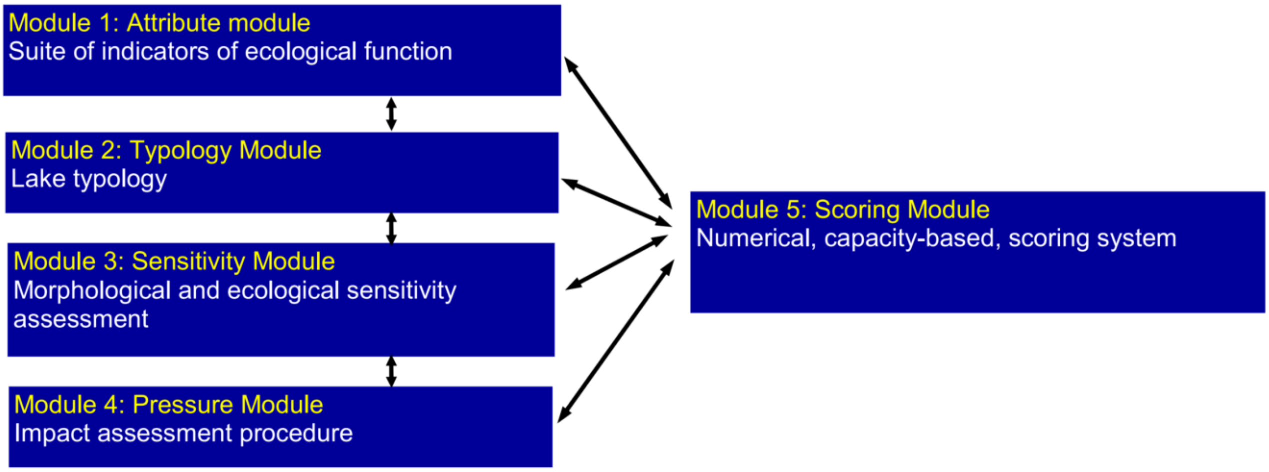


Figure 7.2. Structure of modular components in Lake-MImAS (Source: Armstrong and Johns 2008).

Module 1 - Attribute module

Attributes assigned in module one are closely related to the morphological quality elements in the WFD and they have been selected for either supporting ecological communities (e.g. structure and extent of riparian vegetation) or supporting the processes relevant to creating and maintaining environments for ecological communities.

Module 2 - Typology module

The typology module categorizes lakes based on the two typology systems used in England and Ireland. There are five main categories dependent for example on elevation, mean depth and alkalinity. Lakes within the same lake type group are assumed to react in a similar way to hydromorphological pressures. Output of this typology module of a single lake is the *Relevance,* defining binarily if a geomorphic attribute plays a role for the respective lake type (e.g. the attribute "*stratification/mixing*" is not relevant for very shallow lakes since stratification is not expected to occur).

Module 3 - Sensitivity module

The sensitivity module uses information of both attribute and typology module to assess the generic sensitivity to external pressures and the sensitivity of the different biological quality elements of the WFD to changes in the attributes. Its output is *Ecological sensitivity* and *Morphological Sensitivity*.

Module 4 - Pressure module

The considered categories for anthropogenic pressures on lakes and respective examples in Lake-MImAS are tabulated in Table 7.2.

Table 7.2. Hydromorphological pressures and examples for Lake-MImAS.

Pressure category	**Example(s)**
Water level control and regulation	Raising or lowering of water level, Active dynamic regulation
Shore zone alteration	Shore reinforcements, flood embankments
Within lake strutures/alterations	Dumping, Sediment extraction
Lakeside pressures	Recreational pressures, riparian vegetation loss
Catchment alterations	Catchment hydrology alteration through upstream reservoir regulation

Pressures are further categorized by significance: either they are locally restricted or they may affect the whole lake system. The pressure module's quantitative output is the *Likelihood of impact* and *Zone of impact*, the first describes the probability of change due to a specific pressure and the latter the extent of change (e.g. restricted to shore zone or whole lake).

Module 5 - Scoring module

The scoring module incorporates all output from the above modules to generate the score or the percentage of system capacity used respectively.

$$Activity\ Impact\ score = Relevance\ x\ Ecological\ Sensitivity\ x\ Morphological\ Sensitivity\ x \\ Likelihood\ of\ impact\ x\ Zone\ of\ impact$$

The used capacity of a single pressure is then calculated as the product of its impact score and its activity footprint, the latter being a metric for the extent and nature of the pressure. The total score is comprised of the sum of the single pressure scores. For an individual lake, scores for the open water/profundal and for the shore zone are generated.

Once the metrics of all modules are established and agreed upon, the calculation of the two scores is executed using an excel sheet based on data input for the different pressures as either Activity Footprint Scores, relative lengths (e.g. for shore reinforcements) or relative areas.

7.2.2 Discussion of Lake MImAS

An advantage of MImAS is that the assessment of the hydromorphological status is not based on the deviation from reference conditions. Reference conditions of water-bodies are often not known, the generation of information about them might be difficult. Methods to create knowledge about reference conditions often include estimates or modelling, which include the risk of uncertainties that can be relatively large in comparison to the class limits of the classification system, therefore reducing its reliability. As the assessment through MImAS does not include a comparison to pristine conditions and is to a large extent based on the occurrence and intensity of human pressures on the lakes, these can be measured in relatively simple ways, avoiding the prior mentioned problems.

Since the hydromorphological elements are defined as "supporting parameters" in the WFD, it may improve the acceptance and understanding by stakeholders if the employed classification system is based on a link between hydromorphological parameters and habitat quality and biodiversity. Such empirical correlations can be difficult to find and are often site-specific (Hirsch et al. 2017). The class boundaries were created based on expert knowledge, correlation between scores and ecological status are not a priority. The classification system MImAS defines the risk of ecological impacts, whereas the goal of this project was to find a classification system of hydromorphological status.

The impact scores in MImAS are dependent on the sensitivity and therefore on the typology. This concept can be beneficial during the development and testing of a classification system, because the importance of pressures and deviations from reference conditions can be adjusted by the sensitivity. Also, it can be considered that lakes of a certain type might be less sensitive to specific pressures. The main disadvantage of the included typology-sensitivity module is the added complexity and effort to create the typology system.

Due to MImAS reliance on the Lake Habitat Survey, the discussion on LHS also applies for MImAS. The activity footprint score system for water level alterations is divided into different scores for very shallow and shallow/deep lakes. This way, very shallow lakes (mean depth <3 m) are more sensitive to water level drawdown. The system is based on the metric "average water level change" which is further divided into active and passive water level regulation. Given that water level fluctuations are one of the major impacts on Norwegian lakes, we recommend a more refined system. Furthermore, a system for Norwegian lakes should also consider the time scale and frequency of water level fluctuations.

MImAS generates two different scores: pelagic and shoreline. This distinction may be useful for scientific purposes to understand impacts on different habitats, it might however not meet the expected simplicity for management purposes. A simple solution to this mismatch in complexity can be that the lower of both scores defines the overall score.

7.3 GLAHF - Great Lakes Aquatic Habitat Framework

7.3.1 GLAHF Description

This framework covers the five Great lakes of North America. The lakes are an interconnected lake system that is located in several US states and Canada, most of its area is within Michigan. The lake surface areas range from 19.000 (Lake Ontario) to 82.000 km^2 (Lake Superior).

The GLAHF is spatially hierarchical database that comprises ecological and socioeconomic information. Databases were created by a variety of US American and Canadian institutions, the data includes measurements of the bathymetry, the shoreline and the substrate. The lakes' catchment properties were defined and their respective influences on the lakes was quantified using a mathematical model.

The framework consists of five different components:

- Hierarchical spatial framework
- Spatial data base
- Hydrography dataset
- Hierarchical environmental classification
- Visualization tools and maps

The framework includes an extensive monitoring that employs satellite imagery amongst other measurement techniques.

Satellite images from the Landsat satellites were employed for mapping of the extent of submerged aquatic vegetation, which was especially important because of the rapid expansion of nuisance green algae *Cladophora*. The mapping was done for zones where a return of light from the bottom was possible. Maps with 30 m resolution were realized in order to map the spatial extent and to estimate the biomass.

Furthermore, eleven years of MODIS satellite imagery was used to estimate chlorophyll concentrations along shore transects. This data was in turn used to estimate the nearshore zone, which is defined as the region of water directly influenced by its proximity to the coast. The results showed both spatial and seasonal variation influenced by mixing and transport of nearshore waters (Warren et al. 2017).

A fish dataset was created as a part of the spatial data base. It identifies stream segments of the lake tributaries delimited by the lake shore and the first major barrier upstream. The dataset was realized using existing databases: the USGS Anthropogenic Barrier Dataset (US) and a dams and barriers dataset provided by Ontario Ministry of Natural Resources and Forestry (Canada).

The classification system is not finalized yet (by July, 2018). It is not clear if an ecological status classification will be included. The classification may also be related to exposures to anthropogenic pressures. It is clear however, that it will classify different zones within the lakes, i.e. there is a spatially discrete gridded zonation within each lake and each grid cell is classified.

7.3.2 Discussion of GLAHF

Since there is no information available about the proposed classification system in GLAHF, the discussion focusses on the survey method.

GLAHF is developed for only a very few and very large lakes, and it distinguishes between gridded sub-elements of the lakes. This does not suit the needs of a hydromorphological classification system in Norway, due to the large number of lakes that have to be covered. A further sub-division into spatially explicit elements within individual lakes would make the system very comprehensive to apply.

The methods based on satellite imagery in GLAHF could be used for an ecological classification focussed on nutrients for large lakes, for which the resolution of satellite images does not limit applicability. The immediate application within the scope of this project is not recognizable.

The GLAHF sets a good example for making results publicly available via their website (https://www.glahf.org). Since international hydromorphological assessment of lakes and reservoirs is not well established, it is beneficial to the scientific community and managers to create a transparent overview of the work progress.

7.4 Other Classification systems

Many ecological status assessment systems are not directly related to hydromorphological parameters. The most common systems rely on the correlation between eutrophication pressure and taxonomic composition and abundance of fish, macrophytes and invertebrates (Søndergaard et al. 2011, Lyche-Solheim et al. 2013).

7.4.1 HydroMorphology of Lakes Protocol (HML)

HML was developed and tested using the data of 80 lakes in Germany, and the protocol has been used to assess anthropogenic alteration of hydromorphological features of lake shores based on information gained through ground surveys and high-resolution ortho-photos.

The ortho-photos allowed for an object-oriented classification approach that investigates spatial units of the lakeshore regarding the occurrence of predefined objects. The objects are categorized and impact scores are assigned to the different object categories. During the development, LHS was also tested for several of the lakes, however the LHS results showed strong deviations from expected results. Miler et al. (2015) assumes that HML characterizes lake shore characteristics more precisely.

The shore assessment of a selection of individual stretches can be extrapolated to the whole lake extent using GIS supported physical habitat analyses of aerial photographs. Miler et al. (2015) shows that their hydromorphological impact scores are correlated with macroinvertebrate metrics. Whole lake assessments were realized by correlating HML scores to the multi-metric biological assessment index LIMCO, which is based on macroinvertebrates. LIMCO scores were directly linked to the status classification according to WFD and cover all classes from high to poor (Miler et al. 2013).

7.4.2 Landscape-Based Assessment of Human Disturbance for Michigan Lakes

Wang et al. (2010) pointed out from studies in Michigan, USA, that detailed assessment of lake impairment status of a large geographic areas is usually hindered by the lack of reliable field data. They proposed a process to quantify human disturbance on the lakes that uses agricultural disturbance variables, urban variables, point-source variables and other disturbance variables. All sub-factors of mentioned variables can be calculated using GIS data and other existing data sources, and site visits were therefore not necessary. 9260 lakes were assessed using a human disturbance score.

As hydromorphological changes in lakes caused by river regulation are dominating in Norway, this system seems to be less suitable for Norwegian conditions.

Figure 7.3. A weir can act as a barrier to upstream and downstream migration (Photo: Tor Haakon Bakken).

8 Outline of a hydromorphological classification system for lakes

8.1 Principles of the hydromorphological classification system

The hydromorphological classification system outlined in Section 8.2 is developed based on three overall problem types, named quality elements in EU WFD-terminology, affecting ecological conditions in regulated rivers;

1. Hydrological changes
2. Changes in morphological conditions
3. Fragmentation and barriers hindering migration

This follows closely the definition of hydromorphological quality elements defined by EU CIS Guidance document 13 (EU WFD CIS Guidance Document No. 13 2005). The status of lakes and reservoirs are potentially also strongly affected by pressures in upstream and downstream water bodies, which must be taken into considerations when assessing the hydromorphological status and alteration of a lake. These changes in hydrological and morphological conditions, as well as fragmentation/barriers, are assessed separately from the pressures within the lakes. The geographical structuring of the hydromorphological classification system reflects that both upstream and downstream pressures must be assessed. As such, the classification system is structured according to different geographical zone, i.e. upstream and downstream of the lake under assessment, and within and along the lake. The zones and colour codes used in the classification system (Section 8.2) are shown in Figure 8.1.

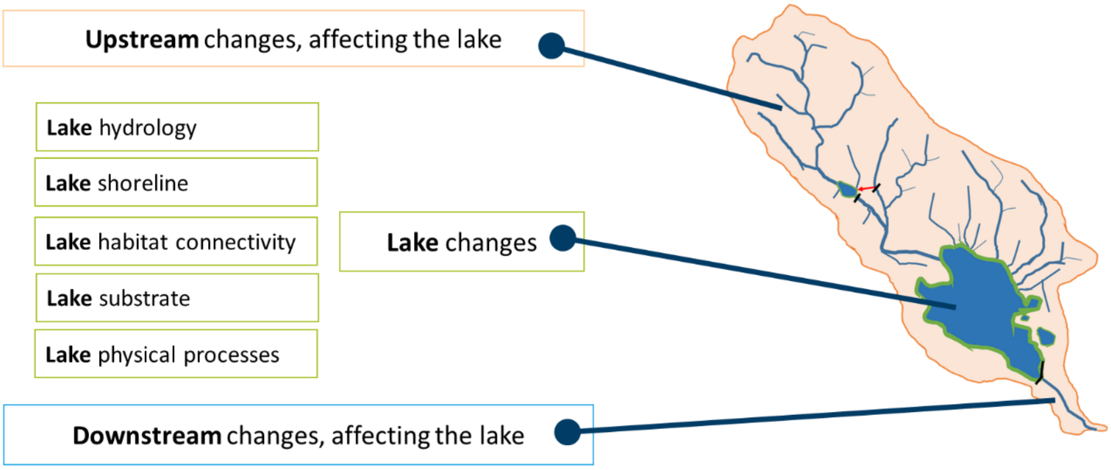


Figure 8.1. Illustration of the how the assessment of the hydromorphological state or alteration of a specific lake or reservoir water body is made, by assessing both upstream changes affecting the lake/reservoir under consideration, as well as pressures introduced in a downstream water body. The green zones indicate the shorelines.

EU WFD manages the aquatic environment in 'water bodies' as the spatial unit. A water body is a geographical unit that has similar natural characteristics, level of pressures and ecological state. The effect of an additional pressure (or reduction of a pressure) and natural state should preferably have a uniform response for the entire water body. The extent of a lake water body varies extensively across Norway. Most lakes are single water bodies, but a few, larger lakes are also split into two or more water bodies. The assignment of hydromorphological modifications are made on water bodies as spatial units, i.e. one single value is made representative for the entire water body. As such, a system for the assessment of status or alteration must be designed in such a way that representative values for the water body can be found.

The proposed hydromorphological classification system for lakes and reservoirs has been developed in two steps;

1. A set of hydromorphological parameters considered relevant in the description of the hydromorphological state and alterations is defined
2. Class borders for the selected parameters are suggested

The following principles formed the basis for the inclusion of hydromorphological parameters;

- The state of, or change in the hydromorphological parameter, is a common human alteration in lakes and is considered an important descriptor of the water body. As such, this parameter could 'stand alone' and describe the hydromorphological state or change.
- The hydromorphological parameter is assumed to be relevant in describing the ecological state of or change in the water body, i.e. the ecosystem has some sensitivity to change in this hydromorphological parameter in short (days, weeks) or long time horizons (years).
- It should be possible to find data/information about the state of, and change in this hydromorphological parameter with reasonable efforts, i.e. via publicly available data sources, from measurements or by use of computer models.

The proposed class borders are based on the following sources of information:

- Some sort of scientific evidence (documented or expert judgment)
- Comparison with or inspiration from similar systems (or methods) developed in other countries
- Statistical stratification of data from existing national data sources (i.e. all lakes/reservoirs should not end up in the same class unless a particular reason). The simple approach could be to divide the dataset into 5 classes holding a pre-defined number of the water bodies in each class (eg. 10%, 25%, 30%, 25% and 10%, respectively, or 20% in each)

The classification system follows the standardisation that has been developed for presenting ecological status in the EU Water Framework Directive (EU WFD), ranging from 'high' to 'bad' ecological status, alternatively 'Near-natural' to Severely modified'. As there is limited scientific evidence to argue for a 5-class system, given the difficulties of defining 'hard class borders' where clear ecological changes seem to happen, we have selected to use a 3-class system, as given in CEN TC 230/WG 2/TG 5: N65 (2008). When a 3-class system is used, the colour codes and description of classes are as given in Table 8.1.

Table 8.1. Generalised 3-class system following the standardised approach used in EU WFD for hydromorphological changes (CEN TC 230/WG 2/TG 5: N65 2008).

Class	Code	Description
1	🟦	Near-natural
3	🟨	Slightly to moderately modified
5	🟥	Extensively to severely modified

It should be noted that the terminology used in Table 8.1 refers to 'changes' or 'modifications' from a situation prior to the human intervention, in WFD-terminology called reference conditions, and not the hydromorphological status. This means that it must be able to describe the hydromorphological state before the regulation or pressure is introduced, as well as the conditions after the changes. The conditions prior to the alteration will also be the goal for the restoration, according to the EU WFD.

In Norway, a common way of establishing a reservoir is to use an existing lake and control the outflow of this by a dam, in contrasting to building a dam on the river which will change a flowing section of the river into an artificial lake. A conversion from a lake to a reservoir will introduce a much smaller hydromorphological and ecological change compared to transforming a river into a reservoir. As the latter is a such a fundamental change, these water bodies will be defined as either heavily modified water bodies or artificial water bodies, while the regulation of an existing lake can be defined as a natural water body, with different environmental goals.

It can be a scientific challenge to be able to assess the hydromorphological conditions prior to a regulation (e.g. river regulation) that might have been introduced 100 years back in time, as relevant data are rarely available. Model tools can in some cases be useful for such a hindcasting, but the precision of the results will vary on the state of knowledge and representation of the specific process, and can, of course, hardly be verified.

For each of the quality elements a set of abiotic parameters are selected to describe the changes quantitatively, with a few exceptions where only qualitative descriptions are possible with the present knowledge. A requirement for each of these parameters is that they should be possible to measure out in the field (or via remote sensing techniques), can be modelled/calculated, or that information about their state can be found from existing databases. Threshold values are then assigned to each of these parameters. The selection of parameters for each problem type (quality element) is proposed in Section 8.2, along with the accompanying class values. The rationale for selecting parameters and class values are described in Table 8.2.

It is limited evidence available to propose a clear methodology for weighing of the individual parameters into an overall score. However, as water level fluctuation is the factor driving changes in many of the other hydromorphological parameters in the classification system, it stands out as sensible to assign water level fluctuations more weight than many of the other parameters. We propose that weighing is further discussed during a real testing of classification system. We also refer to the work carried out and reported in Harby et al. (2018) for further inspiration of weighing.

We would underline that the system has not undergone any systematic testing. A real testing of the system will form the basis for revising the selection of parameters included in the system, their indicated importance as well as the proposed class borders. Testing the system will also evaluate if there is a balance between the data needs and the data availability, and if the system can be applied with reasonable efforts and competence.

8.2 Proposed hydromorphological classification system

The proposed hydromorphological classification system is presented in Tables 8.2-8.5. The system stands out as a comprehensive system requiring extensive resources to apply for all lake water bodies in Norway. The system is developed based on the idea that all parameters considered relevant should be included in the very first version of the system, and that the number of parameters could be reduced when the system is tested and experiences gained. It is also possible to develop a much less extensive version of the system for screening purposes. Based on the present knowledge, the column "Importance" (Table 8.2) indicates which parameters that are considered most important during a classification, and parameters considered having low importance are at present candidates to be left out if a reduced system shall be developed. Related to this, it should also be mentioned that some parameters can have high importance in some types of lakes/reservoirs (e.g. in mountainous regions), while having low importance in other lakes/reservoirs, for instance in lowland reservoirs.

The colour codes given in column 1 and 3 in Table 8.2, and column 1 in the Tables 8.3-8.5 refer to Figure 8.1 and indicate the different geographical areas affecting the water body under consideration to be assessed, i.e. upstream areas, downstream areas and within the lake/reservoir.

The colour codes given in column 5 in Table 8.2 refer to the main types of hydromorphological state or alterations, i.e. hydrological change, morphological change and barriers/fragmentation (hydromorphological quality elements). These changes can geographically originate from the upstream areas, downstream areas and within the lake, respectively.

🟧	Changes upstream, affecting the lake/reservoir under consideration	🟩	Hydrological change
🟩	Changes directly at the lake/reservoir under consideration	🟧	Morphological change
🟦	Changes downstream, affecting the lake/reservoir under consideration	⬛	Barrier, fragmentation

Figure 8.2. Colour codes used to group the assessment geographically (left), and colour codes used to identify what type of hydromorphological quality element the given parameter is related to.

It is a pending issue if downstream changes shall be included in this classifications system. It appears clear that downstream changes, such as barriers, might hinder migration of some species, but downstream barriers will not affect flow or sediment transport. As such, downstream barriers will affect the ecology directly, but not the hydromorphology of the lake/reservoir under consideration. Downstream changes are still kept in this first version of the classification system, but this is an open issue that should be re-considered during a possible future testing of the system.

Table 8.2. Proposed hydromorphological classification system for lakes and reservoirs (1/4).

Area considered	Type of effect	No	Parameter	Qual. elem.	Impor-tance	Why important?
Upstream changes	Changes in upstream areas, which are independent of changes introduced in the assessed lake/reservoir	1.10	Hydrology: Change in annual inflow	🟩	High	Change in volume/filling of lake/size of habitat
		1.11	Hydrology: Changes in periodicity (inflow)	🟩	Medium	Change in timing of filling of lake/timing of availability of habitat
		1.12	Change in water temperature of inflowing water	🟩	Medium	Change the water temperatures/ice in receiving lake/reservoir
		1.13	Barriers affecting availability of upstream habitat	⬛	Low	Will change access to upstream areas for migration/spawning
		1.14	Sediment changes due to upstream barriers	🟧	Medium	Will change natural sediment dynamics
Flow/volume of water and water level of lake/reservoir (<u>hydrology</u>)	Directly affected by water level changes (due to change in inflow and/or release of water) in the assessed water body	2.10	Water level changes	🟩	High	Change in water level due to regulation
		2.11	Total volume change of lake	🟩	High	Total amount of flow is important for lake ecology as well as all user interests
		2.12	Seasonal change: Summer	🟩	High	Change in timing of filling of lake/timing of availability of habitat
		2.13	Seasonal change: Fall	🟩	High	Change in timing of filling of lake/timing of availability of habitat
		2.14	Seasonal change: Winter	🟩	Medium	Change in timing of filling of lake/timing of availability of habitat
		2.15	Seasonal change: Spring	🟩	Medium	Change in timing of filling of lake/timing of availability of habitat
		2.16	Short term water level variations (days)	🟩	Medium	Indicator if reservoir is used for short-term hydro-peaking
		2.17	Short term water level variations (weeks)	🟩	Low	Indicator if reservoir is used for medium-term hydro-peaking
		2.18	Annual maximum flood level	🟩	Low	Near-shore areas prevented from annual submerging
Processes along the <u>shoreline</u> of the lake/reservoir (shoreline morphology)	Factors directly determined by water level changes	2.20	Dewatered areas	🟩	High	Habitats dewatered, freezing, drying out, fragmentation
		2.21	Relative lake level fluctuation	🟩	High	Habitats dewatered, freezing, drying out, fragmentation, measured as relative to lake/reservoir depth
		2.22	Dewatered littoral zone versus total littoral zone (ratio)	🟩	High	Habitats dewatered, freezing, drying out, fragmentation
		2.23	Shoreline development (dimensionless number)	⬛	Medium	Area of shoreline habitat
		2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	⬛	High	Access to tributaries, backwaters, natural shoreline habitats/shelters
		2.25	Riparian zone changes	⬛	Low	Provider of shelter, source of allochthonous organic material
		2.26	Erosion introduced by changes in flow pattern/filling/water level variations	🟧	Medium	Changes in habitat qualities, clarity of water
<u>Fragmentation & barriers within</u> lake & reservoir (habitat connectivity)	Potentially second order effect of water level changes	2.30	Connection/de-connection of lakes due to regulation/water level changes	⬛	Medium	Lakes might be connected or separated due to regulation, possibly affecting the whole ecosystem
		2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	⬛	Low	Hydraulic variation, fragmentation, barriers
Processes within the lake related to <u>substrate</u> of lake & reservoir	Potentially second order effect of water level changes	2.40	Removed or added gravel, rocks, sand and other sediments	🟧	Low	Changes in habitat qualities, flow patterns important for biota
		2.41	Porosity of substrate	🟧	Medium	Shelter and habitat - important for biota
<u>Physical and chemical</u> processes in the water of the lake & reservoir	Potentially second order effect of water level changes	2.50	Flow velocity changes due to changes in inflow/outflow	🟩	Low	Affects physical processes, such as water temperature, ice formation and erosion, in particular near inlet/outlet structures
		2.51	Water temperature	🟩	High	Growth of organisms
		2.52	Ice conditions (surface, shore ice)	🟩	Medium	Changes habitat and predation, light conditions, potentially important for migrating terrestrial animals
		2.53	Water clarity	🟩	Medium	Habitat quality, predation, access to food
Downstream changes	Independent of changes within assessed lake	3.10	Barrier effects (hindering migration between lake/reservoir and downstream areas)	⬛	Medium	Barriers affecting migration in/out of lake, reducing access to habitats

Table 8.3. Proposed hydromorphological classification system for lakes and reservoirs (2/4).

No	Parameter	Metrics for change
1.10	Hydrology: Change in annual inflow	m^3 water/year or % change from natural conditions, given as degree of regulation
1.11	Hydrology: Changes in periodicity (inflow)	No of days changed filling compared to a benchmark date (July 1st)
1.12	Change in water temperature of inflowing water	Change in inflowing water from natural conditions in period with > 8 deg C, in day degrees
1.13	Barriers affecting availability of upstream habitat	Barriers in upstream area affecting availability of habitat/connectivity
1.14	Sediment changes due to upstream barriers	Change in sediment yields/year from natural conditions, in percentage or m3/year
2.10	Water level changes	Highest regulated water level (HRWL) - Lowest regulated water level (LRWL)
2.11	Total volume change	Change in volume of reservoir from natural conditions, in percentage (%)
2.12	Seasonal change: Summer	No of days changed filling compared to a benchmark date (e.g. July 1st)
2.13	Seasonal change: Fall	No of days changed filling compared to a benchmark date (e.g. October 1st)
2.14	Seasonal change: Winter	No of days changed filling compared to a benchmark date (e.g. January 1st)
2.15	Seasonal change: Spring	No of days changed filling compared to a benchmark date (e.g. April 1st)
2.16	Short term water level variations (days)	Water level change and dewatered area (given as water level change in meters)
2.17	Short term water level variations (weeks)	Water level change and dewatered area (metric adjusted to lakes)
2.18	Annual maximum flood level	Change in areas submerged (due to regulation), given as change in frequency
2.20	Dewatered areas	Dewatered areas due to regulation, in percentage area dewatered compared to total area (measured as surface area)
2.21	Relative lake level fluctuation	Dewatered areas due to regulation, in percentage area dewatered compared to total area (measured as surface area)
2.22	Dewatered littoral zone versus total littoral zone (ratio)	Total of the littoral zone (only) affected by the regulation (ratio)
2.23	Shoreline development (dimensionless number)	Change in dimensionless number
2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	Extent of shoreline affected, in percentage of total shoreline
2.25	Riparian zone changes	Extent shoreline with changes in higher vegetation (below treeline), in percentage
2.26	Erosion introduced by changes in flow pattern/filling/water level variations	Extent shoreline affected, in percentage
2.30	Connection/de-connection of lakes due to regulation/water level changes	Degree of fragmentation/interconnection, modifications assessed qualitatively
2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	Extent of lake/reservoir affected changed, changes assessed qualitatively
2.40	Removed or added gravel, rocks, sand and other sediments	Extent of lake/reservoir bottom affected, in percentage
2.41	Porosity of substrate	Change in shelter class affecting habitat quality
2.50	Flow velocity changes due to changes in inflow/outflow	Changes in flow velocities at representative locations (m/s)
2.51	Water temperature	Change in growth season (when temp > 8 deg. C) (should take into account changes in stratification)
2.52	Ice conditions (surface, shore ice)	Change in number of days with surface ice, in percentage at a given date
2.53	Water clarity	Change in secchi depth before/after regulation at representative locations (m)
3.10	Barrier effects (hindering downstream connectivity)	Barrier effects hindering upstream migration/connectivity

Table 8.4. Proposed hydromorphological classification system for lakes and reservoirs (3/4).

No	Parameter	Near natural	Slightly to moderately modified	Severely modified
1.10	Hydrology: Change in annual inflow	<20 % regulation upstream	20-50% regulation upstream	>50% regulation upstream
1.11	Hydrology: Changes in periodicity (inflow)	<15 days change compared to filling 1st July	15-30 days change compared to filling July 1st	>30 days change compared to filling 1st July
1.12	Change in water temperature of inflowing water	<1 deg. C change at given location (surface, centre at given date)	1-3 deg. C change (surface, centre at given date)	> deg. C change (surface, centre at given date)
1.13	Barriers affecting availability of upstream habitat	<10 % reduction in available spawning areas upstream due to barriers	10-50 % reduction in available spawning areas upstream due to barriers	>50 % reduction in available spawning areas upstream due to barriers
1.14	Sediment changes due to upstream barriers	<20 % reduction in sediment yields	20-60 % reduction in sediment yields	>60 % reduction in sediment yields
2.10	Water level changes	<3 meter	3-10 meters	>10 meters
2.11	Total volume change	<10 % change from natural volume	<10-30 % change from natural volume	>30 % change from natural volume
2.12	Seasonal change: Summer	<10 days change compared to filling by benchmark date	10-20 days change compared to filling by benchmark date	>20 days change compared to filling by benchmark date
2.13	Seasonal change: Fall	<10 days change compared to filling by benchmark date	10-20 days change compared to filling by benchmark date	>20 days change compared to filling by benchmark date
2.14	Seasonal change: Winter	<10 days change compared to filling by benchmark date	10-20 days change compared to filling by benchmark date	>20 days change compared to filling by benchmark date
2.15	Seasonal change: Spring	<10 days change compared to filling by benchmark date	10-20 days change compared to filling by benchmark date	>20 days change compared to filling by benchmark date
2.16	Short term water level variations (days)	<0.5 meters change during one day (90-percentile day during a year)	0.5-1 meter during one day (90-percentile day during a year)	>1 meter during one day (90-percentile day during a year)
2.17	Short term water level variations (weeks)	<1 meter within a week (90-percentile of a week during a year)	1-3 meters in a week (90-percentile of a week during a year)	>3 meters during one week (90-percentile week during a year)
2.18	Annual maximum flood level	'Annual submerge' happens more frequent than every 5 years	'Annual submerge' happens every 5-20 years	'Annual submerge' happens less frequent than every 20 years
2.20	Dewatered areas	<10 % dewatered compared to natural surface area	10-40 % dewatered compared to natural surface area	>40 % dewatered compared to natural surface area
2.21	Relative lake level fluctuation	<50 in relative lake level fluctuations	50-100 in relative lake level fluctuations	>100 in relative lake level fluctuations
2.22	Dewatered littoral zone versus total littoral zone (ratio)	<10 % affected by dewatering	10-40 % affected by dewatering	>40 % affected by dewatering
2.23	Shoreline development (dimensionless number)	<20 % reduction in Shoreline development	20-50 % reduction in Shoreline development	>50 % reduction in Shoreline development
2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	<20 % of shoreline affected	20-50 % of shoreline affected	>50 % of shoreline affected
2.25	Riparian zone changes	<20 % of riparian vegetation affected (measured as % of shoreline)	20-50 % of riparian vegetation affected (measured as % of shoreline)	>50 % of riparian vegetation affected (measured as % of shoreline)
2.26	Erosion introduced by changes in flow pattern/filling/water level variations	<20 % of shoreline affected by changes in erosion	20-50% of shoreline affected by changes in erosion	>50% of shoreline affected by changes in erosion
2.30	Connection/de-connection of lakes due to regulation/water level changes	Near natural	Slightly to moderately modified	Severely modified
2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	Near natural	Slightly to moderately modified	Severely modified
2.40	Removed or added gravel, rocks, sand and other sediments	<20 % of shoreline or areas near-shoreline affected	20-50 % of shoreline or areas near-shoreline affected	>50 % of shoreline or areas near-shoreline affected
2.41	Porosity of substrate	No change in shelter classes	Shelter reduced by one class	Shelter reduced by two classes
2.50	Flow velocity changes due to changes in inflow/outflow	<30% increase/decrease (when higher than 0.5 m/s)	30-100% increase/decrease (when higher than 0.5 m/s)	> 100% increase/decrease (when higher than 0.5 m/s)
2.51	Water temperature	<1 deg. C change at given location (surface, centre at given date)	1-3 deg. C change (surface, centre at given date)	> 3 deg. C change (surface, centre at given date)
2.52	Ice conditions (surface, shore ice)	<20 % reduction in ice cover	20-50 % reduction in ice cover	> 50 % reduction in ice cover
2.53	Water clarity	<20 % reduction in secchi depth (surface, centre at given date)	20-50 % reduction in secchi depth (surface, centre at given date)	>50 % reduction in secchi depth (surface, centre at given date)
3.10	Barrier effects (hindering downstream connectivity)	<20 % reduction in available spawning areas upstream due to barriers	20-50 % reduction in available spawning areas upstream due to barriers	<50 % reduction in available spawning areas upstream due to barriers

Table 8.5. Proposed hydromorphological classification system for lakes and reservoirs (4/4).

No	Parameter	Scientific reference	Relevance for other use/interests	Possible data sources
1.10	Hydrology: Change in annual inflow	Expert judgement	Landscape, boat activities, fishing	Numerical model, measurements
1.11	Hydrology: Changes in periodicity (inflow)	Expert judgement	Landscape, boat activities, fishing	Numerical model, measurements
1.12	Change in water temperature of inflowing water	Forseth and Harby (2013)	Swimming, possibly fishing	Numerical model, measurements
1.13	Barriers affecting availability of upstream habitat	Sandlund et al. (2013)	Possibly fishing in lake/reservoir	Site measurements, aerial photos (possibly NVE 'inngrepsdatabase')
1.14	Sediment changes due to upstream barriers	Expert judgement	Landscape, fishing	Numerical model for reference conditions and measurements
2.10	Water level changes	Mjelde et al. (2012)	Landscape, boat activities, fishing	Remote sensing, measurements, information from HP operators
2.11	Total volume change	Expert judgement	Landscape, boat activities, fishing	Bathymetry, remote sensing and information from HP operators
2.12	Seasonal change: Summer	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.13	Seasonal change: Fall	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.14	Seasonal change: Winter	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.15	Seasonal change: Spring	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.16	Short term water level variations (days)	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.17	Short term water level variations (weeks)	Expert judgement	Landscape, boat activities, fishing	Remote sensing, measurements and information from HP operators
2.18	Annual maximum flood level	Expert judgement	Landscape, fishing	Historical flood maps, modelling
2.20	Dewatered areas	Expert judgement	Landscape, boat activities, fishing	Bathymetry and Information from HP operators
2.21	Relative lake level fluctuation	See Section 3.2	Landscape, boat activities, fishing	Bathymetry and Information from HP operators
2.22	Dewatered littoral zone versus total littoral zone (ratio)	Expert judgement	Landscape, boat activities, fishing	Bathymetry and Information from HP operators
2.23	Shoreline development (dimensionless number)	Expert judgement - See definition in Section 2	Landscape, boat activities, fishing	Bathymetry and Information from HP operators
2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	MQI (Rinaldi et al. 2016)	Landscape, boat activities, fishing	Bathymetry and DEM and river network in GIS
2.25	Riparian zone changes	Modified from Harby et al. (2018)	Landscape, boat activities, fishing	Aerial photos
2.26	Erosion introduced by changes in flow pattern/filling/water level variations	Expert judgements	Landscape, boat activities, fishing	Site monitoring of sediments?
2.30	Connection/de-connection of lakes due to regulation/water level changes	Sandlund et al. (2013)	Recreation on the lake/reservoir	Site measurements, aerial photos, high resolution bathymetry
2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	Modified from Harby et al. (2018)	Recreation on the lake/reservoir	Aerial photos (possibly NVE 'inngrepsdatabase')
2.40	Removed or added gravel, rocks, sand and other sediments	Modified from Harby et al. (2018)	Landscape	Site measurements, high resolution bathymetry (in the future)
2.41	Porosity of substrate	Forseth and Harby, 2013, or preferably some specific for lakes	Swimming	Site measurements, high resolution bathymetry (in the future)
2.50	Flow velocity changes due to changes in inflow/outflow	Expert judgement; Example calculations in Charmasson (2012) and Tjomsland and Bakken (2012)	Swimming, possibly fishing	Site measurements, modelling
2.51	Water temperature	Forseth and Harby (2013), Example calculations in Charmasson (2012) and Tjomsland and Bakken (2012)	Swimming, possibly fishing	Site measurements, modelling
2.52	Ice conditions (surface, shore ice)	Expert judgement; Example calculations in Charmasson (2012) and Tjomsland and Bakken (2012)	Swimming, possibly fishing	Site measurements, modelling
2.53	Water clarity	Water quality standards	Swimming, possibly fishing	Site measurements
3.10	Barrier effects (hindering downstream connectivity)	Sandlund et al. (2013)	Possibly fishing in lake/reservoir	Site measurements, aerial photos (possibly NVE 'inngrepsdatabase')

Figure 8.3. Shoreline protection, in this case due to hydropower regulation, changes the hydromorphological conditions of a lake (Photo: Tor Haakon Bakken).

9 Conclusions

The purpose of this project has been to; i) review existing data sources and their usefulness to describe the status and alteration of hydromorphological conditions in Norwegian lakes/reservoirs; ii) assess the potential of using high-resolution bathymetric data and remote sensing techniques to derive hydromorphological information; iii) assess the relevance of existing, international methods to describe hydromorphological status, and; iv) outline a hydromorphological classification system applicable for Norwegian lakes and reservoirs. Based on the findings in this study we conclude the following way:

- The databases maintained by NVE are the principal sources of information about Norwegian lakes. They cover fundamental abiotic information such as lake shape, area and position. More detailed information such as volume and regulation height are available for a sub-selection of lakes. Bathymetric maps and derived variables thereof can greatly increase hydromorphological knowledge and are relevant for other fields such as lake ecology and habitat modelling.
- The statistics derived based on combining a set of NVE-hosted databases show that 67 % of the reservoirs are regulated less than 10 meters, and around 5% of the reservoirs are regulated more than 40 meters. The majority (79 %) of the regulated lakes have a surface area less than 2 km^2, and less than 3 % of the regulated lakes have a surface area larger than 20 km^2. 68 % of the reservoirs hold a regulated volume (between LRWL and HRWL) equal to or less than 20 mill. m^3, and less than 12 % a regulated volume greater than 100 mill. m^3.
- International data sources such as ICOLD and GRanD have most likely limited value. We found that the national databases maintained by NVE include more lake attributes and information with more details. Results from this report showed that data from national databases in Norway could contribute to improve international databases by supporting them with more and continuously updated data about the reservoirs.
- The existing bathymetric maps hold a potential of deriving more hydromorphological information than what is directly given in databases. GIS-processing of digitally available maps makes it possible to calculate dewatered areas from a certain water level reduction, slope of the dewatered zone, and also the extent of the littoral zone compared to the pelagic zone, if information about the depth of the littoral zone (light penetration) is available. Establishing the relationships between the water level and surface area and reservoir volume for each reservoir can potentially identify break points where ecological changes potentially accelerate.
- The reviewed hydromorphological systems did not seem to be very suitable for the assessment of hydromorphological status of Norwegian lakes. All reviewed systems are focussing on some types of pressures that are not very pronounced in the majority of Norwegian lakes. Water level regulation, a main pressure on Norwegian lakes, are defined by too few variables in both MImAS an LHS in order to depict the variety in extent and intensity. Furthermore, their survey methods are too labour intensive and costly to be applied across Norway by experts. The approach in LHS to create the survey in a way that it can be carried out by local government agencies can, however, be viable. The GLAHF covers few large lakes in an extensive way which is not suitable for thousands of Norwegian conditions, however concepts for monitoring via satellite data could be tested for this project.
- Scientific evidence for causal links between hydromorphological parameters and ecological status (e.g. occurrence and abundance of indicator species) is difficult to find. Research aimed at identifying the relationship between hydromorphological pressures and state of the fish population has basically been non-conclusive, while it appears that research has been more successful when linking hydromorphology with macrophytes (instead of fish) across a broad range of Nordic lakes. Similarly, it is difficult to find scientific evidence for the proposed class borders.

- The proposed hydromorphological classification system for Norway is a 3-class system developed on the following hydromorphological problem types (quality elements); hydrological changes, changes in morphological conditions, and fragmentation and borders hindering connectivity. The system is geographically structured into changes in the upstream areas, changes within the lake or along the shoreline, and changes in the downstream end of the lake.
- It is large uncertainty related to the importance of the included hydromorphological parameters, and the proposed class borders. For this reason, we recommend that the system is tested with respect to the relevance of the parameters included, their class borders, as well as the practical applicability. A testing of the system should include elaboration of possible approach to weight/sum the scores of the various hydromorphological parameters. As the proposed hydromorphological classification system appears to be comprehensive, testing of the system should also form the basis for reducing the number of parameters. A test should also form the basis for an updated and possibly simplified version of the classification system.
- We strongly recommend that the system is tested, evaluated and possibly adjusted before applied for management purpose.

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