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Report

Testing and evaluation of a HYMO classification system for lakes and reservoirs

Proposed new and modified hydromorphological (HYMO) classification system

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ABSTRACT
This project has tested and evaluated a hydromorphological (HYMO) classification system for lakes and reservoirs, published in 2018. The results revealed that applying the full set of parameters require extensive resources, and for some parameters data is hardly available. Based on the test results and the following evaluation, a revised version of a classification system is proposed. The revised system is divided into five classes, ranging from 'near natural' to 'severely modified' and consists of 17 HYMO parameters, in contrast to the original 30 parameters. The selected parameters are all considered being ecological relevant. The parameters are a mix of parameters describing alterations from natural conditions and degree of alterations. Many of the parameters can be calculated by employing hydrological models and with the use of digital bathymetric maps, if available. We have proposed a procedure for aggregating the individual parameter values into overall types of HYMO alterations, i.e. hydrological change, morphological change and barriers and fragmentation. Furthermore, we have proposed a system for screening of lakes and reservoirs with the purpose of sorting out those lakes that are either limited modified by HYMO alterations or extensively/ severely modified. This will reduce the number of lakes that will need to undergo a full classification procedure.

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Acknowledgement

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The actual testing of the hydromorphological classification system is to a large extent based on the master thesis carried out by Valerie Beck, submitted to the University of Stuttgart. Valerie was supervised by Tor Haakon Bakken at SINTEF/NTNU and Markus Noack and Stefan Haun from Stuttgart, and she also received extensive support from colleagues at SINTEF during her stay in Trondheim.

We would like to acknowledge the contributions and feedback on the test results and the proposed new hydromorphological classification from a number of national and international experts during the workshop held in Trondheim 28th – 29th of October, 2019. The following persons participated: Johan Kling and Katharina Vartia (HaV, Sweden), Georg Lamberty (Planungsbüro Zumbroich, Germany), Martina Bussettini (ISPRA, Italy), Seppo Hellsten (SYKE, Finland), Christine Argillier (IRSTEA, France), Jan-Erik Thrane (NIVA, Norway), Steinar Sandøy (Norwegian Environment Agency, Norway), Atle Harby (SINTEF, Norway), Lennart Schönfelder (SINTEF, Norway) and Tor Haakon Bakken (NTNU/SINTEF, Norway). We appreciate your very valuable input to this work.

We would like to thank Miljødirektoratet (Norwegian Environment Agency) for financing the project, where Steinar Sandøy has acted as the main contact. We are grateful for the close cooperation during the project and the very useful discussions, which we believe the report has benefitted from.

Tor Haakon Bakken, Trondheim, January, 2020

Extended Summary

This project has tested and evaluated a hydromorphological (HYMO) classification system for lakes and reservoirs. The results revealed that applying the full set of parameters require extensive resources, and for some parameters data is hardly available. Based on the test results and the following evaluation, a revised version of a classification system is proposed, with the following characteristics:

- The revised hydromorphological classification system uses five classes instead of three, in order to be more consistent with how classification systems are defined for other quality elements.
- It contains a reduced set of parameters, going from a system holding 30 parameters, to a system with 17 hydromorphological parameters.
- The majority of the parameters can be calculated based on hydrological data (water balance of the lake before and after regulation) and bathymetric maps (to be processed in GIS).
- The revised system is dominated by hydrological parameters, as parameters describing morphology and continuity are generally more work-intensive (or very difficult) to calculate.
- The hydromorphological parameters are aggregated into the three main types of hydromorphological alterations, i.e. hydrological change, morphological change and barrier/ fragmentation. The weight of each parameter is given according to importance during aggregation. Uncertainty of the parameter scores should not be accounted for in the weighting, but indicated beside the classified values when registered in the WFD database.
- The application of the revised classification system requires expert knowledge on hydrology, hydrological modelling and use of GIS. As such, it appears rational if a national classification is carried out by a few dedicated experts (e.g. by NVE or a consultant/researcher).

Fundamental questions that need further work are:

- Should the hydromorphological classification system be based on a description of the hydromorphological alterations and the severity of these, without considering the ecological response they might introduce? Or should the selection of parameters and class borders be defined based on to what extent the hydromorphological alteration cause an ecological response, as such being a proxy for ecological status? The parameters defined in the system proposed in Chapter 7 are selected as they are important for hydro-morphology alone, but they are also considered being ecological relevant, and at the same time suitable for use in all lakes with reasonable efforts.
- Should all the parameters be designed in such a way that they compare the present situation with the situation before any hydromorphological modifications are introduced (before regulations)? Or should we allow the inclusion of parameters that describe the degree of regulation? In the revised system it is a mix of these two fundamentally different approaches.
- It should be discussed and clarified the role is of the hydromorphological classification system in the context of designation of HMWBs.

The table presents the revised hydromorphological classification system. The columns describe the following; Parameter number (light red = upstream areas, light green = within the lake/reservoir), name of the parameters, the unit of each parameter, the metric for change, if the parameters describe changes from unregulated situation or the degree of modifications and what type of hydromorphological quality elements (green = hydrology, brown = morphology, grey = barrier/fragmentation). The numbers in the column to the very right indicate assumed importance (3=high, 2=medium, 1=low).

No	Parameter	Unit	Metric for change	Natural vs degree of regulation		HYMO element (Importance)
				Natural	Degree of reg.	
100	Change in annual inflow	%	Change in annual inflow from the unregulated conditions, expressed by degree of regulation	X		(3)
101	Upstream barriers affecting sediment processes	%	Percentage of upstream areas (river reaches) blocked due to man-made barriers, compared to a river without encroachments	X		(1)
200	Water level changes	Meter	Highest regulated water level (HRWL) - Lowest regulated water level (LRWL)	X	X	(3)
201	Total volume change	%	Change in volume of lake compared to the natural conditions, in percentage (%)	X		(3)
202	Change in retention time	%	Change in retention time of lake compared to the natural conditions, in percentage (%)	X		(2)
203	Change in date of filling	Days	No. of days changed start of filling compared to the date in the natural condition	X		(2)
204	Change in date of emptying	Days	No. of days changed in start of emptying compared to the date in the natural condition	X		(2)
205	Water level change at filling date	%	Relative deviation at filling date, given as deviation between natural water level and actual water level at this date, divided on max depth	X		(3)
206	Water level change at emptying date	%	Relative deviation at emptying date, given as deviation between natural water level and actual water level at this date, divided on max depth	X		(3)
207	Short term water level variations (days)	Meter/ day	Water level changes, given as water level change in meters per day	X	X	(2)
208	Short term water level variations (weeks)	Meter/ week	Water level changes, given as water level change in meters per week	X	X	(2)
210	Dewatered areas	%	Dewatered areas due to regulation, i.e. dewatered areas at lowest level compared to total area at highest level (measured horizontally)		X	(3)
211	Relative lake level fluctuation	%	Relative water level variations, defined as HRWL – LRWL divided on mean depth		X	(1)
212	Dewatered littoral zone versus total littoral zone (ratio)	%	Percentage of the littoral zone affected by the regulation (measured horizontally)		X	(3)
213	Loss in lateral connectivity along the shoreline	%	Percentage of the shoreline affected by embankments or other types of erosion protection	X		(3)
214	Riparian zone changes	%	Percentage of riparian vegetation along the shoreline affected by hydromorphological alterations	X		(3)
220	Change in substrate qualities	%	Changes in extent of areas of given substrate qualities	X		(1)

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1 Introduction

1.1 Introduction to hydromorphology and the EU WFD

The Water Framework Directive (WFD) (EU WFD 2000/60/EC 2000) came into force on December 22nd, 2000 and established a new framework for the management, protection and improvement of the water resources across the European Union (EU). According to the directive, all bodies of surface water and groundwater should reach good ecological status by 2015, unless there are grounds for derogation. If so, achievement of good status may be extended to 2021, or by 2027 at the latest.

Norway is connected to the European Union as an EFTA country, through the Agreement on the European Economic Area (EEA). The WFD was formally taken into the EEA-agreement in 2009, granting the EFTA countries extended deadlines for the implementation. The WFD was transposed into the Norwegian Regulation on a Framework for Water Management, normally referred to as Vannforskriften (The Water Regulation), entering into force in 2007. Norway has taken full part in the Common Implementation Strategy (CIS) for the WFD since it was established in 2001 (EU WFD CIS Guidance Document No. 13 2005).

Hydromorphological alterations (HYMO alterations) are one of the main pressures causing deviations from 'good ecological status' in EU. In Norway, hydropower regulations are the single most important reason why rivers and lakes are designated as 'heavily modified water bodies' (Vann-Nett 2019). According to statistics available in Vann-Nett (www.vann-nett.no), the national maps-based portal for the registration of WFD-information, there are in total 6426 lake water bodies in Norway, with a surface area of 11 980 km^2. Among these, 1026 lakes are defined as heavily modified water bodies (Table 1.1 and Table 1.2).

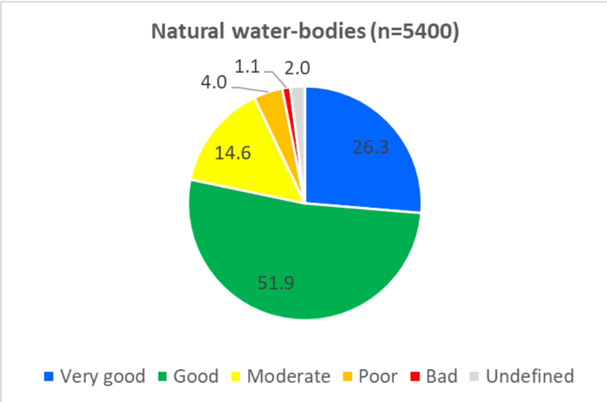
Table 1.1. Overview of all lake natural water bodies and their ecological status and the level of precision in information available for assessing status (Vann-nett 2019).

Status	Number	Percentage	High precision	Medium precision	Low precision
Very good	1421	26.3	35	307	1079
Good	2801	51.9	125	274	2402
Moderate	789	14.6	170	163	456
Poor	218	4.0	80	30	108
Bad	61	1.1	33	10	18
Undefined	110	2.0	0	0	110
All	5400	100.0	443	784	4173

Table 1.2. Overview of all heavily modified lake water bodies and their ecological potential (Vann-nett 2019).

Status	Number	Percentage	High precision	Medium precision	Low precision
Good and above	487	47.5	30	68	389
Moderate	446	43.5	25	124	297
Poor	79	7.7	5	18	56
Bad	9	0.9	1	0	8
Undefined	5	0.5	0	2	3
All	1026	100.0	61	212	753

It is also interesting to read from Table 1.1 and Table 1.2 that the status of a very large share of the lakes water bodies has been assessed with information considered being of low precision, i.e. 77.3 % of the natural water bodies and 73.4 % of the heavily modified lake water bodies.



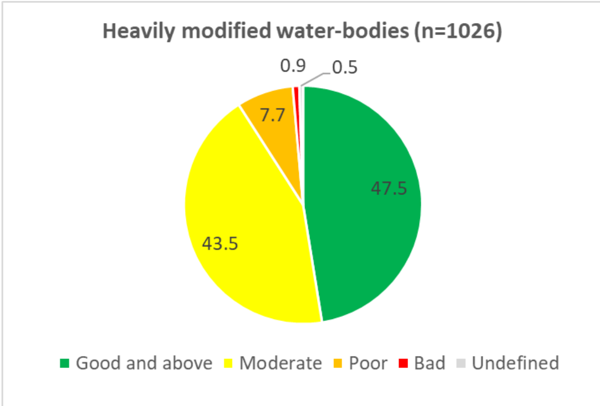


Figure 1.1. Natural lake water bodies and their ecological status (to the left) and heavily modified lake water bodies and their ecological potential (to the right). The graphs show the same data as presented in Table 1.1 and Table 1.2.

Definition of lake, regulated lake and reservoirs:

As the EU WFD does not distinguish between lakes, reservoirs and regulated lakes, but rather uses the terms natural lake water bodies, heavily modified lake water body and artificial water bodies, no distinct definition of lakes, regulated lakes and reservoirs are introduced in this report. The term 'lakes and reservoirs' is usually used in this report or in short only 'lakes', which underlines that the described classification system can be applied to both unregulated lakes as well as lakes regulated for human purposes.

The actual human purpose is neither commented upon in the report. By far, all regulated lakes in Norway are established for the purpose of producing electricity. Outside Norway, other purposes such as irrigation, drinking water supply and flood control are common.

The Norwegian Environment Agency has initiated a process to establish a hydromorphological classification systems for rivers and lakes, which until recently have been missing. In 2018, the first version of a classification system was defined for rivers (Harby et al. 2018) and a similar system for lakes and reservoirs was proposed (Bakken et al. 2018). During the last months, these systems have undergone the first testing, and a report presenting the results from testing the hydromorphological classification system for rivers is in preparation (Harby et al. 2019). The development of a hydromorphological classification system will supplement the ecological and chemical classification systems. The results of a system that contains all aforementioned types of classification will provide a broader picture on the status of the water resources. This report presents the results from testing of the hydromorphological classification developed for lakes and reservoirs and proposes a revised hydromorphological classification system for lakes and reservoirs based on the experiences from testing.

1.2 Aim of the project

The aim of this project has been to test the applicability of the recently published hydromorphological classification system for lakes and reservoirs (Bakken et al. 2018). The project has tested if the use of the current hydromorphological classification is feasible for all lakes and reservoirs in Norway, given the current availability of data, state of modelling tools and monitoring techniques. This is carried out by selecting several case study lakes among lakes included in the ØKOSTOR/ØKOFERSK monitoring programmes (Miljødirektoratet 2019). Based on the outcome of the testing, an updated version of a hydromorphological classification system is proposed.

1.3 Description of the HYMO system to be tested and evaluated

Bakken et al. (2018) proposed in Chapter 8 a hydromorphological classification system for lakes and reservoirs, based on the following principles;

- The classification should follow a three-class system, going from 'Near natural', to 'Slightly to moderately modified' and 'Extensively to severely modified'. The main principle for the classification scheme is natural conditions (reference state) prior to any human interventions and alterations from these reference conditions.
- The hydromorphological quality elements are hydrological change (green in Table 1.3), morphological change (brown in Table 1.3) and barriers/fragmentation (grey in Table 1.3), and the HYMO parameters are grouped according to these quality elements.
- The HYMO parameters are geographical structured according to their location compared to the lake/reservoir to be classified, i.e. 'changes upstream, affecting the lake/reservoir under consideration', 'changes directly at the lake/reservoir under consideration' and 'changes downstream, affecting the lake/reservoir under consideration'.

Table 1.3. Proposed hydromorphological classification system for lakes and reservoirs (from Bakken et al. 2018). The light red cells (beige) in columns 1 and 3 refer to upstream areas. The light green ones show parameters within the assessed lake, parameters with a light blue background consider downstream areas. The colour codes in the column to the very right refer to; green are hydrological alterations; brown are morphological alterations and grey are barriers and fragmentation (continuity). Further details about each parameter (e.g. metrics for calculation and the estimated importance) are given in Bakken et al. (2018).

Area considered	Type of effect	No	Parameter	Qual. elem.
Upstream changes	Changes in upstream areas, which are independent of changes introduced in the assessed lake/reservoir	1.10	Hydrology: Change in annual inflow	
		1.11	Hydrology: Changes in periodicity (inflow)	
		1.12	Change in water temperature of inflowing water	
		1.13	Barriers blocking inflow of sediments	
		1.14	Sediment changes due to upstream barriers	
Flow/volume of water and water level of lake/reservoir (hydrology)	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	
		2.11	Total volume change of lake	
		2.12	Seasonal change: Summer	
		2.13	Seasonal change: Fall	
		2.14	Seasonal change: Winter	
		2.15	Seasonal change: Spring	
		2.16	Short term water level variations (days)	
		2.17	Short term water level variations (weeks)	
		2.18	Annual maximum flood level	
Processes along the shoreline of the lake/reservoir (shoreline morphology)	Factors directly determined by water level changes	2.20	Dewatered areas	
		2.21	Relative lake level fluctuation	
		2.22	Dewatered littoral zone versus total littoral zone (ratio)	
		2.23	Shoreline development (dimensionless number)	
		2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	
		2.25	Riparian zone changes	
		2.26	Erosion introduced by changes in flow pattern/filling/water level variations	
Fragmentation & barriers within 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	
		2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	
Processes within the lake related to substrate of lake & reservoir	Potentially second order effect of water level changes	2.40	Removed or added gravel, rocks, sand and other sediments	
		2.41	Porosity of substrate	
Physical and chemical 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	
		2.51	Water temperature	
		2.52	Ice conditions (surface, shore ice)	
		2.53	Water clarity	
Downstream changes	Independent of changes within assessed lake	3.10	Barrier effects (hindering migration between lake/reservoir and downstream areas)	

Important note on the classification system tested:

The classification system defined in Bakken et al. (2018) uses a three-class system where the three classes are defined as ‘Near natural’, ‘Slightly to moderately modified’ and ‘Severely modified’. The reason for using a three-class system was that it was scientifically difficult to defend a more detailed classification system. The test results presented in Chapter 3 and further discussed and evaluated in Chapter 5 are based on the use of the classification system as it is defined in Bakken et al. (2018), including the use of colour codes and class terms.

The three-class system suffers from a lack of differentiation of the two classes defining better status than ‘Moderately modified’. As such, the proposed revised system (in Chapter 7) follows the standardised five-classes system that is used for the majority of the quality elements. This also makes our proposal more consistent with the other classification systems developed for the EU WFD.

2 Methodology and material

2.1 Criteria for assessment of suitability

The testing of the hydromorphological classification system (Table 1.3) should be evaluated with respect to the following criteria:

- The classification system should include parameters that are considered being important descriptors of hydromorphological alterations
- The parameters should overlap each other only to a limited extent
- The class borders should cover the range of hydromorphological alterations, and the parameters should be reasonably sensitive to hydromorphological changes
- The parameters must be unambiguously defined
- The parameters should have an ecological relevance
- It should be data and/or tools available (today or in the near future) to analyse/calculate the given parameters for a classification
- It should be possible to calculate the parameters with reasonable resources

The parameter set presented in Table 1.3 was developed based on the philosophy that 'all possible hydromorphological changes should be included', ending up with a total of 30 parameters. It was known at that stage that this was a too extensive list, a gross list of parameters, and after testing the 'net list of parameters' should be reduced to around 15 parameters, as the maximum. An ambition for this project was then also to significantly reduce the list of parameters to the most important parameters, containing only parameters that are considered applicable for use.

2.2 Description of case study lakes/reservoirs

The lakes/reservoir included in this test project were first of all selected among lakes included in the national, long-term monitoring programmes ØKOSTOR and ØKOFERSK (Miljødirektoratet 2019). The reason for selecting lakes from these monitoring programmes was to ensure that biological and chemical data was available to support the hydromorphological assessment. Furthermore, lakes were selected within the geographical regions the HYPE model had been configured (Schönfelder et al. 2017; Adera et al. 2018), to guarantee that hydrological information about natural inflow was available. Figure 2.1 and Table 2.1 present the geographical distribution of the lakes and some key statistics about them.

Figure 2.1. Map showing the location of the study lakes used in this project.

Table 2.1. The table presents volume, surface area, upstream catchment area, altitude and regulation height of each of the test lakes. The regulation height corresponds to the highest regulated water level (HRWL) minus the lowest regulated water level (LRWL).

Lake	Volume [mill. m^3]	Surface area [km^2]	Catchment [km^2]	Altitude [masl.]	Regulation height [m]
Røsvatn	2309	218.1	1503	383	11.3
Lundevatn	123	27.5	1900	49	4.5
Øyeren	157	73.1	40436	101	2.44
Møsvatn	1064	79.1	1503	919	18.5
Årdalsvatn	603	7.5	980	2	Unregulated
Byglandsfjord	212	33.7	2806	203	5.0
Selbusjøen	348	57.8	2876	159	6.3
Krøderen	100	43.9	5092	133	2.6
Limingen	490	93.3	674	418	8.7

In the following (Figures 2.2 – 2.6), a map of each test lake and their upstream catchments are presented. Lakes given as 'natural lakes' (in the legends) are lakes that are not regulated. The coordinates are in WGS 84 / UTM zone 33N (EPSG: 32633).

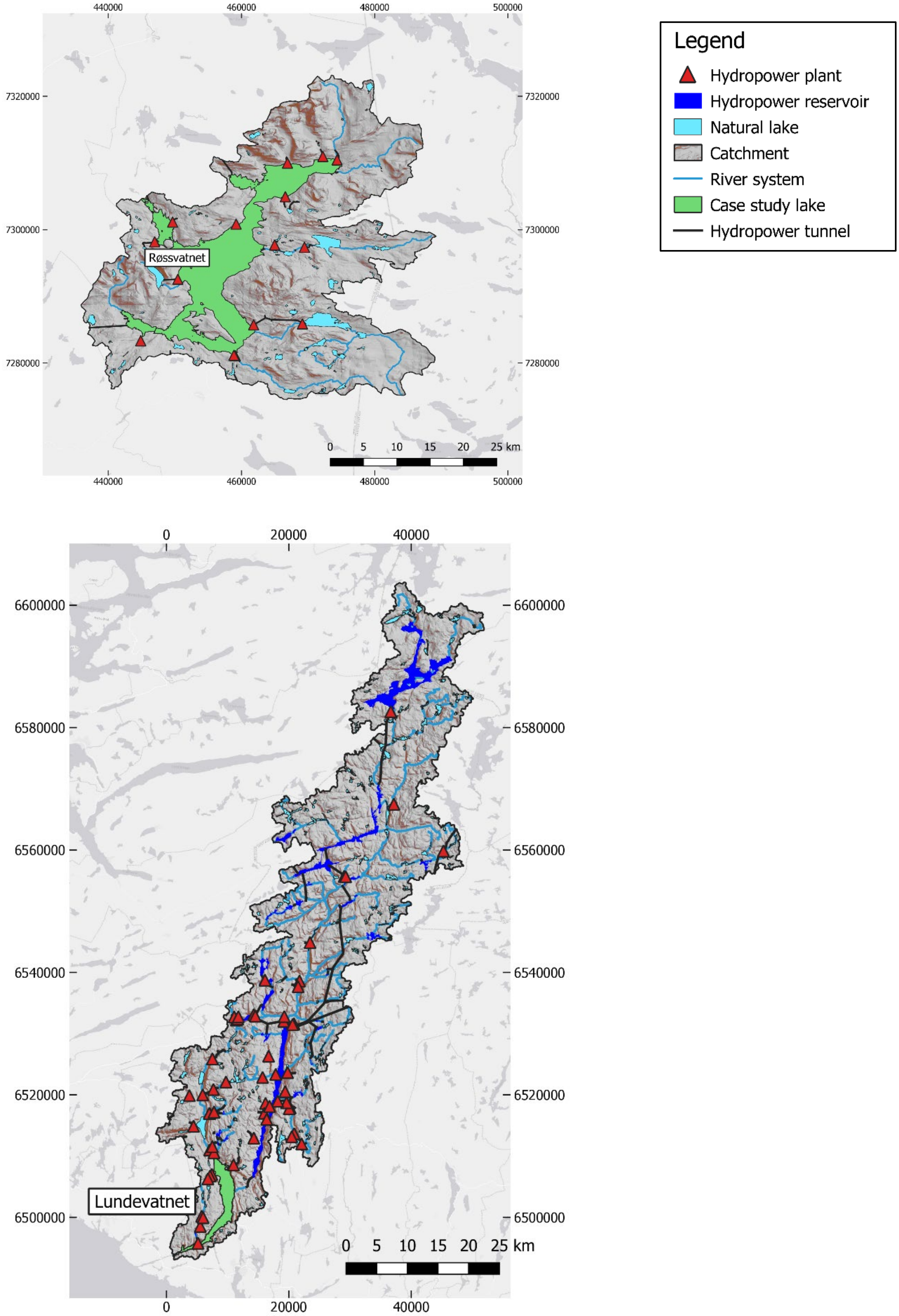


Figure 2.2. Map of Røsvatn (top) and Lundevatn (bottom).

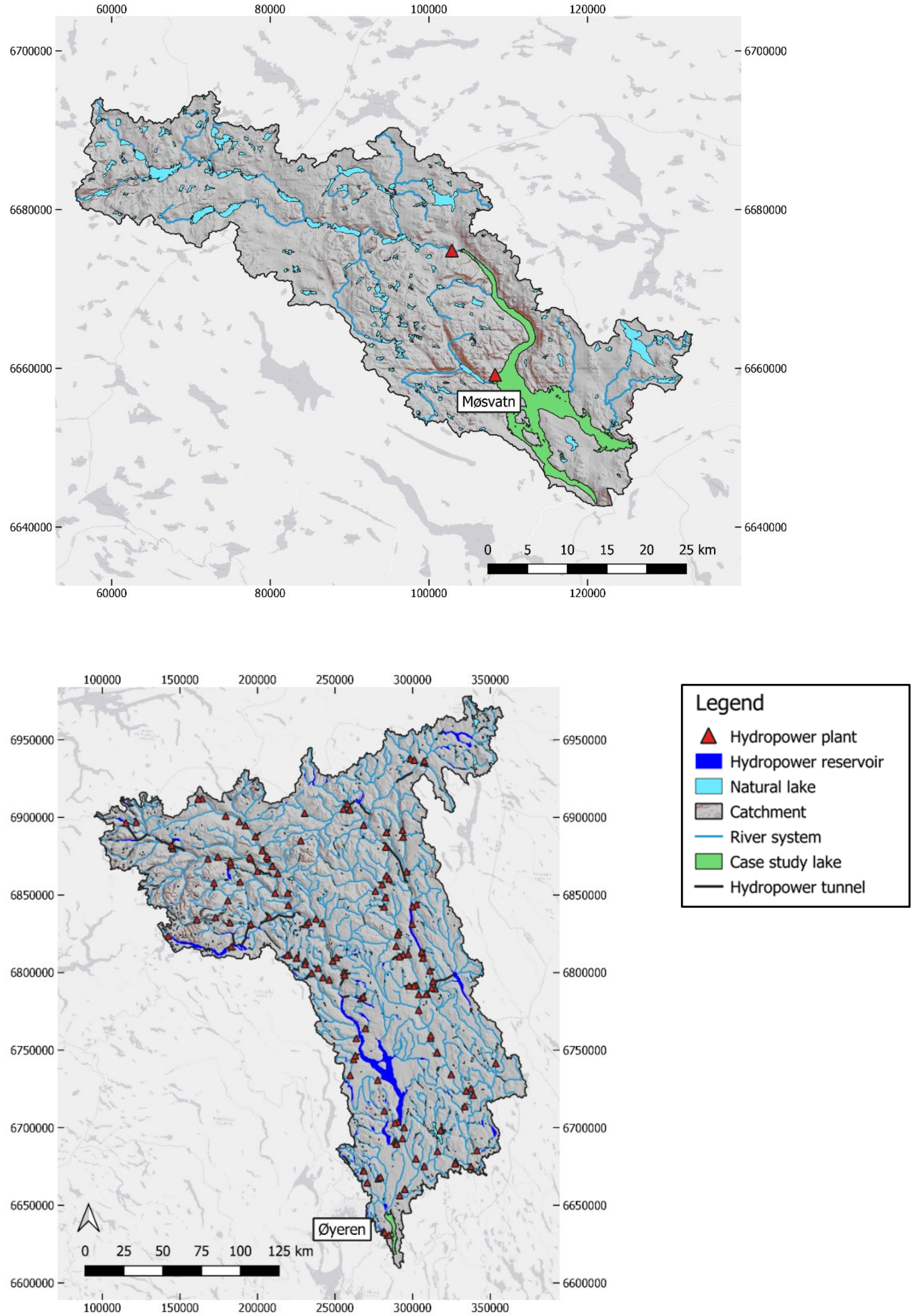


Figure 2.3. Map of Møsvatn (top) and Øyeren (bottom).

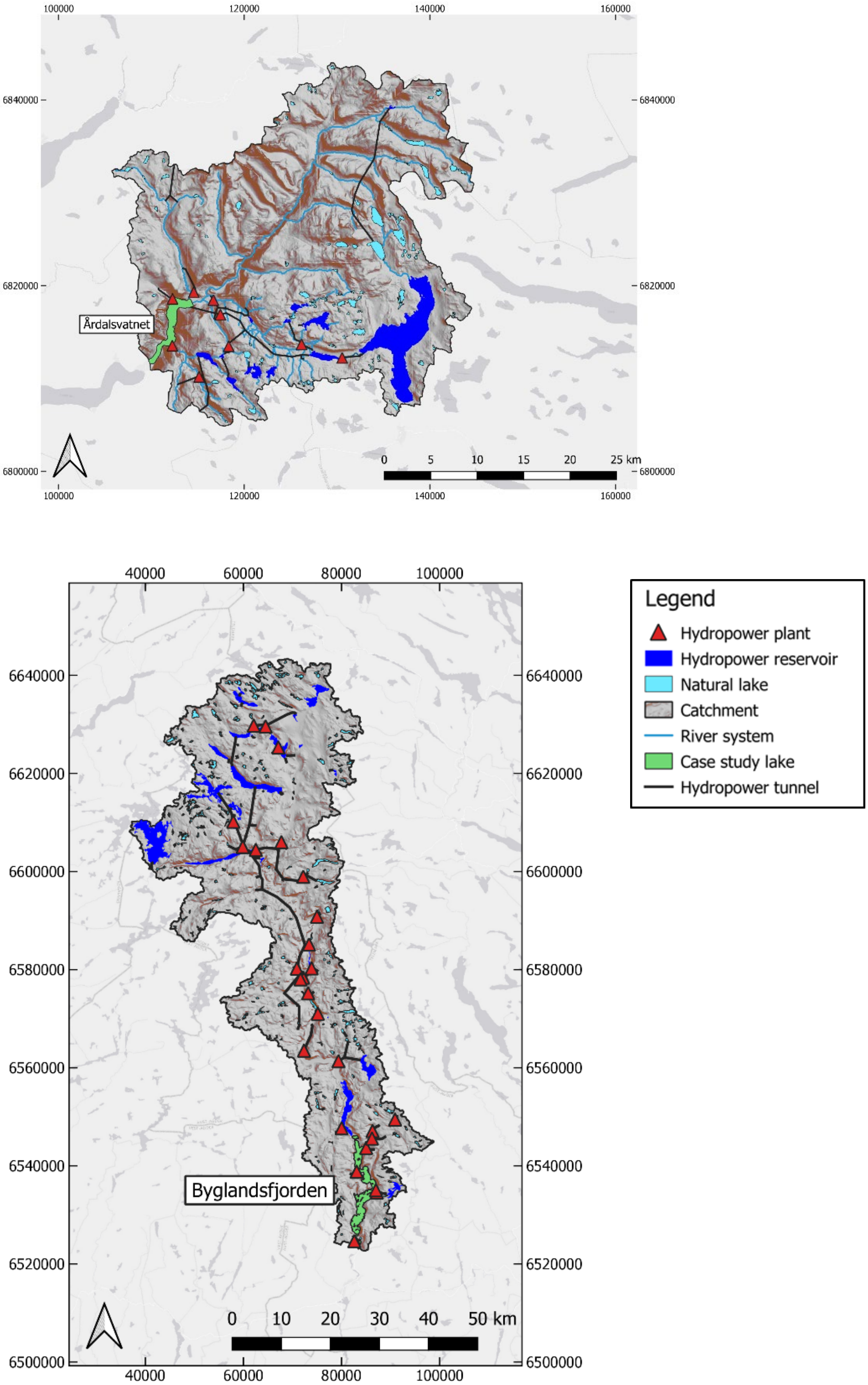


Figure 2.4. Map of Årdalsvatn (top) and Byglandsfjorden (bottom) and their upstream areas.

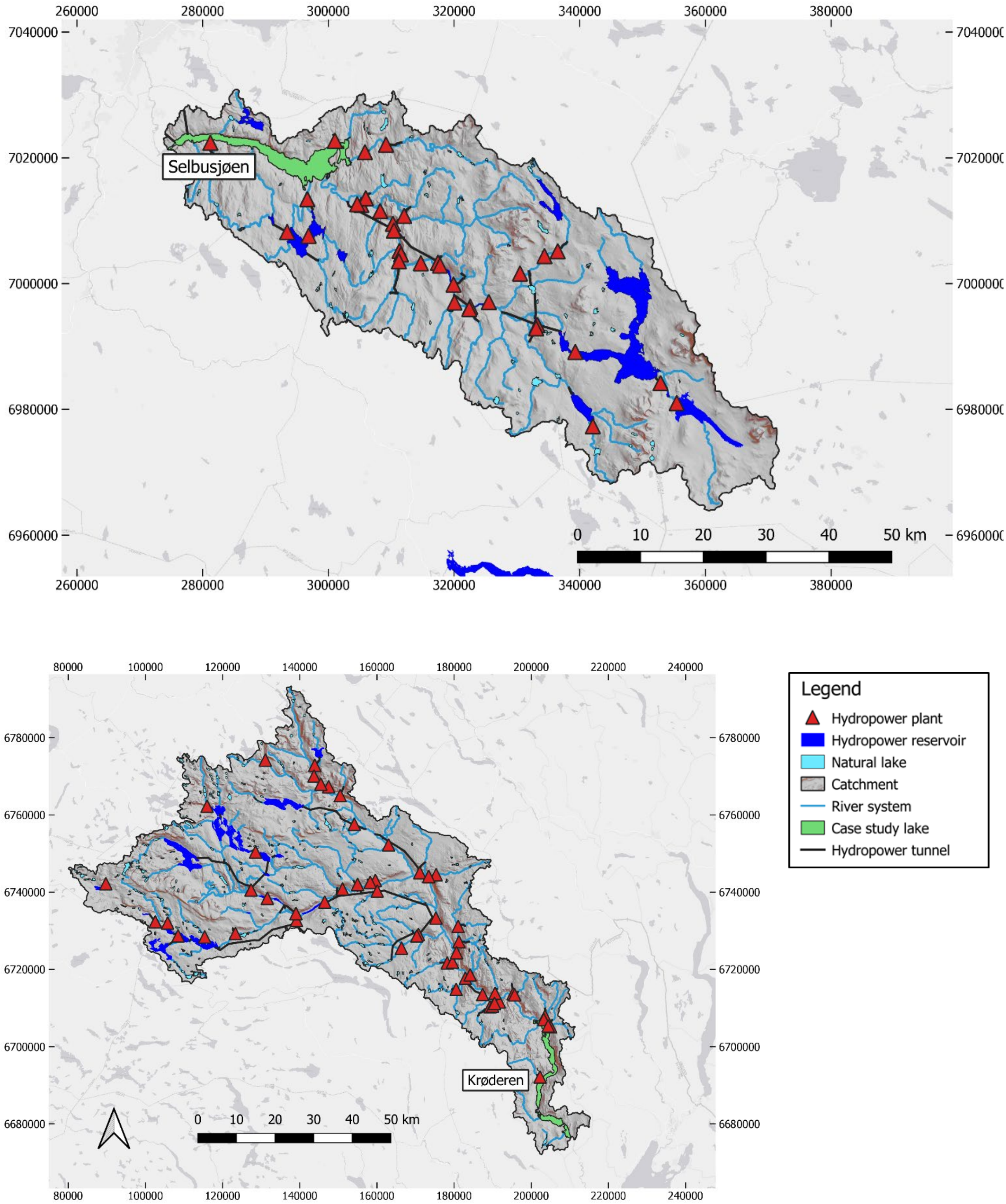


Figure 2.5. Map of Selbusjøen (top) and Krøderen (bottom) and the upstream areas.

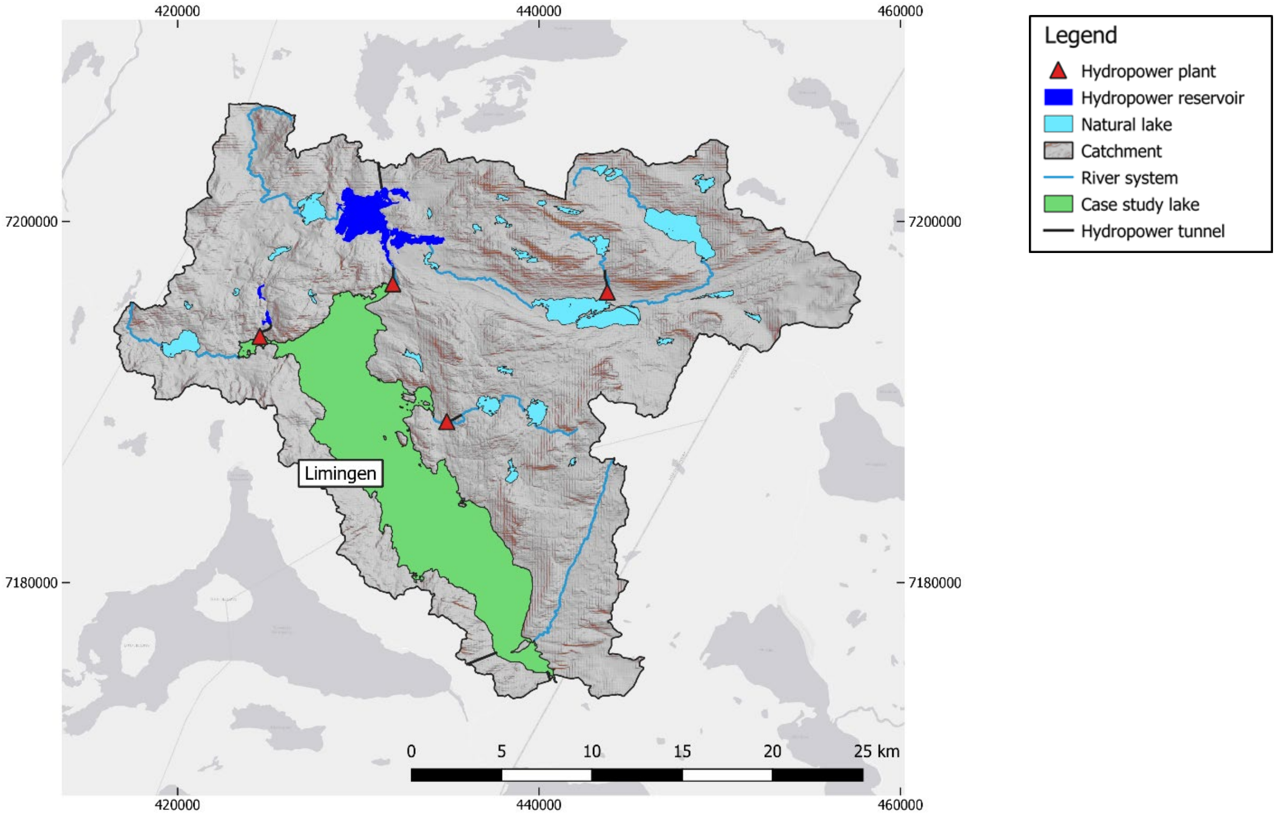


Figure 2.6. Map of Limingen including its catchment area.

2.3 Description of data sources

National databases where used during the project and these data sources are described briefly in the following, as well as the HYPE model (Schönfelder et al. 2017) that was used to simulate hydrological conditions during unregulated state.

Table 2.2. Overview of the main data sources used in the hydromorphological classification of the test lakes.

Data source (host)	Short description	Useful in relation to parameter no.
NVE Atlas (NVE)	This data source map-based information about catchments, rivers, lakes and reservoirs, and hydropower-related constructions and infrastructure (power stations, dams, water transfers, etc.)	1.10 – 1.14, 2.10, 3.10
Hydra II database (NVE)	This database contains historical timeseries of a set of hydrological parameters, including discharge and water levels.	1.10 - 1.12, 2.10 – 2.18, 2.51
NEVINA	NEVINA can be used to calculate catchment areas and catchment characteristics as a set of hydrological indices for user-specified locations.	1.10, 1.14, 2.10 – 2.11, 2.18

Bathymetric maps (NVE)	NVE offers fully digitized and geo-referenced bathymetric data from approximately 360 lakes in Norway in formats allowing further processing in GIS. In addition, scanned paper maps are available maps for some more lakes.	1.13, 2.20 – 2.24, 2.26, 2.30, 2.31, 3.10
Norgeibilder (Norwegian Mapping Authority, NIBIO and the Norwegian Public Roads Administration)	This data source contains present and historical orto photos which is useful for showing natural and human-induced changes in the landscape. Some of the photos date back to 1935.	2.23 – 2.25, 2.30, 2.31, 3.10
Vann-Nett (NEA/NVE)	The web portal Vann-Nett is owned by the Norwegian Environmental Agency (NEA) and NVE and is developed to support the implementation of EU WFD. This data source contains status information about all water bodies in Norway.	Comparison of ecological and HYMO status
Vannmiljo.no (NVE)	This is a map-based data source that holds historical monitoring data from a large number of rivers and lakes. The database is owned by Environmental Agency (Miljødirektoratet) and are together with the regional managers the main users.	2.51, 2.53
HYPE (SINTEF)	HYPE is a process-based semi-distributed rainfall-runoff model which has been developed at SMHI (Swedish Meteorological and Hydrological Institute). 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. We used the regionally calibrated distributed HYPE to generate lake inflow time series and water-level fluctuations for unregulated conditions.	1.10, 1.11, 2.10 – 2.18

More specific references are given directly in the text where relevant.

In Figure 2.7 the use of Norgeibilder is shown, where a photo from 1955 (left side) and the extent of embankment, sand deposition (on beaches) and riparian vegetation can be compared with the present state (right side). Such classification work requires manual assessment. Figure 2.8 shows the results of processing a bathymetric map in GIS.

Figure 2.7. The photos from Norgeibilder show the southern parts of Tunevannet in Østfold in 1955 (left) and today (right). Changes in riparian vegetation and land use changes can be seen especially in the lower right end of the photos.

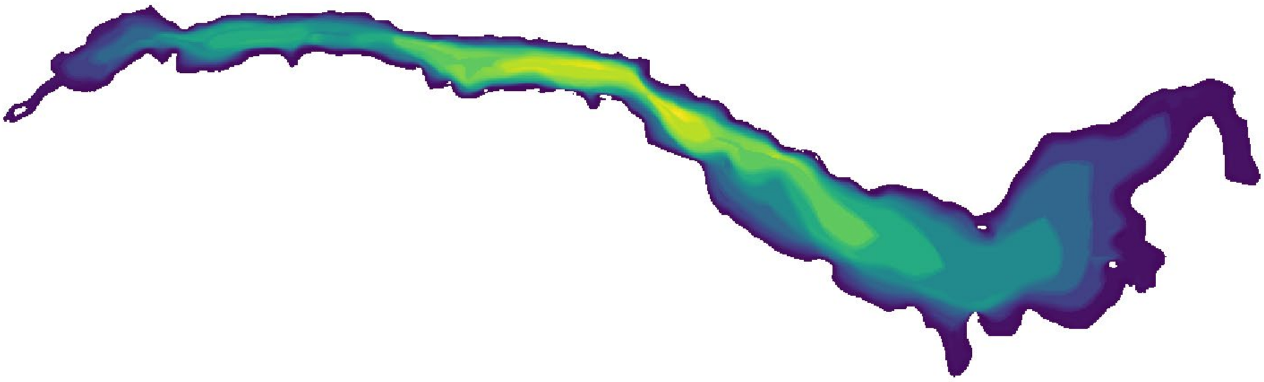


Figure 2.8. The figure shows the bathymetry of Selbusjøen prepared in a GIS-system (QGIS), where the yellow parts are the deeper and dark blue the shallow parts (based on map from NVE's bathymetry database).

3 HYMO classification and evaluation of results

3.1 Summary of results

In Chapter 3.1 the classification values for each parameter and each of the test lakes are presented with their numerical values (where the classification is quantitative) and the classified values given with their class colours (able 3.1). Cases where sufficient data was not available, the missing results are indicated by 'n.a.' and the cells given with grey as their background colour. Overview of parameters that are not calculated for any of the lakes are given in Chapter 3.2.18.

Important note on the classification system tested:

The classification system defined in Bakken et al. (2018) uses a three-class system where the three classes are defined as 'Near natural', 'Slightly to moderately modified' and 'Severely modified'. The reason for using a three-class system was that it was scientifically difficult to defend a more detailed class system. The test results presented in Chapter 3 and further discussed and evaluated in Chapter 5 are based on the use of the classification system as it is defined in Bakken et al. (2018), including the use of colour codes and class terms.

The three-class system suffers from a lack of differentiation of the two classes defining better status than 'Moderately modified'. As such, the proposed revised system (in Chapter 7) follows the standardised five-classes system that is used for the majority of the quality elements. This also makes our proposal more consistent with the other classification systems developed for the EU WFD.

Table 3.1. The table presents the classification results for each parameter and each lake. The colours correspond with the classes (as defined in Bakken et al. 2018), i.e. blue represents 'near natural', yellow is 'Slightly to moderately modified' and red refers to 'Extensively to severely modified'. The grey cells (n.a.) do not include any values as it was not enough data available to use the parameter. The parameter numbers refer to Table 1.3, while the asterisk (*) behind the numbers indicate that the parameters are slightly modified from what is given in Table 1.3. Further description of each parameter is given in Table 1.3 and in Bakken et al. (2018).

Para-meter No.	Byglands-fjorden	Krød-eren	Limingen	Lunde-vatn	Møsvatn	Røsvatn	Selbu-sjøen	Øyeren	Årdals-vatn
1.10*	0	0.1	1.0	65.5	0	0	0	0.05	-8.0
1.13	76.9	70.8	52.8	67.0	0	1.0	70.3	97.0	37.5
2.10	5	2.6	8.7	4.5	18.5	11.3	6.3	2.44	2.4
2.11	-22.4	n. a.	n. a.	n. a.	43.4	n. a.	-28.0	18.5	0.3
2.12*	-17	n. a.	n. a.	> 20	9	n. a.	9	1	-6
2.13*	57	n. a.	n. a.	> 20	45	n. a.	76	-4	-21
2.14*	0.4	n. a.	n. a	> 30	5.0	n. a.	-1.6	1.0	0.3
2.15*	0.0	n. a.	n. a.	> 30	4.9	n. a.	-1.3	-1.2	-0.3
2.16	0.1	n. a.	n. a.	0.2	0.16	n. a.	0.1	0.1	0.17
2.17	0.6	n. a.	n. a.	0.4	1.1	n. a.	0.7	0.4	0.5
2.20	9.8	n. a.	n. a.	n. a.	50.1	n. a.	7.5	33.0	2.5
2.21	8.8	8.1	10.0	2.6	92.5	17.1	9.0	17.4	3.8
2.22	81.6	43.3	96.7	64.3	284.8	86.9	136.8	113.7	44.4
2.23	-3.0	n. a.	n. a.	n. a.	13.1	n. a.	-10.8	-1.6	-0.5
2.24	31.8	18.1	3.0	20.5	4.3	7.4	18.1	6.1	13.4
2.25	22.8	24.48	3.0	26.8	2.4	8.8	12.1	6.0	21.0
2.26*	2	n. a.	n. a.	2	3	n. a.	3	3	3
2.30	n. a.	n. a.	n. a.	n. a.	1	n. a.	n. a.	n. a.	3
2.31	3	n. a.	n. a.	n. a.	1	n. a.	3	2	3
3.10	100	92.6	100	100	100	100	87.9	26.3	0

The numbers given in Table 3.1 are mostly calculated based on the data sources given in Table 2.2. A more detailed elaboration of each of the parameters are given in Chapter 3.2. The parameters are not given any weight based on assumed importance or any other criteria. This topic is further discussed in Chapter 3.3.

3.2 Discussion of the results for each parameter

3.2.1 Change in annual inflow (P 1.10)

Parameter 1.10 is used to classify the change in annual inflow. The metrics and the boundaries of this parameter were changed during testing. The assumption is that the annual inflow changes only if water is transferred between catchments due to regulations. The sub-catchment area of each intake point, which transfers water between catchments, is calculated. All of these sub-catchment areas are correlated to the whole catchment area. By using the sub-catchment size, it is assumed that every water transfer is proportional to its catchment size. The transferred area is calculated as:

$$A_T = \frac{\sum_{i=1}^{n} A_{Ii} - \sum_{i=1}^{n} A_{Oi}}{A_C} \cdot 100$$

A_T: transferred catchment area [%]

A_I: sub-catchment area where water is transferred into the actual catchment [km^2]

A_O: sub-catchment area where water is transferred out of the actual catchment [km^2]

A_C: original catchment area of the lake [km^2]

The transferred catchment area is calculated as the sum of areas where water is transferred into the catchment minus the areas where water is taken out divided by the total catchment area. Thus, a positive result means that there is more water coming in than before regulation. In the case of Årdalsvatn, the transferred area is calculated as described in:

$$A_T = \frac{\sum_{i=1}^{n} A_I - \sum_{i=1}^{n} A_O}{A_C} \cdot 100 = \frac{0-(15.21+25.21+12.89+25.43)km^2}{979.6\ km^2} \cdot 100 = -8{,}0\ \%$$

This negative result means that there is water transported out of the catchment area. The area where the water is diverted away from the lake, is 8.0 % of the original lake catchment. A positive result means that there is water transferred into the catchment. The result from the lake Lundevatn is 65.5 %, thus there is water coming from an area with a size equal to 65.5 % of Lundevatn's catchment area. The lowest possible value is 0 %, which means there is no water transfer between different catchment areas. A change below 20 % is classified as near natural and above 50 % it is classified as severely modified.

The parameter is calculated based on the area of the catchments that are transferred in or out of the catchment of the lake to be classified. This can lead to a significant under- or over-estimation in those cases water from large sub-basins are transferred. Lundevatn's catchment is affected by five sub-catchment areas, where water is transferred from or into. Two of this five sub-catchment areas are as big as 60 % of the total catchment size of Lundevatn, and the calculation of this parameter is then sensitive to errors. A fairly simple check if the catchment size is a good proxy for water volumes transferred can be to compare specific runoff coefficients. Another aspect to consider is the transfer capacities related to floods. An over-estimation can happen in cases where for instance floods are not fully transferred into Lundevatn, due to limitations in capacities. Except Lundevatn, all the other lakes end up in the category 'near natural', i.e. small changes in annual inflow compared to the situation before regulation.

3.2.2 Barriers blocking inflow of sediments (P 1.13)[1]

The idea of this parameter is to assess if there are man-made structures upstream of the lake under consideration that will block upstream supply of sediments. In order to do the classification, an investigation of dams in the upstream area is performed. Dams are barriers blocking the connection between habitats, whereby migration is blocked as well. It is assumed that every dam is a barrier, even though there might be for example a fish pass which allows migration. The upstream river is also checked for other potential blockages, such as water gates. The sub-catchment area of each dam is calculated and then the sum of these areas is compared to the whole catchment size. The parameter is calculated as follows:

$$\mathrm{B} = \frac{\sum_{i=1}^{n} A_{Di}}{A_C} \cdot 100$$

B: Percentage of area affected by barriers [%]

A_D: Sub-catchment area of upstream barriers [km^2]

A_C: Catchment area of the lake [km^2]

The result represents the percentage of the catchment area which is affected by upstream barriers. The larger the result the larger the affected area. Below 10 % the classification is near natural and above 50 % it is severely modified. The lowest score is reached by Møsvatn. It has no upstream barriers, so the result is 0 %. Byglandsfjord has the highest score of 76.9 %, which means 76.9 % of the upstream area is affected by barriers.

Øyeren has the highest score (97 %) and the second highest is Byglandsfjord with 76.9 %. The high score from Øyeren indicates that there are either a lot of dams covering the entire catchment area of Øyeren or one dam which is close to the lake. There is one dam close to the inlet of Øyeren which (theoretically) blocks the inflow of sediments from a large upstream catchment area. We must, however, underline, that these results are theoretical, as there are several barriers upstream of Øyeren that may hold back sediments. It may be necessary to conduct more detailed investigations to verify this parameter

If a national 'barrier database' enabling rapid assessment of the changes migration barriers could be established this parameter could be kept in the classification system. If not, it is recommended to take it out as the results can be misleading. Please note that this parameter has been changed and simplified in the proposed new classification system.

3.2.3 Water level changes (P 2.10)

This parameter is calculated as the difference between the highest and the lowest regulated water level (HRWL – LRWL), and data that easily can be obtained for all reservoirs. Data can be taken from NVE Atlas and is a very simple parameter to calculate for regulated lakes. Simply using HRWL and LRWL can over-estimate the changes as these legal limits are the maximum and minimum water levels and we do not know if the regulation is fully utilised by the hydropower companies. In some cases, these limits are violated and

[1] The description of the rationale for this parameter should be changed. After discussions in workshops, the project group recommends that the focus should be on how barriers alter processes related to sediment transport. As this will not change the calculated results, the test results are kept in the report as they were calculated.

the actual difference between the highest and lowest water level may be larger than the legal limits, for instance due to severe floods or civil works at the dam.

Unregulated lakes do not have regulated water levels. In such cases the minimum and maximum water levels are simply taken from monitored or modelled data, i.e. the natural fluctuation of a lake. The classification system defines water level variation smaller than 3m to be classified as near natural and greater than 10 m as severely modified. Årdalsvatn, which is the only unregulated lake, has the lowest water level change with 2.37 m, while the water level changes in Møsvatn is 18.5 m. The results for this parameter show a nice spread with three lakes classified as near natural, three as slightly to moderately modified and two as severely modified (Møsvatn and Røsvatn).

As water level changes in regulated lakes are not calculated based on the conditions prior to the regulation, but rather how it is regulated, this parameter value must be seen as a parameter that describes the severity of the regulation.

3.2.4 Total volume change of lake (P 2.11)

This parameter is calculated the following way:

$$V_C = \frac{V_A - V_B}{V_B} \cdot 100$$

V_C: total volume change [%]

V_B: Volume before regulation [million m^3]

V_A: Volume after regulation at full supply level [million m^3]

Thus, it is the ratio of the difference in present volume compared to the volume before regulation, which represents the reference condition. The calculation should be based on the total volume under both conditions (i.e. not only active volume after regulation). A negative result means that the water level after regulation is in average lower than before regulation. Using Møsvatn as an example, the total volume change is:

$$V_C = \frac{V_A - V_B}{V_B} \cdot 100 = \frac{(656.9 - 457.9)\ mill.m^3}{457.9\ mill.m^3} \cdot 100 = 43.4\ \%$$

This means that the volume of Møsvatn is increased by 43.4 % compared to the volume before regulation (see Figure 3.1). A change below 10 % is evaluated as near natural and above 30 % it is evaluated as severely modified. Møsvatn has the largest change in volume with 43.4 % and Årdalsvatn has the smallest change with 0.3 %.

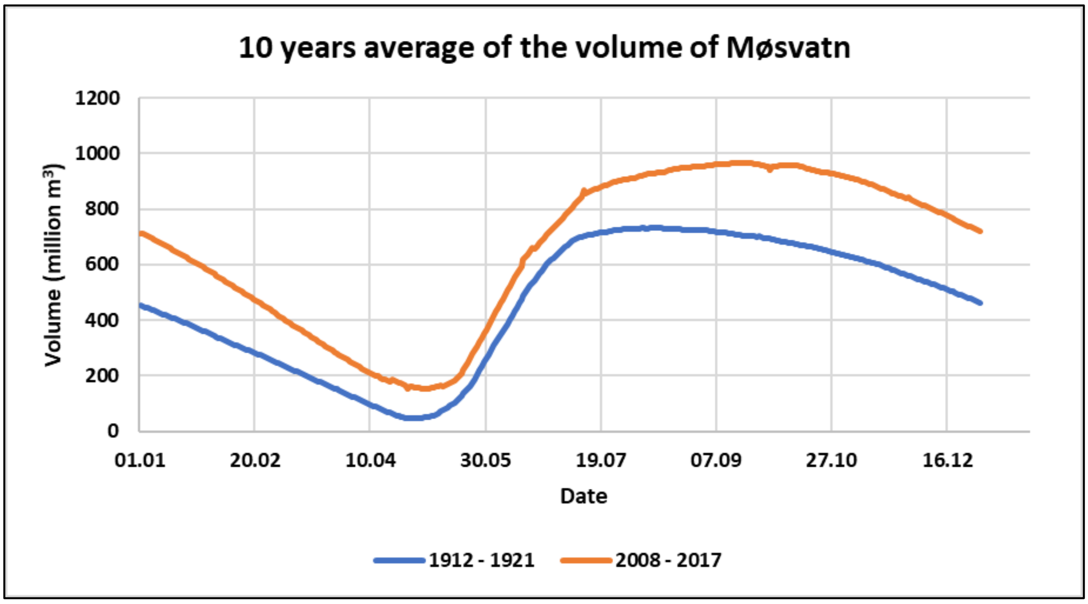


Figure 3.1. Calculated time series of 10-year average volumes from Møsvatn, comparing a smaller regulation (1912-1921) with the period with the present regulation (2008-2017).

It should be noted that the variation in volumes of Møsvatn in the period 1912-1921 is not from a completely unregulated situation, as it was a smaller regulation also in this period, i.e. that the graphs compare a small regulation (1912-1921) compared to the present situation (2008-2017). This can also be seen on the water level curves (Figure 3.4). Results from Selbusjøen are presented in Figure 3.2, showing that average volume of water stored in the lake has decreased after regulation. This is due to upstream regulation and the need to secure the areas around the lake from flooding, which was a regular problem before regulation. Modifications of outlet might also affect the flood risks around lakes.

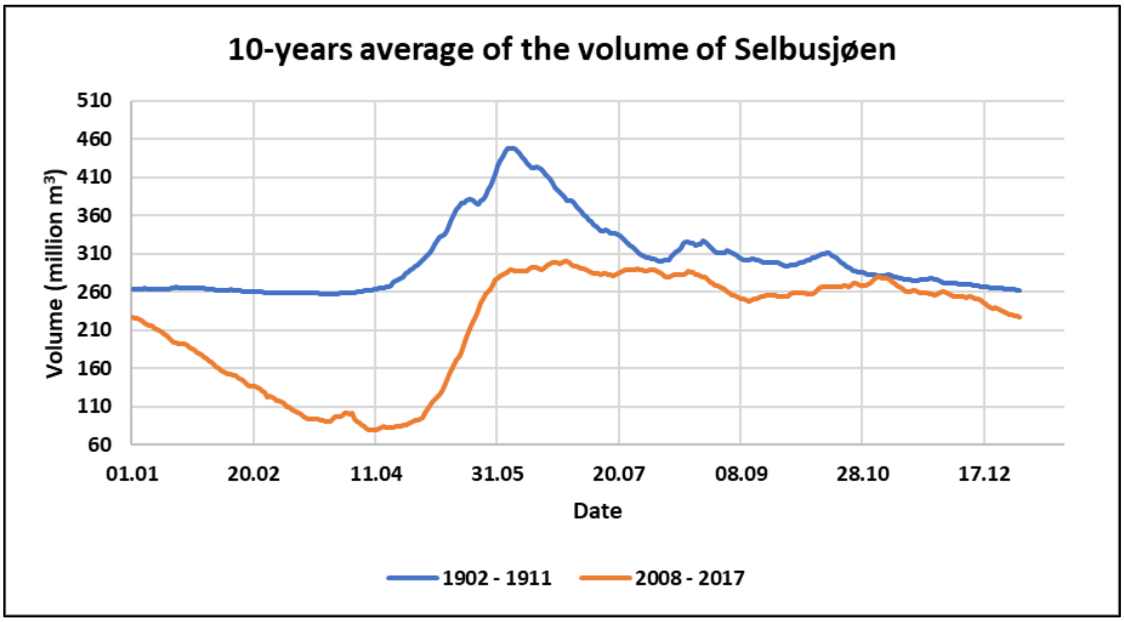


Figure 3.2. Volume time series from Selbusjøen as a 10-year average from before (blue line) and after (orange line) regulation.

The total volume change is a parameter which was easy and quick to calculate, if t time series of volume are available. If time series of volume are not available, time series of volume can be calculated using bathymetry and water level time series. Each cell of the bathymetry grid stores information about the depth and the cell size. To calculate the volume, the cell size has to be multiplied with its depth for every cell which is lower than or equal to the given water level for each time step.

The values used for classification of parameter 2.11 *Total volume change*, and for other hydrological parameters (2.11 – 2.17) were 10-years averages. The first 10 years of the available timeseries represent the situation before regulation and the last 10 years after regulation. We also tested using 5-year-average and 20-year-average data. The 5-year-average showed strong fluctuations depending on the chosen time frame and the sample size was considered too small. It was difficult to find 20 continuous and complete measured years from before regulation, therefore 10 years seemed an appropriate sample length.

3.2.5 Seasonal change in date filling of filling and emptying (P 2.12 – 2.13)

The parameters 2.12 – 2.15 (Seasonal changes) were modified as they appeared difficult to apply as originally defined (see e.g. Figure 3.3). The reason is that establishment of a reservoir often will change the water level in a way that the absolute values are not directly comparable anymore. The new parameters are change in date of filling (2.12) and change in date of emptying (2.13). In these parameters the date when the lake starts to fill (or empty) before regulation is compared to the corresponding date after regulation. The result is a number of days between the start of filling and the start of emptying, respectively, i.e. a shift in the timing emptying and filling.

A change that is less than 10 days is classified as near natural and a change longer than 20 days is classified as severely modified. This applies to both parameters 2.12 and 2.13. The smallest possible result is 0 days, which means no change. The largest shift has Selbusjøen, where the start of emptying (parameter 2.13) happens 76 days later after regulation compared to before regulation. The smallest difference in days occurs in Øyeren, where the filling date is shifted one day. For all lakes the date of emptying has shifted more than the date of filling. Parameter 2.12 can be sensitive to changes in climate as climate change might imply that melting starts earlier, giving an earlier filling of the lake.

To find the date when the filling and emptying starts, graphs with water level series were used. Figure 3.3 shows the water level series of Årdalsvatn before and after regulation, including the start of filling before (pink line) and after (pink dashed line) regulation. For Årdalsvatn the starting date of filling before regulation is 27.04, and the starting date after regulation is 21.04. Thus, the timing has shifted 6 days, which indicates a near natural classification (see parameter 2.12, Table 3.1). The start of emptying before regulation is 02.07 and the start after regulation is 10.06. Thus, there is a 22 days shift, which then classify this parameter for Årdalsvatn to severely modified. The graph also shows that the water level of Årdalsvatn in winter has changed slightly since regulation. The difference in average water level in winter is approximately 0.5 m (Figure 3.3).

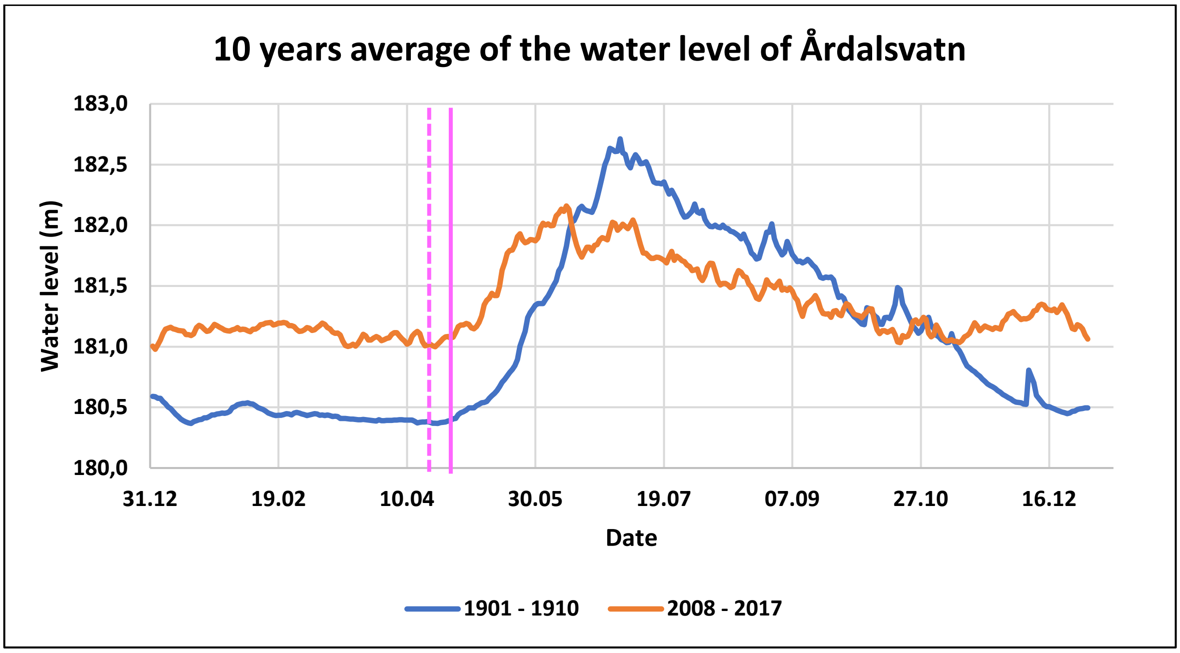


Figure 3.3. Water level time series of Årdalsvatn as a 10-years average before and after regulation, where the start of the filling is indicated for both situations.

It is also, as expected, a very clear correlation between the dynamics of water level variation and the changes in volume, as it appears to increase and decrease at the same date. This might appear as obvious, but the reason why this is mentioned, is that it has been discovered several inconsistencies in data during the project that needs manual work, so detailed checking of data must be accounted for before calculating the classification values. This topic is also handled in Chapter 5.3.

What also stood out when comparing the results from 2.12 and 2.13 were the results from Byglandsfjord. The decline of the volume of Byglandsfjorden (Figure 5.6, left part) in the year 2000 influences the classified values, because it is based on the average from 2008 to 2017. The calculated result of the total change in volume is -22,4 %, which means slightly to moderately modified. If the total change in volume is calculated based on the years 1990 to 1999, the result is 7.8 %, i.e. shifting from slightly to moderately modified to near natural. As it is not clear what happened from 1999 to 2000, it is difficult to say which result is correct. The results from the period 2008-2017 is used for combining the parameters, but the certainty is lowered. Usually, the total change in volume has a certainty of 3, which is the highest certainty, but in this case, it is reduced to 1, the lowest certainty.

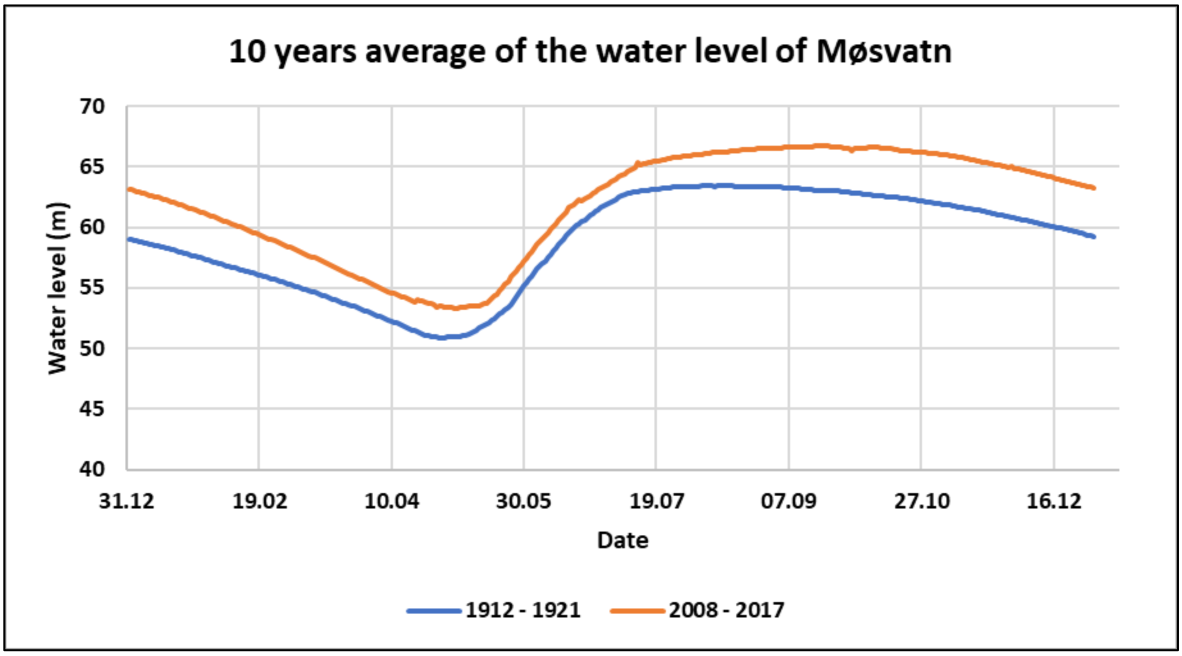


Figure 3.4. Water level time series of Møsvatn as an average of 10 years from before and after regulation. The situation 'before regulation' is not without any regulation, as the lake was regulated in the period 1912-1921, but later further extended.

The shape and behaviour of the water level from before regulation are similar to after regulation, and the water level variations from 'before regulation' are much larger than expected from an unregulated lake. The reason is that Møsvatn was regulated also in the period 1912-1921, but further extended later. The first concessions (issues in 1903 and 1908) gave a 14.5 meters regulation height, and in 1942 this was extended 4 meters to 18.5 meters. Thus, the actual operation start was before the water level measurement and thereby affect the water level series denoted as 'before regulation' (1912-1921).

In this case the comparison is not between before and after regulation, but rather a milder regulation compared to the present regulation. The water level fluctuation from 'before regulation' is too high compared to expected during the unregulated state, but rather follows the shape of the present regulation with smaller oscillations. Thereby, the actual changes from before to after regulation are probably underestimated as the natural water level would have lower fluctuations than seen in Figure 3.4 and a larger difference to the water level after regulation. This example shows that hydropower plants, which are further downstream, can have a strong impact, and each individual case must be handled with great care. Therefore, it is important not to check only the information about the operation start on the website NVE Atlas, but also the water level time series. If there is found an unusual behaviour, further data sources should be checked. The water level is the basis for several parameters, which means several parameters could be affected by this underestimation, such as the change in filling and emptying date (Parameter 2.12 and 2.13).

Figure 3.5 shows the average water level series of Byglandsfjord from before and after regulation, and the period between filling and emptying. The period is not only shifted in one direction, but extended in both directions. The extension in both directions may have different effects on the lake and the ecosystem than an extension in only one direction. The modified parameters take only into account the number of shifted days and not which direction it might be shifted. It should be noted that this result is based on data from the time period 2008-2017 to represent the present situation (see also Chapter 5.3 on problems with the data in Byglandsfjorden).

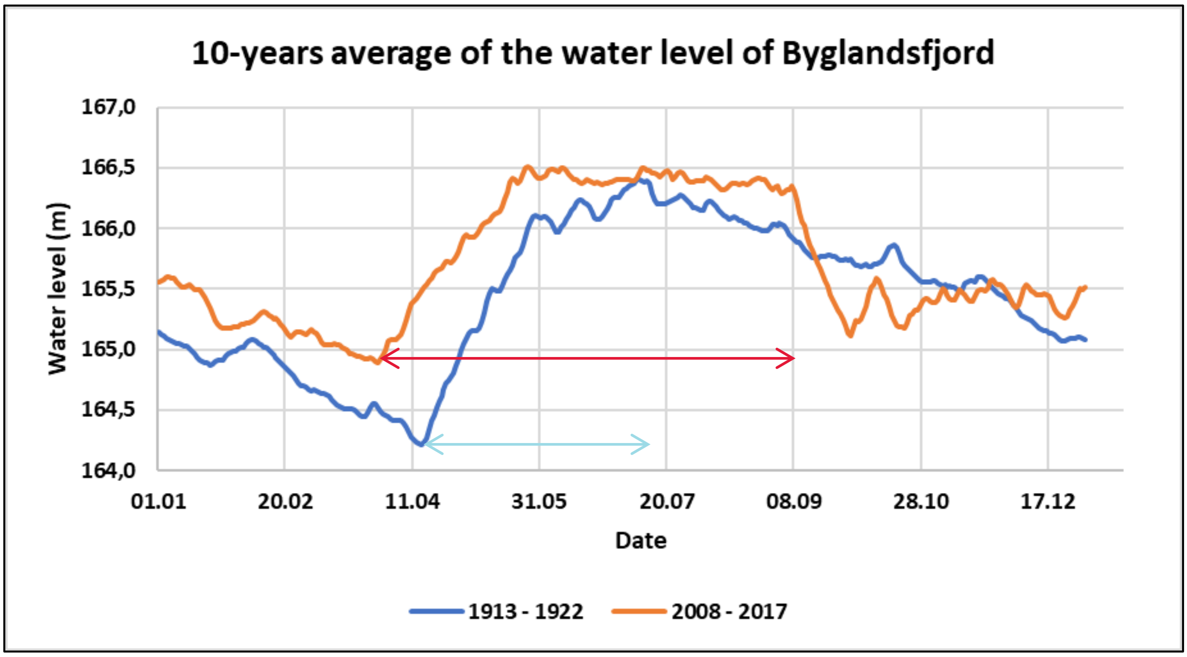


Figure 3.5. Average water level time series of Byglandsfjord showing the period between filling and emptying from before (blue arrow) and after regulation (orange arrow).

3.2.6 Seasonal change in water levels of filling and emptying (P 2.14 – 2.15)

Parameters 2.14 and 2.15, describing the *change in water level at the filling date* and *at the emptying date* respectively, are also modifications of the original parameters. Using Årdalsvatn as an example; before regulation the lake starts filling at 27.04 and after regulation at 21.04. Thus, parameter 2.14 is calculated as the relative deviation between the water level at 27th of April and 21st of April. The water level change at the filling date of Årdalsvatn is 0.3 % of the maximum depth. Parameter 2.15 is calculated the same way, but by using the water level at the emptying date instead. For both these parameters (2.14 and 2.15) a change smaller 10 % is evaluated as near natural and a change larger than 30 % is evaluated as severely modified. Møsvatn has the largest water level change at both the filling (5 %) and emptying date (4.9 %)

Figure 3.6 presents the average water level series of Øyeren from before (blue line) and after (orange line) regulation. It shows that the water level variations after regulation is smaller than before regulation, which is due to the need of flood control of the densely populated areas around the lake, and to a less extent the power production downstream of the lake.

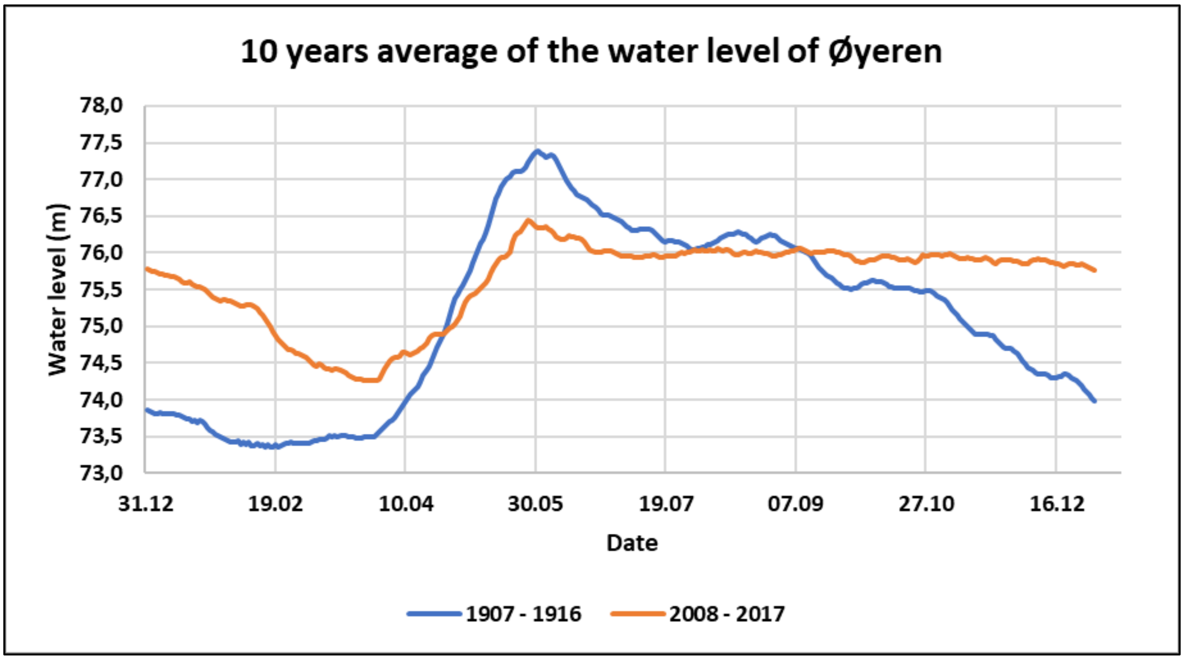


Figure 3.6. Water level time series of Øyeren as an average of 10 years from before and after regulation.

The water level series of Møsvatn shows a different picture as the regulated water level is constantly above the water level as monitored during the period 1912-1921. The reason is probably the effect of increasing the height of the dam to increase the volume of the reservoir and gaining more head for power production. It should be noted that the graph from the period 1912-1921 also includes the effect of a regulation, but a smaller regulation and lower dam than the present regulation.

When looking at the parameters 2.14 and 2.15 in Table 3.1, all lakes except Lundevatn are classified as near natural. Lundevatn (Figure 3.7) is an exception because it does not follow natural filling or emptying. After regulation the water level is relatively stable and fluctuates less (Figure 3.7). According to the definition of these parameters, the water level after regulation is still in a near natural status compared to the water level before regulation even though the filling and emptying is shifted (parameter 2.12 and 2.13). Byglandsfjord for example, is classified as slightly to moderately modified for parameter 2.12 and severely modified for 2.13 but has one of the best scores for 2.14 and 2.15, which is 0.4 % and 0 %.

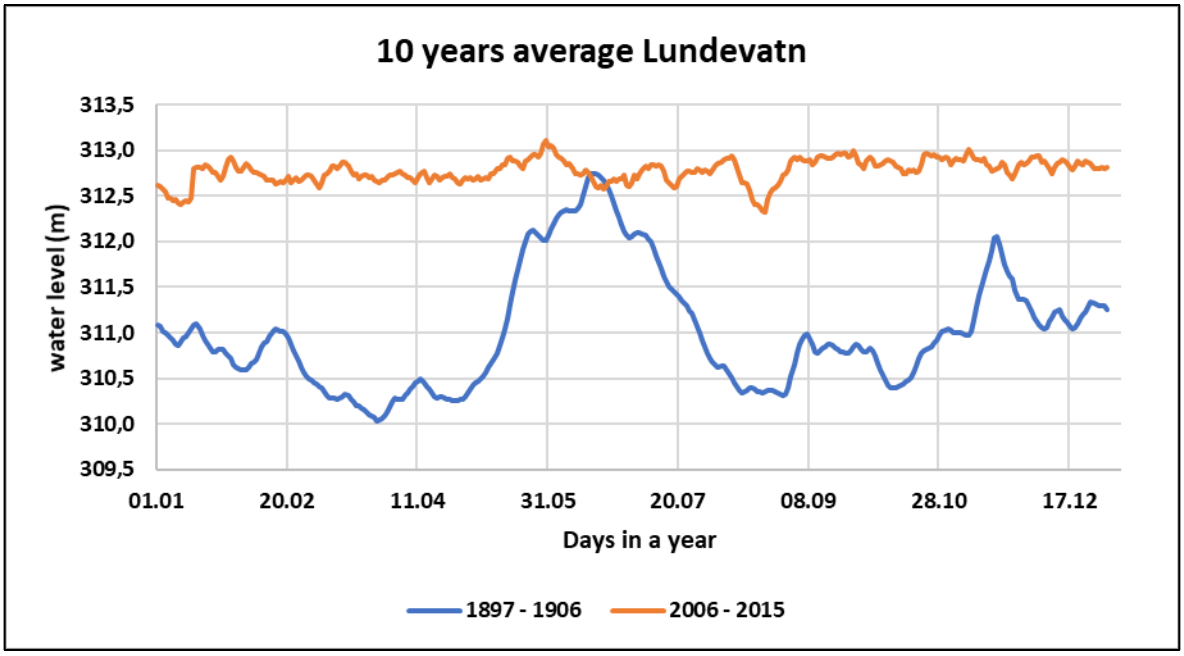


Figure 3.7. Water level series from Lundevatn as 10-years average from before (blue line) and after (orange line) regulation.

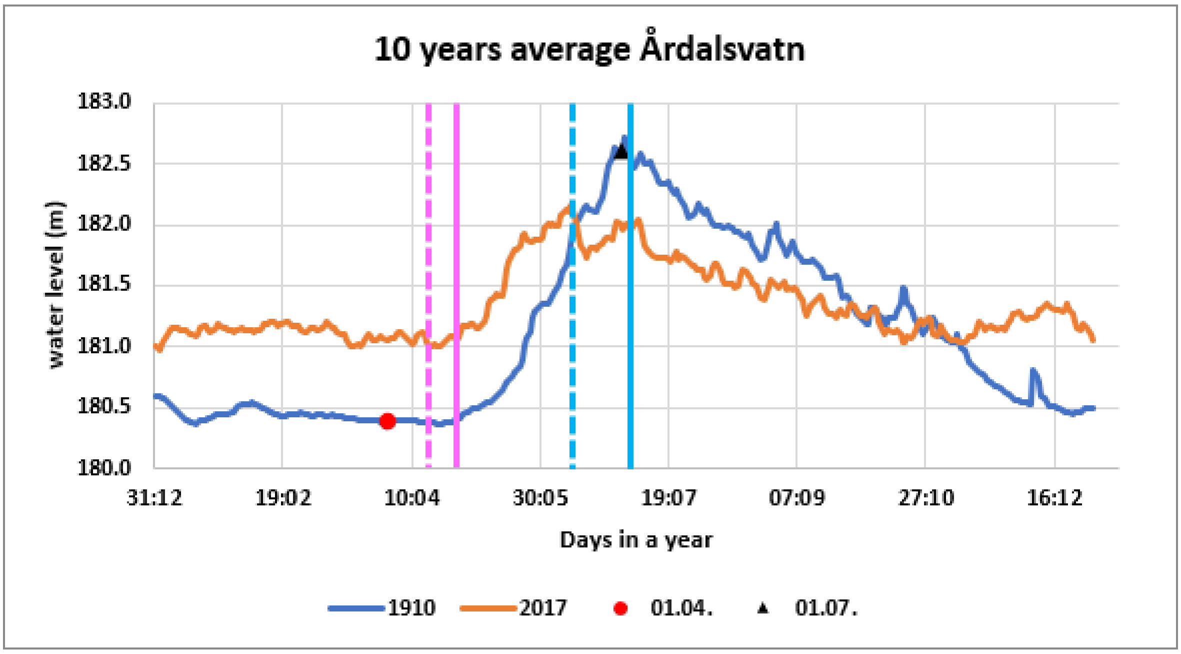


Figure 3.8. Water level series from Årdalsvatn from before (blue line) and after (orange line) regulation. The pink solid line shows the start of filling before regulation and the pink dashed line after regulation. The blue solid line shows the start of emptying before regulation and the blue dashed line after regulation. The red and black dots indicate the start of April and July, respectively.

In the proposed system, each season is represented by a benchmark date. The goal is to show if the timing of filling and emptying has changed from before to after regulation, which is not necessarily demonstrated by the usage of these seasonal parameters. In the case of Årdalsvatn (Figure 3.8), both the beginning of filling and emptying are shifted, but can hardly be related to specific seasons, as proposed in the original classification system (see Table 1.3). For this reason, it is suggested to have two parameters representing the filling and emptying, respectively, and two parameters representing the corresponding water level change. The start date of filling needs to be found and afterwards it is possible to count the days between the start before and after regulation. This should also be done for the start date of emptying. The water level at the filling date could be described as the ratio of the water level at the filling date after regulation to the water level at the filling date before regulation. This calculation applies to the water level at the starting date of emptying as well.

For the water level change, the relative deviation should be calculated as follows:

$$water\ level\ change = \frac{(h_a - h_b)}{h_b} * 100$$

h_b: water level at the start of filling/emptying before regulation

h_a: water level at the start of filling/emptying after regulation

3.2.7 Short term water level variations (days) (P 2.16)

Parameter 2.16 is included in the classification system to capture possible hydrological alterations related to short-term fluctuations in water level (hydropeaking) and operations between days. Rapid and frequent variations in water level will most likely affect both the ecosystem directly and other physical processes such as erosion along the shoreline. This parameter shall be calculated from the 90th-percentile of the daily water level change in a year, in order to pick out one of the extremes, but not the very most extreme (or outliers). Thus, the absolute value of the water level change from day to day is calculated and then the 90-percentile is taken. By using absolute values, it is assumed that it does not matter whether the water level is increasing or decreasing, and that the effects of are similar. Values below 0.5 m mean near natural and above 1 m imply severely modified. It stands out that all results are in the category near natural, which is probably due to the large surface area of our test cases. The highest short-term daily variation was in Lundevatn with 0.21 m (per day).

It is difficult to judge if the fact that close to all lakes ends up as 'near natural' is due to the fact that the class borders are not sufficiently strict or if it reflects that hydropower operations or hydropeaking only can have a small impact on short-term water level fluctuations in large reservoirs. More data on water level variations from other types of lakes would provide a better overview of the range of variation in lakes and provide a better basis for setting reasonable class borders for these two parameters. It should also be considered if the class borders should be related to specific periods of the year as water level fluctuations can potentially be more problematic in certain periods of the year.

3.2.8 Short term water level variations (weeks) (P 2.17)

Parameter 2.17 is included in the classification system to capture possible hydrological alterations related to short-term fluctuations in water level (hydropeaking) and operations between wees. Rapid and frequent variations in water level will affect physical processes such as ice conditions and erosion along the shoreline. In order to calculate this parameter, the weekly average has to be calculated first. Afterwards, the procedure is the same as for Parameter 2.16. The absolute difference between the averages are calculated. The result to be used, is the 90th-percentile of all differences. Also, for this parameter it is assumed that it does not matter whether it is an increase or a decrease. Below 1 m, parameter 2.17 is classified as near natural and above 3 m it is classified as severely modified. Only Møsvatn, which has a variation of 1.11 m (between weeks), falls into the category slightly to moderately modified. The rest of the lakes are classified as near natural.

3.2.9 Dewatered areas (P 2.20)

This parameter is defined as the dewatered area due to regulation and calculated based on HRWL and LRWL. It is derived from a bathymetric map of the lake and describes how large areas (projected to a horizontal surface) are dewatered when the water level is lowered from the highest to the lowest regulated water surface elevation. As this is not calculated based on the conditions prior to the regulation, but rather how it is regulated, this parameter value must be seen as a parameter that describes the severity of the regulation.

To calculate this parameter, the surface area at the highest and lowest water level is calculated from maps. For Møsvatn the lowest regulated water level is 50 m above the bed of the lake. Thus, the surface area is calculated as the sum of the area of all cells from the reservoir bed until 50 m. This area is compared to the area at the highest regulated water level. The result for Møsvatn is 50.1 %, which means 50.1 % of the surface area is dewatered when the lowest regulated water level is reached. Results lower than 10 % are evaluated as near natural and results higher than 20 % are evaluated as severely modified. Møsvatn reaches the highest value, which means the worst score. The lowest result is reached by Årdalsvatn. Møsvatn and Øyeren are classified as severely modified with respect to parameter 2.20, while the other lakes (where data is available) are evaluated as near natural. Large dewatered areas can have large ecological implication as the lake will shrink dramatically when the water level drops, and large dewatered areas will also have negative aesthetical impacts. Large dewatered areas can also make use of the lake for boat and fishing less attractive.

Figure 3.9. Lake Mead on Colorado River, dammed by the Hoover Dam, has been establish in a canyon with a close to vertical shoreline, giving small dewatered areas when the water level drops.

3.2.10 Relative lake level fluctuation (P 2.21)

This parameter is the difference between the highest and lowest regulated water level (parameter 2.10) divided by the mean depth. The purpose of adding this parameter is to be able to differentiate the impacts from the same regulation if the lakes is shallow compared to deep, i.e. the same regulation (in meters) might have a different impact in a deep compared to a shallow lake. Below 10 % the classification is near natural and above 20 % it is severely modified. The highest result was found in Møsvatn with 92.5 %. The lowest result, and the best score, is reached in Årdalsvatn with a relative lake level fluctuation of 3.8 %.
As this is not calculated based on the conditions prior to the regulation, but rather how it is regulated, this parameter value must be seen as a parameter that describes the severity of the regulation.

3.2.11 Dewatered littoral zone versus total littoral zone (ratio) (P 2.22)

This parameter is used to assess the proportion of the regulation zone that lies within the littoral zone. The extent of the littoral zone is measured at HRWL. The regulation zone is the area between HRWL and LRWL. In order to calculate this parameter, the secchi depth (depth of visibility) at HRWL is needed, which determines the extent of the littoral zone. Figure 3.10 illustrates this, with use of data from Årdalsvatn. The outer circle represents the highest regulated water level (HRLW), the middle circle shows the lowest regulated water level (LRWL) and the inner red circle shows the depth where the littoral zone ends when the water level is at HRWL. In this example, the LRWL is higher than the littoral zone, which means not the whole littoral zone is lost when the lake is at its LWRL. To calculate the dewatered littoral zone, the surface area was needed and calculated using the bathymetry. Using the example of Årdalsvatn, the result is determined as shown below:

$$L = \frac{A_H - A_L}{A_H - A_{Lit}} \cdot 100 = \frac{(7.1-7.0)km^2}{(7.1-6.9)km^2} \cdot 100 = 44.4\ \%$$

L: Loss in littoral zone [%]

A_H: Surface area at the HRWL [km^2]

A_L: Surface area at the LRWL [km^2]

A_{Lit}: Surface area at the depth of littoral zone [km^2]

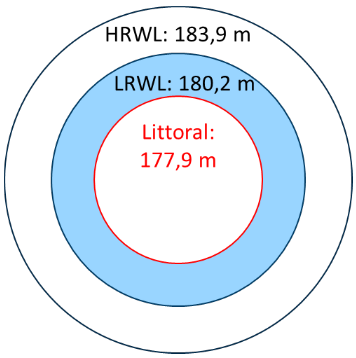


Figure 3.10. Example of highest regulated water level (outer circle), lowest regulated water level (middle circle) and littoral zone at HRWL (red circle), based on data from Årdalsvatn.

This means the dewatered area covers 44.4 % of the total littoral zone at HRWL. Results below 10 % are classified as near natural and results greater than 30 % are classified as severely modified. Any number higher than 100 % means that the entire littoral zone at HRWL is dewatered when the water level is at LRWL. Thus, 100 % is the highest result, which can be the case if the entire littoral zone and more is dewatered. For some test lakes, the bathymetry was not available. In these cases, the loss in littoral zone was calculated with the same equation but using depth instead of area. This was the case for Krøderen, Limingen, Lundevatn and Røsvatn.

When comparing all parameters in this group to each other (P 2.20 – 2.26), the dewatered littoral zone (parameter 2.22) stands out. It is the only parameter where all lakes are classified as severely modified. All lakes lose large parts (>40 %) of the total littoral zone. The lakes Møsvatn, Selbusjøen and Lundevatn have results higher than 100 %, which means the total littoral zone (and areas below this zone) is lost when the water level is at the LRWL.

As this parameter is not calculated based on the conditions prior to the regulation, but rather how it is regulated, this parameter value must be seen as a parameter that describes the severity of the regulation.

3.2.12 Shoreline development (dimensionless number) (P 2.23)

The change in shoreline development (parameter 2.23) is the shoreline development at LRWL in relation to the shoreline development at HRWL. The shoreline development is calculated as the shore length divided by the perimeter of a circle with equivalent area. Figure 3.11 illustrates the procedure. The shape on the left-hand side is Møsvatn and the circle to the right has the same area. The shoreline development describes how close the shape of the lake is to a circle. The closer the number is to 1 the more similar the lake is to a circle.

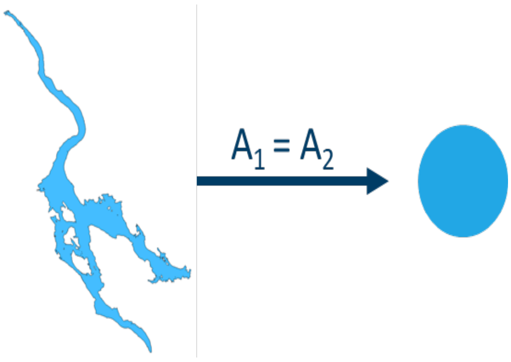


Figure 3.11. Lake Møsvatn (left shape) and a circle with equivalent area (right shape) to calculate the shoreline development.

Using the example of Møsvatn, the change in shoreline development is calculated as described in the following equation:

$$CSH = \frac{SH_L - SH_H}{SH_H} \cdot 100 = \frac{(7.48 - 6.61)}{6.61} \cdot 100 = 13.1\ \%$$

CSH: Change in shoreline development [%]

SH_H: Shoreline development at the HRWL [-]

SH_L: Shoreline development at the LRWL [-]

This means for Møsvatn the shoreline development is at the LRWL 13.1 % smaller than at the HRWL, hence Møsvatn is closer to a circle at LRWL than at HRWL. This is the highest result compared to other lakes.

Below 10 % the parameter is classified as near natural and above 30 % they are classified severely modified. The lowest score that can be reached is 0 %, which means the shoreline development would not change. The lowest score has Årdalsvatn (-0.5 %), meaning that it has the least shoreline development change between HRWL and LRWL.

Møsvatn is classified as slightly to moderately modified when the shoreline development of HRWL and LRWL are compared. The result of Møsvatn is positive, which means the shoreline development is higher at the LRWL than at the HRWL, thus it differs more from a circle. However, it is difficult to understand and interpret the number. As described before, the minimum result for the shoreline development is 1 but there is not any upper limit. This means it is not obvious what the number means. A decreasing shoreline development means the lake has become more like a circle in shape and has fewer niches. The result of Møsvatn is a positive number, thus an increase in the shoreline development and maybe more niches. Shoreline development should be a well-established metric applied on lakes (Bakken et al. 2018), but is appeared not very useful for our purpose, and should be left out in the next version of the classification system.

As this is not calculated based on the conditions prior to the regulation, but rather how it is regulated, this parameter value must be seen as a parameter that describes the severity of the regulation.

3.2.13 Loss in lateral connectivity along the shoreline (P 2.24)

The shore can be affected by anthropogenic changes for example due to embankments, levees, flood and erosion protection (e.g. Figure 3.12). The shoreline is defined as the shoreline at HRWL. If the length of the affected shoreline is less than 20 % of the total length of the shoreline, results are evaluated as near natural, and above 50 % they are evaluated as severely modified. A natural shoreline is assumed to have no embankments. The highest possible value (worst score) is 100 %, which means the entire shoreline is embanked. The lowest score, which indicates the best result, has Limingen with 3.0 %, which means that only 3.0 % of the shoreline is affected by embankments. To measure the length of the shoreline, the website Norgeibilder was used.

Byglandsfjord and Lundevatn are classified as slightly to moderately modified, due to extensive embankments in both lakes. There are, however, some challenges in the calculation of this parameter as the shoreline is not always visible on images as there might be trees blocking the sight of the shoreline. This affects how the certainty of this parameter is set in the results. To get a better view of the shoreline, drones could be used to film or take pictures. This could also improve the resolution of the pictures, which is another difficulty when using the website Norgeibilder. The resolution decreases when zooming to the lake, which makes it challenging to see and evaluate the structures along the shoreline.

Figure 3.12. Embankment along Mjøsa due to establishment of roads and railroads.

3.2.14 Riparian zone changes (P 2.25)

This parameter assesses to what extent the riparian zone is changed compared to natural conditions and is measured along the entire shoreline of the lake. The riparian zone is defined as the area just above the shoreline covered by higher vegetation. Lakes with parameter scores lower than 20 % lost riparian vegetation are classified as near natural and with results higher than 50 % severely modified. Møsvatn has the lowest score with 2.4 %, which means that 2.4 % of the riparian zone is affected by changes. The values of this parameter can range from 0 to 100 % similar. It is assumed that all lakes below the border line of higher vegetation had such vegetation along the full shoreline before any hydromorphological changes were introduced, except for lakes in areas with no natural higher vegetation (e.g. in marsh land).

When the results are compared to parameter 2.24 it stands out that the results from 2.25 are mostly similar or worse than the result from 2.24, but not very different and probably correlated. Parameter 2.25 is measured more away from the shoreline compared to 2.24, tentatively a belt of 50-100 m away from the shore. As both parameters are very time-consuming to measure (it can take several hours per lake), we recommend using either one of these parameters, or combine them directly.

3.2.15 Erosion due to changes in flow pattern/water level variations (P 2.26)

This parameter is considered being important as increased erosion cause reduced secchi depth, and can happen for instance due to more frequent water level fluctuations. One possible approach of assessing the effect of changes in erosion can be to combine Parameter 2.16 (Short term water level variations (days)) with Parameter 2.24 Loss in lateral connectivity, e.g. due to embankment. Increased water level variations will increase erosion, while increased embankment will most likely reduce erosion, i.e. they will have the opposite effects. This parameter tells us that increased erosion potentially can happen.

If both parameters (2.16 and 2.24) have the same classification result, for example both are slightly modified, they even out, as they have contradictory effects. If so, the combined result is 3 (see numbers in cells in Table 3.2), which represents a near natural status. The lowest score (1), indicating the highest change in sediments, is reached when 2.16 or 2.24 is classified as severely modified and the other parameter is classified as near natural. For the remaining combinations the erosion is classified as slightly modified, which is represented by number 2. Møsvatn obtained near natural status for parameter 2.16 and 2.24, thus the combined result for 2.26 is 3, which means the result of the alteration in erosion is near natural. The concept is presented in Table 3.2. Two near natural classification results also produce a near natural result.

We would underline that the concept of combining these parameters must be considered as an experiment in how parameters could be combined, in contrast to present parameters that are defined purely based on the description of one hydromorphological process or pressure, and that the combination proposed (modified Parameter 2.26) lacks scientific evidence. It is not sufficient scientific evidence that combination is a reasonable description of changes in erosion, hence we would recommend introducing this combined parameter in the next version of the hydromorphological classification system.

Table 3.2. Matrix to assess parameter 2.26 by using short-term water level variations (Parameter 2.16) and loss in lateral connectivity (Parameter 2.24).

Classification: Erosion introduced by changes in flow pattern (2.26)		**Classification result:** short-term water level variations in days		
		Near natural	Slightly modified	Severely modified
Classification result: loss in lateral connectivity	Near natural	**3**	2	1
	Slightly modified	2	3	2
	Severely modified	1	2	3

3.2.16 Connection/de-connection due to regulation/water level changes (P 2.30)

The purpose of Parameter 2.30 de-connection of lakes due to regulation is to assess whether a lake has been formed by connecting two or more smaller lakes when a reservoir is created, or if a de-connection happens when the water level decreases. It is possible that the lake was originally two or more lakes but merged to a larger lake/reservoir when a dam was built and the water level elevated. Some reservoirs can only decrease the water level compared to natural, which can lead to isolation of individual bodies of water without connection. Thus, the parameter is evaluated based on the original shape compared to the shape after regulation. It is a parameter without thresholds, which means it requires expert judgment for classification.

An assessment would require access to photos from the before regulation and compare with the present situation. Norgeibilder provides historical photos, but it can be a challenge to find photos from before as old photos are mostly from urban areas. Alternatively, other historical sources, such as books, reports, photos in the possession of hydropower companies, museums or private persons can be used. It is, however, a very time-consuming job to find these sources of information and considered too work-intensive for the purpose of a hydromorphological classification.

Parameter 2.30 was classified for only two lakes in this project (Møsvatn and Årdalsvatn), one ending in the class 'near natural', while the other ended in the class 'extensively to severely modified'. Before regulation, Møsvatn was separated into three lakes. This information is given on the website of NVE, where Møsvatn is described (NVE 2015). The classification result in this case is 1, which means severely modified. In case a lake was not split before regulation, it is classified as near natural (3), such as Årdalsvatn. It is not regulated, which means it is not possible that several lakes were merged together.

Figure 3.13. The through-flow between connected lakes can also be affected by roads, narrowing the openings for exchange of water.

3.2.17 Anthropogenic barriers within lakes due to water level changes (P 2.31)

Parameter 2.31 refers to built constructions within the lake, probably for the purpose of sustaining certain water levels in parts of the lake when the water level drops, or the separation of parts of the lake when the water level drops (see Møsvatn in Figure 3.14, left part). The parameter is assessed by evaluating to which extend the lake separates when the water level is at LRWL. The blue shape is the surface area when the lake is at HRWL, and the red shape shows the surface area when the water level is at the LRWL. It is clear that the red shape is split in several pieces, indicating that the lake loose connectivity when the water level drops. The result is a qualitative classification. Møsvatn is evaluated as being severely modified (score 1), because the lake is separated into several ponds when the water level is at its lowest. The value 2 indicates slightly to moderately modified and the value 3 indicates near natural, which means little or no separation.

Møsvatn separates in several small lakes when the water is at the LRWL, which is why Møsvatn is classified as severely modified. Øyeren is also separated but less than Møsvatn, thus it is classified as slightly to severely modified. Figure 3.14 (right part) shows the shape of Øyeren at the highest regulated water level (brown area) and at the lowest regulated water level (yellow lines). It illustrates that the water level at the LRWL is not one line anymore, which means the lake is separated. However, in other cases it might be difficult to evaluate the separation, which reduces the certainty in the classification of this parameter for this lake.

To what extent the water level variations cause separated parts of the lake, can be assessed by using the bathymetry, i.e. based on the shape of the lake at HRWL and at LRWL. In contrast to the assessment described above, this would be and assessment of the degree of regulation and not a comparison with the situation before regulation, which explains the two crosses in Table 5.2 regarding this parameter.

A built barrier can be seen similar to smaller weirs built in regulated rivers with reduced flow in order to higher the water level. It is not known how common this is, but clearly a hydromorphological change of the lake. It is very difficult to find information about these constructions in lakes, with reasonable resources.

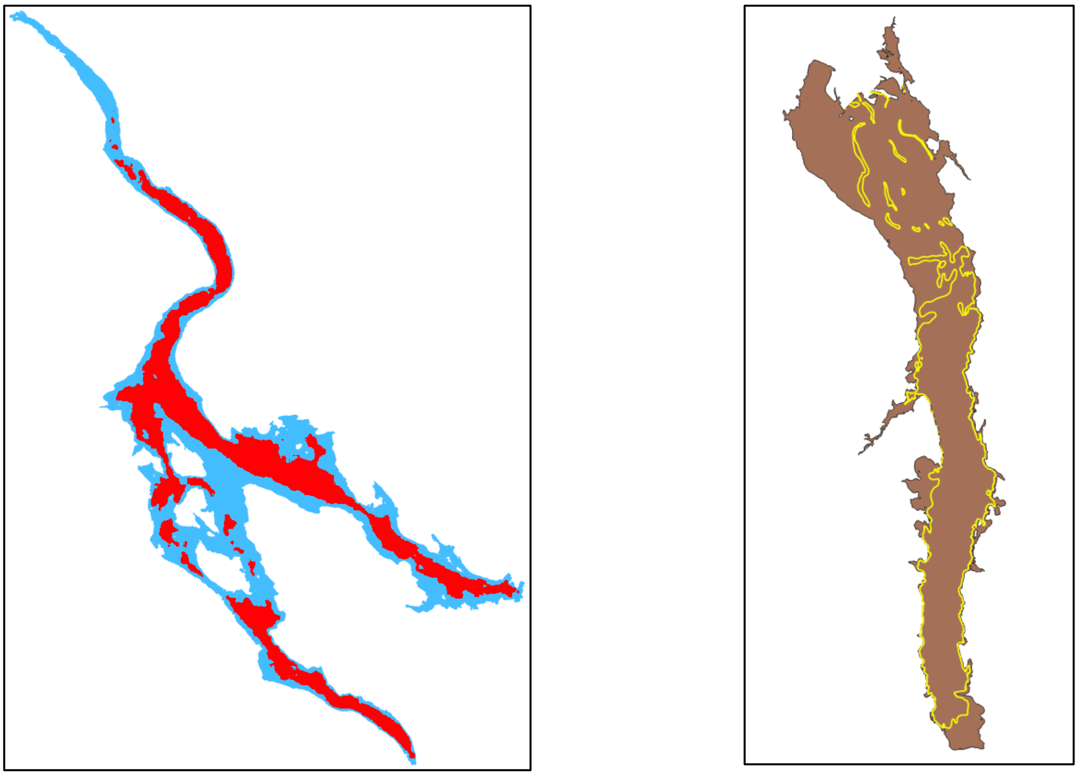


Figure 3.14. The shape of Møsvatn (left) at the highest regulated water level (blue area) and at the lowest regulated water level (red area) and the shape of Øyeren at (right) the highest regulated water level (brown area) and at the lowest regulated water level (yellow lines).

The two parameters 2.30 and 2.31 are very important in the assessment of the hydromorphological alterations of lakes and reservoirs, as they may represent large changes in physical structure through a year. The changes they describe are fundamental for the ecosystem. It should be considered if these parameters should be used to designate heavily modified water bodies from natural lakes instead of classifying the hydromorphological changes of a natural lake.

3.2.18 Barrier effects (hindering migration to/from downstream areas) (P 3.10)

This parameter should cover the full spectrum of effects due to downstream barriers on the water body to be classified. This will include effects such as raised water levels/backwater effects, and changes in water velocities, sedimentation and ice conditions, as well as access to habitats. The original definition (in Bakken et al. 2018) of this parameter was, however, related only to how the downstream barrier affect migration from the lake or reservoir, which is also reflected in the instructions in how this parameter was supposed to be calculated, which is also the way it is calculated in the testing. Parameter 3.10 is calculated by measuring the available river reach from the barrier affecting the lake to the next lake or fjord, and comparing that the with the total river reach from the lake to be classified and to the next downstream lake or fjord. If the barrier (dam) is placed just at the outlet of the lake blocking the downstream river, the parameter should be given the score 100 %, i.e. completely blocked due to this barrier. For Selbusjøen, the blocked reach equals 87.9 % of the total downstream river. If the results are lower than 20 % this parameter is classified as near natural and higher than 50 % as severely modified. 100 % means that the dam is located directly at the lake's outlet and the complete downstream reach is blocked, such as Møsvatn.

The distance of the free-flowing section to measure the barrier might block should be better defined, if it is to the next lake or reservoir, to the fjord or to the next natural (e.g. a water fall) or man-made barrier. In the case of Selbusjøen (Figure 3.15), there are barriers between the outlet of the lake and the fjord, such as Øvre and Nedre Leirfoss.

It appears also difficult to find reliable data on natural and man-made barriers without detailed and time-consuming search among various data sources, and still the results will in many cases be uncertain. Furthermore, the downstream barrier might already be included and accounted for in the downstream water body (which is the case for Selbusjøen) and including parameter 3.10 will introduce some sort of 'double-counting' if the barrier defined as outside the lake water-body. Summed up, it should be considered removing this parameter from the new, proposed classification.

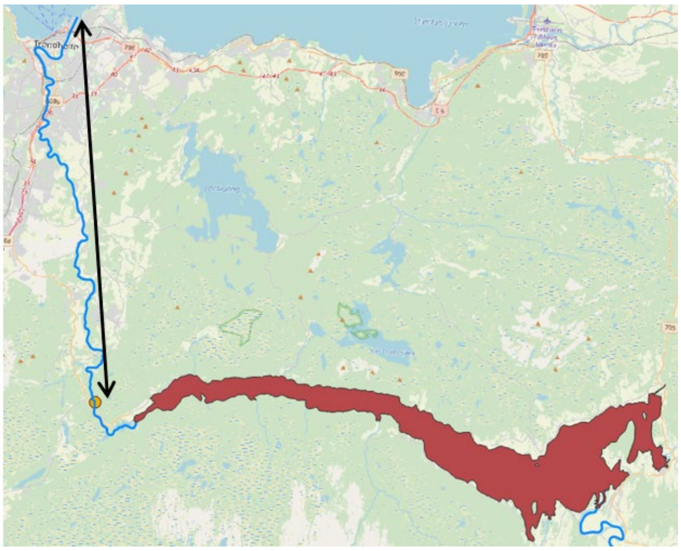


Figure 3.15. Selbusjøen (red shape) and the blocking of access to the fjord. River Nidelva (blue line) flows out of Selbusjøen to the fjord in the North and the orange circle represents the dam of Selbusjøen.

3.2.19 Parameters not included in the test results

The summary table of the test results does not include all parameters that are defined in the classification system in Bakken et al. (2018). Table 3.3 provides an overview of those parameters not tested and described in this report.

Table 3.3. This table provides an overview of those hydromorphological parameters that are not calculated and presented in Table 3.1, and the reason why they are excluded.

No	Parameter	Qual. elem.	Reason for exclusion
1.11	Hydrology: Changes in periodicity (inflow)		Disproportionately work-intensive to collect and analyse data. If a hydrological model for entire Norway is configured and applied, this parameter should be considered included again.
1.12	Change in water temperature of inflowing water		Very difficult or disproportionately work-intensive to collect and analyse data. This is an important parameter, but is for now taken out of the system due to lack of data.
1.14	Sediment changes due to upstream barriers		Very difficult to collect or analyse data.
2.18	Annual maximum flood level		Very difficult or disproportionately work-intensive to collect and analyse data, as it appeared to find impossible to find 30 years of continuous data prior to regulation.
2.40	Removed or added gravel, rocks, sand and other sediments		Very difficult or disproportionately work-intensive to collect and analyse data. It is assumed that only some very few lakes are affected by this HYMO alteration.
2.41	Porosity of substrate		Very difficult or disproportionately work-intensive to collect and analyse data. It should, however, be underlined that adding of gravel or sand, for instance to improve the possibilities for bathing or removal of sediment (dredging) in order to improve the conditions for navigations can be a significant hydromorphological alterations in some lakes and should be considered included in cases where this is known to happen.
2.50	Flow velocity changes due to changes in inflow/outflow		Disproportionately work-intensive to collect and analyse data. It would normally require configuration of a computer model.
2.51	Water temperature		Disproportionately work-intensive to collect and analyse data. It would normally require configuration of a computer model. This change is considered being important to assess, as hydropower reservoirs or lakes affected by regulated flow regimes can experience big changes in water temperatures that might have large ecological impacts.
2.52	Ice conditions (surface, shore ice)		Disproportionately work-intensive to collect and analyse data. It would normally require configuration of a computer model.
2.53	Water clarity		Disproportionately work-intensive to collect and analyse data. It would normally require configuration of a computer model. Significant changes in secchi depth can have large ecological impacts.

The parameters 2.50 Flow velocity changes due to changes in inflow/outflow, 2.51 Water temperature, 2.52 Ice conditions (surface, shore ice) and 2.53 Water clarity are all left out from the testing. All these parameters will require extensive resources to find, which is not considered relevant if a classification is to be made for all lake water bodies in Norway. In order to compare the present situation with the conditions before the regulation, a model tool, such as GEMSS (see description in Bakken et al. 2018) must be adapted to each individual lake. See also further discussion on the exclusion during testing of these and some of the other parameters during testing in Chapter 5.2, and their role in the new, proposed system (presented in Chapter 7).

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3.3 Aggregation of parameters for overall classification

3.3.1 Overall concepts

The scores of the individual parameters must be calculated and combined to obtain the overall classification of a lake. There was no methodology proposed for combining and aggregating the parameters in prior work (Bakken et al. 2018).

Here, we propose the following system: First, the classification of a parameters value is done according to its class boundaries. All alterations from natural conditions were considered to have a negative impact on the hydromorphology, therefore the absolute change of all parameter values is calculated first. The three-class system described in Table 3.4 is used for both the overall score of a lake and for the classification of a single parameter.

Table 3.4. Generalised three-class system following the standardised approach used in EU WFD for hydromorphological changes (CEN TC 230/WG 2/TG 5: N65 2008), classifying the overall hydromorphological score. Column 2 indicates how a weighted score, possibly given decimal numbers as score, is assigned a specific class.

Class / Single Parameter Score	Score range	Code	Description
3	>2.33		Near-natural
2	1.66 - 2.33		Slightly to moderately modified
1	<1.66		Extensively to severely modified

The calculation of a single parameter score is shown in Table 3.5 for the parameter 1.10 of Årdalsvatn. Please note than Årdalsvatn has a reduced change in annual inflow, the original value is -8%, but the parameter score is calculated with the absolute value.

Table 3.5. Parameter score using Parameter 1.10 for Årdalsvatn as an example.

No	Parameter	Metrics for change	Parameter ranges and scores			Value	Parameter Score
			Near natural	Slightly to moderately modified	Severely modified		
			3	2	1		
1.10	Hydrology: Change in annual inflow	% change from natural conditions, given as degree of regulation	< 20	20-50	> 50	8 %	3

3.3.2 Parameter importance and certainty and relating weight

In order to combine all the individual parameter scores into one overall hydromorphological classification values, the parameter values must be aggregated via some sort of weighting. We defined and tested out a set of weighting procedures based on the combination of importance and certainty of the assessment, and weighting based on importance alone.

Importance represents the hydromorphological significance of a parameter and was individually assigned. The importance values were created based on expected impact on hydromorphological quality and expert knowledge. As the basis, we used the importance of each parameter as proposed by Bakken et al. (2018) and given in Table 3.7. The importance distribution over the parameters is consistent for all lakes, i.e. each parameter has the same importance in all lakes. Importance can be assigned to parameters based on the individual importance (see system 1b and 2b in Table 3.8) and based on the parameter group it belongs to (1c and 2c in Table 3.8).

Certainty of a parameters score reflects the reliability and accuracy of the method which was used to acquire the parameter's value. Certainty for measured parameters tends to be higher than for modelled ones, in order to take into account potential model uncertainty.

In Chapter 7.2, where we conclude upon aggregation procedure, we propose that certainty is excluded from use during aggregation. As certainty was included in the assessment of various aggregation procedures during the early stages of the project, this part is still included in the report.

The certainty is specified for each parameter and each lake individually, because the certainty of one parameter can differ between the lakes classified. One example due to different lengths of time series of water level measurements for hydrological calculations. However, the certainty of one parameter can also be equal for all lakes, for example when the data source yields the same data quality for all lakes, as is the case for aerial imagery for the assessment of parameter 2.25 *Riparian zone changes*. The value of 3 indicates that the parameter is certain and the value of 1 indicates it is uncertain (Table 3.6). During testing, the certainties are to a large extent consistent across the lakes for each and the same parameter, because data sources and quality were almost identical for all lakes. However, the mean certainties for each lake differ (see Table 3.7) since the availability of data varies between lakes and the mean certainty is calculated from the available parameters. The data availability and certainty of the data, when available, is expected to vary more extensive for lakes outside the dataset selected for this testing. The weighting procedures tested are explained in detail in the following, while the results of applying different weighting procedures are presented in Table 3.11.

Table 3.6. Possible values for importance and certainty.

	Low	Middle	High
Importance / Certainty	1	2	3

Equation *weight of parameter*:

$$Weight\ of\ parameter_i = \frac{3 \cdot Importance_i + 2 \cdot Certainty_i}{\sum_{i=1}^{n}(3 \cdot Importance_i + 2 \cdot Certainty_i)} \qquad \text{(Equation 3.1)}$$

Equation *Overall lake score*:

$$Overall\ lake\ score = \sum_{i=1}^{n} \frac{Parameter\ Score_i \cdot Weight\ of\ parameter_i}{\sum_{i=1}^{n} Weight\ of\ parameter_i} \qquad \text{(Equation 3.2)}$$

In Equation Overall lake score (Equation 3.2), the impact of importance and certainty to the weight is scaled by 3:2, so that the importance has a stronger impact on the final score than the certainty. The scaling avoids that critical parameters have a too low impact because of the uncertainty of the data generation.

Table 3.7. Overview over classification of all parameters in all lakes, importance/weights of each parameter and certainty in classification. *Imp.* stands for Importance, *Sc* stands for score or classified value ranging from 1 to 3, and *Ce* stands for certainty in the assessment. The bottom row represents the mean certainty of all lake parameters. The asterixis in the first column refer to changes in the original definition of the parameters. The importance (column 2) and the colour coding are defined in Bakken et al. (2018).

Para-meter No.	Imp.	Byglands-fjorden		Krøderen		Limingen		Lunde-vatn		Møsvatn		Røsvatn		Selbu-sjøen		Øyeren		Årdals-vatn	
		Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce	Sc	Ce
1.10*	3	3	3	3	3	3	3	1	3	3	3	3	3	3	3	3	2	3	3
1.13	1	1	2	1	2	1	2	1	2	3	2	3	2	1	2	1	2	2	2
2.10	3	2	3	3	3	2	3	2	3	1	3	1	3	2	3	3	3	3	3
2.11	3	2	3	-	-	-	-	-	-	1	3	-	-	2	-	2	3	3	-
2.12*	3	2	3	-	-	-	-	1	3	3	3	-	-	3	3	3	3	3	3
2.13*	3	1	3	-	-	-	-	1	3	1	3	-	-	1	3	3	3	1	3
2.14*	2	3	3	-	-	-	-	1	3	3	3	-	-	3	3	3	3	3	3
2.15*	2	3	3	-	-	-	-	1	3	3	3	-	-	3	3	3	3	3	3
2.16	2	3	3	-	-	-	-	3	3	3	3	-	-	3	3	3	3	3	3
2.17	1	3	3	-	-	-	-	3	3	2	3	-	-	3	3	3	3	3	3
2.20	3	3	3	-	-	-	-	-	3	1	3	-	-	3	3	1	3	3	3
2.21	3	3	3	3	3	2	3	3	3	1	3	2	3	3	3	2	3	3	3
2.22	3	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1
2.23	2	3	2	-	2	-	2	-	-	2	2	-	-	2	2	3	2	3	2
2.24	3	2	1	3	1	3	1	2	1	3	1	3	1	3	1	3	1	3	1
2.25	1	2	1	2	1	3	1	2	1	3	1	3	1	3	1	3	1	2	1
2.26*	2	2	2	-	-	-	-	2	2	3	2	-	-	3	2	3	2	3	2
2.30	2		-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	3	-
2.31	2	3	1	-	-	-	-	-	-	1	1	-	-	3	1	2	1	3	1
3.10	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	2	2	3	2
Mean Ce			2.47		2.47		2		2		2.53		2.47		2.47		2		2.47

The specification of the alternative weighting procedures tested is given in Table 3.8, while the score/results are given in Table 3.11.

Table 3.8. This table defines the various aggregation/weighting procedures.

Weight factors	ID	Weighing procedure and name	Description of main features of the weighing procedure
Importance	1a	Uniform	No weighting Equation Weight of parameter (Eq. 3.1) is not used, and all weights are given the weight = 1.
	1b	Individual	Parameter weight equals parameter importance. Importance is assigned individually for parameters. Importance values can be looked up in Table 3.7 (second column). Certainty is set equal to 0.
	1c	Grouped	Parameter weight equals parameter importance. Certainty is set equal to 0.
Importance + Certainty	2a	Uniform + Certainty	Certainty is added to IDs 1a, 1b and 1c according to Equation 3.2.
	2b	Individual + Certainty	
	2c	Grouped + Certainty	

For the methods 1a, 1b and 1c, the certainty in equation Weight of parameter (Equation 3.1) is not included, i.e. no effect of uncertain data/assessment. The group importance for 1c and 2c is shown in Table 3.9. The group importance values are an expert-based aggregation of the individual parameter importance, given in Table 3.7.

Table 3.9. Group names, parameter IDs and tested group importance.

Group name and ID	Group importance
Upstream changes (1.10 – 1.14)	3
Hydrology (2.10 – 2.18)	3
Shoreline (2.20 – 2.26)	2
Fragmentation and barriers (2.30 – 2.31)	3
Substrate	1
Physical & Chemical condition	1
Downstream changes	2

Another type of approach to weighting is to calculate the group mean of all parameters first, according to the group definitions given in Table 3.9 under 'Group name'. The different approaches of this type are described in the Table 3.10.

The grouped weighting approaches described in Table 3.10 differ strongly from 1c: in 1c, formula Overall lake score is applied, and the importance values are the same for each group. In 3a/3b/3c, the group averages are calculated first and are then subsequently weighed against each other. In 3, a group that consists of very few parameters can have the same impact as a group consisting of many parameters, whereas the system 1c is more balanced and does not allow a strong impact of single parameters.

Table 3.10. The table defines different alternative weighing procedures using the average group value.

Name	ID	Weighing procedure and name	Description of main features of the weighing procedure
Grouped	3a	Equal weight	All groups have equal weight
	3b	Hydrology 50%	Hydrology group (parameters 2.10 – 2.18) has 50% of the weight, remaining groups the other 50%.
	3c	One out all out	Worst group class defines total score

Grouped (3a, 3b, 3c)

For the grouped variants of the total score system, the means of the groups are calculated first. Then, the group values are weighted against each other.

3.4 Discussion of overall classification results dependent on weighting system

Table 3.11. The table presents the results of the overall hydromorphological classification for each lake using a set of different procedures for weighing of parameters. The weighing procedures are defined in Table 3.8, while importance of each parameter for Weighting procedure 1b, the scores (classified values for each parameter and lake) and certainty in classification is given in Table 3.7.

Weighting procedure	Byglands-fjorden	Krøderen	Limingen	Lunde-vatn	Møsvatn	Røsvatn	Selbu-sjøen	Øyeren	Årdals-vatn
1a - Uniform	2.37	2.38	2.38	1.8	2.16	2.38	2.53	2.47	2.58
1b - Individual importance	2.36	2.5	2.5	1.77	2.16	2.39	2.56	2.56	2.6
1c - Group Importance	2.37	2.37	2.32	1.74	2.16	2.37	2.51	2.51	2.61
2a - Uniform Importance & Certainty	2.38	2.48	2.41	1.78	2.11	2.34	2.5	2.47	2.59
2b - Individual Importance & Certainty	2.37	2.52	2.48	1.77	2.13	2.36	2.53	2.53	2.6
2c - Group Importance & Certainty	2.37	2.44	2.36	1.75	2.13	2.35	2.5	2.49	2.61
3a: Grouped - equal weights	2.53	2.56	2.38	1.93	2.22	2.31	2.61	2.23	2.36
3b: Grouped: Hydrology 50%	2.48	2.71	2.25	1.86	2.185	1.88	2.57	2.48	2.51
3c: Grouped: One out all out	2	2	2	1	1	1	2	2	1

Importance (1a, 1b, 1c)
The simplest calculation of the total lake score is based on the same weight for all parameters. It can be argued that as all parameters were considered being hydromorphological and ecological relevant, they should have the same impact on the system. Another benefit of using this approach is that all parameters have an equal impact on the total score, which justifies the effort to calculate every single one.

Importance and Certainty (2a, 2b, 2c)
These approaches consider parameter certainty as a factor that influences the impact of a parameter on the total score. The meaning behind these approaches is that the total score has decreased sensitivity towards very uncertain parameters. This increases robustness of the result to human error, wrong measurements and model uncertainties. Simultaneously, reliability of the classification system is increased.

Disadvantage of this methods can be that a single parameter can have only 1/9th (certainty and importance = 1) of the impact of another one (certainty and importance = 3). The potential low impact on the total score discourages the use of time- and work-intensive assessment of parameters.

Variant 3a
The three main hydromorphological quality elements have the same weight. The overall classification is calculated by combining the scores for the individual parameters and are classified according to the overall class limits as defined in Table 3.4.

Variant 3b
The group *Hydrology* is assigned 50% of the total importance, the remaining groups have equal shares of the other 50% importance. Many lakes drop one class level in this version, this is partly due to their worse score (Lundevatn) and limited number of parameters for hydrology (Limingen) and partly because groups with a single low-score parameter have a higher impact on the score (Parameter 3.10).

Variant 3c
The 'one out all out' principle applied gives on average the worst classification results. This method is sensitive to the effect that the size of the groups the parameters are divided into can vary extensively. Some groups, like *Physical and Chemical* has four defined parameters, while data was available for only one parameter, and *Downstream changes* has only one parameter as it is defined. If the only parameter in these groups has a low value, the entire lake classification results in the score of this value. If this single parameter is also very uncertain, the whole classification becomes uncertain. To avoid this instability, variant 3c could be adjusted so that the 'One out all out' only applies for large groups with usually good sufficient data such as for *Hydrology* or *Shoreline*. Another feasible variant is to merge the groups so that the group size is never less than four parameters.

3.5 Comparison with ecological status classification

The EUs Water Framework Directive (WFD) is conceptually based on expected impacts of anthropogenic influences on the biota of aquatic ecosystems. Such impacts may be associated with acidification, eutrophication, hydromorphological changes, toxic substances or change in erosion and sedimentation. The impacts will however rarely be interconnected. The WFD accordingly has developed certain specified indices in order to quantify the degree of anthropogenic influences. Such indices have been especially successfully developed for eutrophication and acidification.

The parameters included in the HYMO classification system are assumed to be ecologically relevant, and this chapter discuss the linkages between hydromorphology and ecology. Apart from macrophytes, we lack suitable biological indicators which may quantify effects of artificial water level change in lake reservoirs. When testing the HYMO classification system, we used lakes from the ØKOSTOR monitoring program. These lakes have earlier been classified based on a suite of indices for biological and physicochemical quality elements, including phytoplankton, water plants, benthic invertebrates, fish, nutrient levels and pH. Most of these indices/parameters respond to pressures like eutrophication or acidification (see table 3.2 in Guidance document 02:2018, Committee of Directorates, 2018). Hydromorphological impacts, however, are *a priori* not expected to influence eutrophication or acidification, except from possible effects of altered water retention time on phosphorus retention. Long term water level regulations may reduce phosphorus levels, potentially leading to reduced productivity and an 'oligotrophication' of the system. This would in fact indicate better ecological status with respect to eutrophication.

Among the biological and physicochemical quality elements used in the Norwegian implementation of the WFD, there is only the water level index for macrophytes (WIc; Mjelde et al. 2012) that is developed specifically to respond to hydromorphological impacts. Specifically, the WIc index is sensitive to the level of winter drawdown. There are no indices developed specifically to assess the effect of HYMO on benthic invertebrates, even though critical regulation amplitudes for a few organism groups (e.g. *Gammarus lacustris*, snails, caddis larvae) are listed in the guidance document (Committee of Directorates 2018). These critical values are also used as a basis for defining class borders for regulation amplitude with regards to fish in lakes. The boundary between 'good' and 'moderate' status is set to a regulation amplitude of 5 meters (Committee of Directorates 2018).

Although few indices exist to specifically assess impacts of hydromorphological changes, the parameters defined in the proposed classification system do indeed capture factors that are important for the ecological structure and function in lakes. Several parameters are related to changes in the extent and dewatering of the littoral zone, which is highly important for the production and diversity of water plants, benthic invertebrates and littoral fish. Others are related to upstream barriers that may block sediments, nutrients and organic matter. Changes in the timing of filling and emptying is also highly relevant, especially for organisms spawning in shallow areas at certain times of the year.

In Table 3.12 we have presented the ecological status/potential classification given in Vann-Nett Portal (Vann-nett 2019), that can be compared with the hydromorphological classification done in this project, exemplified with aggregation variants 1c and 2d. The ecological classification system has five classes, which range from very good to a bad ecological status. The status of two of the nine lakes are moderate. The other seven lakes are classified as good. A star behind the status means that lake has been designated as heavily modified showing the ecological potential and not the status. Our HYMO classification is based on a three-class system.

Table 3.12. The table presents the EU WFD ecological status classification (WFD Ecol.) given in Vann-Nett for the study lakes with the hydromorphological classification for two of the HYMO classification procedures. The asterisk (*) behind the ecological classification indicates that these are 'ecological potential', meaning that these water bodies are designated as 'heavily modified'. Be aware that the results presented for 1c - Group Importance and 2b - Individual Importance & Certainty (and in Table 3.11) are given for a three-class system, while the results for WFD Ecol. are based on a five-class system.

Classification procedure	**Byglands-fjorden**	**Krød-eren**	**Limingen**	**Lunde-vatn**	**Møsvatn**	**Røsvatn**	**Selbu-sjøen**	**Øyeren**	**Årdals-vatn**
WFD Ecol.	Good	Good	Good*	Moderate	Moderate*	Good*	Good*	Good*	Good
***1c** - Group Importance*	2.37	2.37	2.32	1.74	2.16	2.37	2.51	2.51	2.61
***2b** - Individual Importance & Certainty*	2.37	2.52	2.48	1.77	2.13	2.36	2.53	2.53	2.6

As the ecological classification system has five classes, not all classes from the ecological system are covered in the hydromorphological system. Very good (ecological) represents near natural (HYMO), moderate (ecological) represents slightly to moderately modified (HYMO), and bad (ecological) represents severely modified (HYMO). A good status is between 'Near natural' and 'Slightly to moderately modified'. A poor status is between 'Slightly to moderately' and 'Severely modified'.

4 Ecosystem responses to hydromorphological alterations in lakes

There is a number of studies that discuss effects of hydromorphological alterations and water level regulation (WLR) on the aquatic environment, and in particular the effects of water level changes related to power production (reviewed in Carmignani & Roy 2017; Zohary & Ostrovsky 2011).
The effects on the ecosystem, however, will depend on both the magnitude of the hydromorphological alterations, the shape and size of the lake, the relationship between catchment and lake volume (especially changes in the water residence time), but also on the species composition and which key species that characterize the aquatic ecosystems. Most lakes include three different habitats - littoral, pelagic and profundal - and these will often respond somewhat differently to water level regulations.

4.1 Effects on the pelagic zone

In the pelagic zone, i.e. the open water masses, the primary production is carried out by phytoplankton. These microscopic 'plants' are grazed by small planktonic crustaceans (zooplankton), which in turn become food for plankton-eating fish – in Norway e.g. whitefish (*Coregonus lavaretus*) and char (*Salvelinus alpinus)*. Phosphorus (P) is usually the limiting nutrient for primary production in Norwegian lakes. P is supplied to the pelagic primarily from the catchment through streams and rivers, but some P can also come from the littoral zone, especially in small and shallow lakes. In some eutrophic lakes in the lowlands, and in many tropical artificial reservoirs, the sediments in the deeper areas can also release P to the water masses if the water becomes oxygen-free, but this is not common in Nordic lake reservoirs. On the contrary, large Nordic lakes and reservoirs often have very low concentrations of P. The supply of P to a lake is affected by geology, soil, and the size and land use of the catchment. In particular, the latter may affect the relative amount of soluble and particulate phosphorus washed into streams and rivers, and eventually the lake. In addition to the supply, the concentration of P in a lake is influenced by the water residence time, i.e. how long time the water spends in the lake.

The theoretical water residence time (WRT; years) is defined as the basin volume (V; m^3) divided by the yearly water flow into the lake (f; m^3/year): WRT = V/f

A large lake with a small catchment will have a long WRT, while a small lake with a large catchment and fed by larger streams and / or rivers will have a short WRT. The retention of P in a lake has an asymptotic relationship with the lake's theoretical residence time (Figure 4.1).

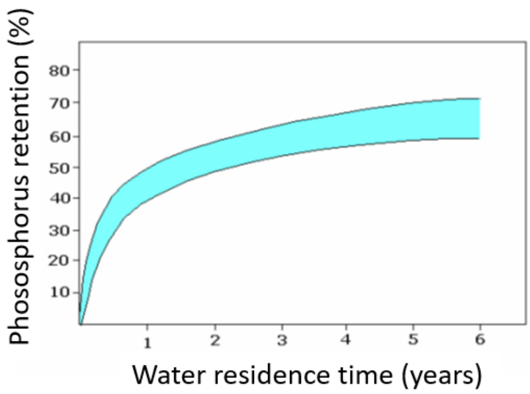


Figure 4.1. The relationship between the WRT and the retention of phosphorus in lakes (From Berge 2010).

As the residence time increases, P-containing particles like phytoplankton, faeces from zooplankton and colloids of dissolved organic material (humus) will increasingly sink out of the productive euphotic zone. The longer the water stays in the lake, the more phosphorus will sink out, and the less productive the lake's pelagic ecosystem will be.

Changes in lake volume and / or water supply as a result of hydromorphological alterations may change residence time and thus also the retention of phosphorus. If a lake is regulated and the water volume increases (without the water supply increasing), the residence time - and thus the phosphorus retention - will increase accordingly. One can also imagine situations where the residence time is reduced, i.e. if the water supply to a lake or reservoir is increased through transfer of water between catchments.
One hypothesis which emerged from the monitoring of large lakes in Norway (the ØKOSTOR monitoring program), is that some reservoirs are prone to 'oligotrophication" – a depletion of phosphorus in the free water masses, which further reduces the already low biological production. This process may result from a combination of increased residence time and a wash-out of nutrients from littoral zone resulting from many years of unnatural water level fluctuations (Carmignani & Roy 2017).

Hydromorphologic alterations such as changed water volume, frequency and time of filling/emptying, and transfer of water from other catchments may affect physical factors like temperature, stratification and light conditions. Changes in temperature conditions will affect the metabolism and growth of aquatic organisms and influence the vertical distribution of different organism groups in the lake. However, there is little data on how HYMO affects the temperature conditions in reservoirs, although data on temperature can be obtained by installing temperature loggers at various depths.

Effects of hydromorphological impacts on light conditions are possible through changes in erosion and turbidity. An example of such a response was seen in the Ringedal reservoir in western Norway, when the lake was lowered to unusually low water levels during the summer of 1985 (Borgstrøm et al. 1992). The lowering exposed fine sediments to wave erosion, which brought particles into the open water masses. The resulting increase in turbidity reduced the light penetration to a minimum, severely reducing primary production and zooplankton biomass. The brown trout in the system, which in this particular lake mainly fed on zooplankton, got reduced condition (weight relative to length) and the number of spawning fish also decreased.

4.2 Effects on the littoral zone

The littoral zone is the areas of the lake where there is enough light for aquatic macrophytes to grow. The littoral zone offers a highly productive ecozone, which is crucial for benthic invertebrates, fish and water birds. Several fish species, in Norway especially trout and several cyprinids (carp fish) are adapted to the littoral zone. Additionally, the littoral zone comprises crucial habitats for fish fry of a number of other species, which graze on benthic and littoral microcrustacean food and seek shelter in the vegetated protected shores. The shallow parts are utilized by numerous wading birds, not the least during migration and breeding periods. Diving duck species graze on water plants and algae, and carnivorous feeders utilize fish and invertebrates. The littoral zone comprises the most productive and diverse ecosystem of lakes.

4.3 Macrophytes

Aquatic macrophytes, or water plants, harbour the littoral zones of lakes. Some species of water plants are especially sensitive to water level changes, while others are less. This gradient in sensitivity has been utilized to develop an index for water level changes in Norwegian lakes (the WIc index; Mjelde et al. 2012). Drought, freezing, ice-scour, and light are factors determining a species' sensitivity to water level regulations (Mjelde et al. 2012). While desiccation can be critical in summer, for many species a low water level is worse in winter due to freezing. Effects of water level regulations can be highly critical in ice covered lakes due to ice scour (Rørslett 1984; Rørslett 1989), which results in mechanical damage on both the plants and their substrate. This can be problematic for some groups of water plants, especially large isoetids (Mjelde et al. 2012).

Plants that don't tolerate desiccation must retreat deeper than the lowest regulated water level (the LRW). The problem with this strategy is that light levels can become insufficient during periods of raised water levels. Light levels at the LRW decrease with increasing regulation amplitude and decreasing Secchi disc depth (a proxy for water clarity). The interacting effects of regulation amplitude and Secchi disc depth on the survival water plants can be illustrated with the species *Isoetes lacustris,* which is a common species in northern, calcium poor lakes, and the most important indicator species for water level regulations (Hellsten 2002, Mjelde et al. 2012).

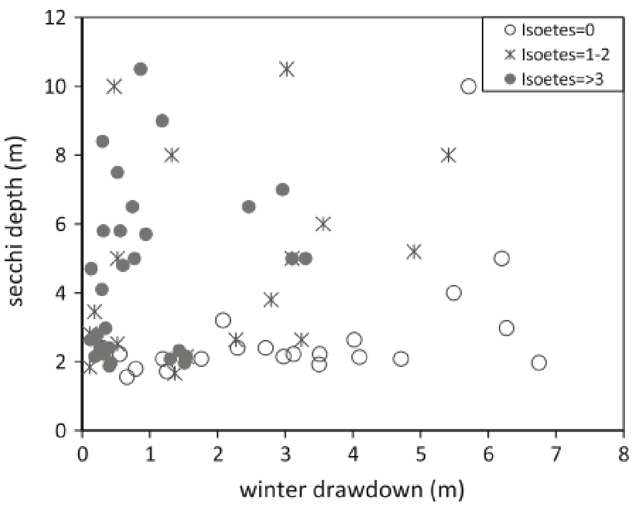


Figure 4.2. Abundance of the macrophyte *Isoetes lacustris* in lakes with different levels of winter drawdown and Secchi disc depth. The abundance of Isoetes is shown on a semi-quantitative scale: filled circles means that the species is common, stars that the species is rare/scattered, and open circles that the species is absent. From Mjelde et al. (2012).

If the winter drawdown is < 3-3.5 m, *Isoetes lacustris* can be relatively abundant (Figure 4.2). But if the level of winter drawdown increases further, the abundance is reduced or decimated completely. The boundary between good and moderate status in the water level index for water plants (the WIc index) is set to 3.5 m based on this condition (Mjelde et al. 2012). The reason for the decreased abundance below a drawdown of 3.5 m is that the light levels below LRW becomes too low for positive photosynthesis. In clear water lakes (lakes with high Secchi disc depth), however, the species may even be present at drawdown levels > 3-3.5 m, as light penetrate deeper, allowing photosynthesis and growth at higher depths (Figure 4.2).

Water plants require suitable sediments for the roots to anchor to the bottom. In regulated lakes, sediment coarsening is a common effect seen in the upper littoral zone (Carmignani & Roy 2017). Wave erosion washes fine substrate into the deeper areas in the lake, potentially leaving the upper littoral with a dominance of coarse substrate, unsuitable for many plant species. Wave erosion often create coarse substrate in the upper littoral zone of natural lakes as well, especially when the shore is steep. The effect is, however, often larger in regulated lakes, because the wave erosion impacts a greater vertical extent of the shoreline. Substrate coarsening and less fine sediment reduces the habitat quality for water plants and may reduce both abundance and diversity. Based on data from 44 regulated lakes in Norway, Sweden and Finland, the species richness of macrophytes decreased significantly with increasing winter drawdown (Mjelde et al. 2012).

4.4 Macroinvertebrates

Macroinvertebrates inhabit the lake bottom (benthic invertebrates). Of particular importance for lake ecosystems are the macroinvertebrates dwelling in the littoral zone. This group reaches from the large noble crayfish and other crustaceans (*Lepidurus, Gammarus, Asellus*) to insect nymphs and larvae, worms, nematodes, snails and molluscs. The shallow, sunlit areas along the shore usually comprises higher habitat complexity than the deeper ‘profundal', with a mix of different substrate types, including water plants and a broad scale of particles reaching from large rocks to pebbles, sand and fine sediments. This variability offers a mosaic of microhabitats for species with different niche preferences. Furthermore, the littoral is rich in biofilms and benthic algae, which offer high quality food sources for numbers of invertebrates. Pristine lakes (at least below the tree-line) are encircled by riparian vegetation and forests, which perform complex ecological interactions within the lake littoral zone, not the least by means of shading and litter production, which many invertebrates feed on. High habitat complexity may hence facilitate macroinvertebrate diversity (Schmude et al. 1998).

Dewatering of the littoral zone due to anthropogenic water level fluctuations negatively influences the benthic invertebrate fauna, but the sensitivity differs between taxa (Carmignani & Roy 2017). As observed for water plants, the regulation amplitude is important for the degree of impact. In a study of 28 regulated (for hydropower) and 20 unregulated lakes in Canada, the macroinvertebrate diversity (family richness) decreased significantly with regulation amplitude (White et al. 2011; Figure 4.3). A similar pattern was observed in Finnish lakes (Aroviita & Hämäläinen 2008).

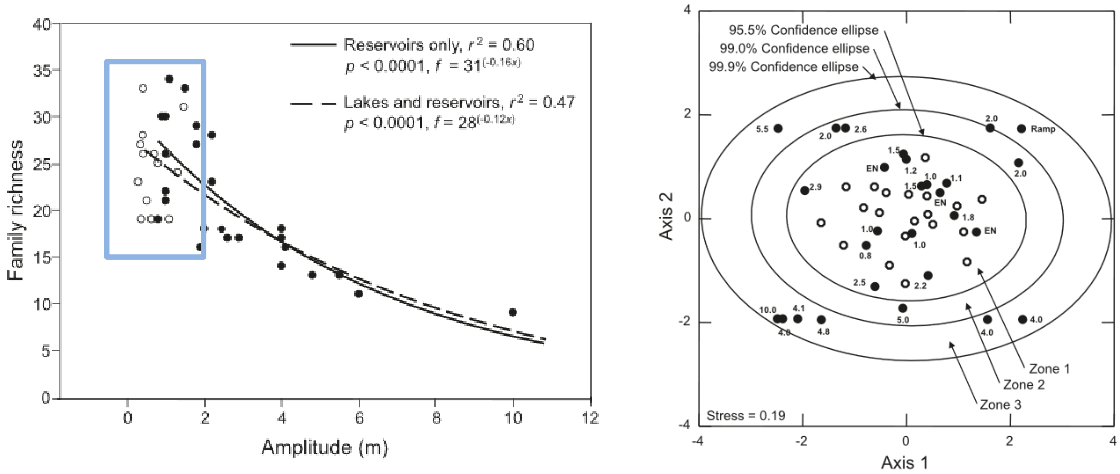


Figure 4.3. Left: Family richness of macroinvertebrates as a function of regulation amplitude in Canadian lakes. Filled circles are reservoirs, while open circles are natural, unregulated lakes. Blue rectangle highlights lakes with regulation amplitude < ca. 2 m. Right: An ordination diagram showing differences in community structure of macroinvertebrates in the same lakes. The number beside each dot is the regulation amplitude. From White et al. 2011.

In the Canadian lakes, the effect of regulation amplitude on diversity was not present when comparing lakes with amplitude is less than ca. 2 m (orange circle in figure 3, left). The community composition in lakes with less than ca. 2 m regulation amplitude was also similar to natural lakes (Figure 4.3, right). When the amplitude increased above 2 m, the community composition began to deviate significantly from natural communities. These results indicate that there may be a threshold around 2 m before significant effects are observed on diversity and community structure. Interestingly, this threshold was not observed in Finnish lakes (Aroviita & Hämäläinen 2008). Here, the diversity decreased rapidly when moving from unregulated lakes to lakes with regulation amplitude on 1-2 m, and thereafter stabilized at a low level with increasing amplitude. The difference in response may be related to differences between the sets of lakes, e.g. in basin slope or morphometry, or in the mode of water level variation.

Brabrand (2010) analysed the effects of HYMO on macroinvertebrate species that are important food sources for vertebrates, as reflected in gut content analyses from trout, using a large dataset from 55 regulated Norwegian lakes. To our knowledge, this study comprises the largest addressing littoral macroinvertebrates conducted in Norway, although the study only includes macroinvertebrates found in trout gut contents. Brabrand's analyses (based on Aass 1969) is of relevance also because it specifies effects of regular (seasonal) water level variation (38 lakes) from effects of rather unpredictable water level change, most typical seen related to 'hydro-peaking' (17 lakes). The first category represents the typical seasonal water level variation seen in most reservoirs during the last century, where water level variation roughly followed a seasonal pattern. LRW was reached by onset of snowmelt (early spring), before the reservoirs re-filled during summer, peaking in autumn, and water levels again dropped during winter. This somewhat 'predictive water level variation' allows some adaptive responses in the littoral fauna, where species with dry resistant eggs were favoured. Presently however, water level varies rather rapid and stochastic in many reservoirs, due to new regimes of oprating the reservoirs. This new type of reservoir management makes it much more difficult to predict impacts of regulation on the littoral community.

Following Brabrand (2010), it is convenient to distinguish categories of littoral macroinvertebrates according to mobility and habitat differences and preferences. Certain taxonomic groups, like snails and caddies fly larva, are rather immobile. Such taxa are expected to be strongly negatively affected by (fast) water level changes. Other, like *Lepidurus,* dragonfly and mayfly nymphs are mobile and should be less affected. Finally, certain invertebrates, notably Chironomids, are rather unselective in terms of habitat preferences, and inhabit profundal fine sediments as well as the shallow littoral. Such taxa should be expected to respond indifferently to water level variation.

The gut content analyses of trout from reservoirs with relatively predictable water level fluctuations corresponded well with these expectations (Table 4.1). The amphipod *Gammarus* was absent from trout diets in reservoirs with water level variation > 6 m, while caddies fly larvae were found in trout guts from reservoirs of 10-12 m regulation heights. Certain crustaceans, notably tadpole shrimp (*Lepidurus*) and *Eurycercus lamellatus* (linsekreps), and likewise Chironomids, were largely independent of regulation heights.

Table 4.1. Occurrence of various invertebrates from 38 regulated lakes, as related to regulation amplitude. While the amphipod *Gammarus lacustris* (marflo) solely were found in trout inhabiting basins < 6 m regulation and caddis flies (*Trichoptera*) occurred in the diet even in lakes of 12 m regulation heights, rapid moving species like the tadpole shrimp (*Lepidurus*) were still present in trout diet even in reservoirs with considerable regulation height. The data solely concerned reservoirs with predictable water level variation. After Brabrand (2011).

Group	**Critical regulation amplitude**
Gammarus lacustris (marflo)	*6 m*
Snails	*8 m*
Caddis larvae	*10-12 m*
Chironomids	*> 35.5 m*
Tadpole shrimp (Lepidurus)	*> 35.5 m*
Eurycercus lamellatus (Linsekreps)	*> 35.5 m*
Bytotrephes	*> 35.5 m*
Daphnia sp.	*> 35.5 m*

Taken together, the hypothesized negative impacts of lake regulation on littoral macroinvertebrates, especially on species richness, is generally confirmed empirically. It is also reasonable to expect that total productivity of benthic invertebrates will decrease with regulation amplitude, in proportion with loss of suitable, wet habitat. The effect will however differ depending on factors like taxon behaviour, regulation height, basin shape and morphometry, and substrate characteristics.

4.5 Fish

Water level regulations and other hydromorphological alterations may influence both the macrophyte- and macroinvertebrate communities, as well as the abiotic structure of lake ecosystems, including substrate structure and distribution, reduced nutrient (phosphorus) levels over time, and barriers within and between systems. Being high up in the food-chain, and relative long-lived, fish are considered to integrate effects of environmental stressors on lower trophic levels (Hirsch et al. 2017). Moreover, since many species spawn either in the littoral zone or in streams/rivers entering the reservoir, fish can be susceptible to changes in substrate quality and water level, and timing of water level changes.

Effects of water levels changes on fish in alpine hydropower reservoirs is reviewed in Hirsch et al. (2017), and much of the text in this chapter is based on this review. They point out that, even though fish are expected to be influenced by the ecosystem changes imposed by e.g. water level regulations, there may be complex interactions between hydromorphology and natural processes, making predictions on fish response far from straight forward. For example, reservoirs are generally believed to become depleted in nutrients over time, with reduced littoral habitat heterogeneity and corresponding reduced densities of littoral prey items. Recruitment may also be negatively influenced. Still, fish yield in 67 Norwegian reservoirs showed no response to regulation amplitude (Hirsch et al. 2017). Comparing regulated and natural lakes in Finland, Sutela & Vehanen (2008) found no significant differences in fish density or species diversity. However, the fraction of littoral and zoobenthos-feeding fish in the biomass along stony shores was significantly reduced in lakes with higher winter drawdown. This supports the hypothesis that species feeding and / or spawning in the littoral are more susceptible to water level regulation (WLR) than pelagic species. Along a gradient of WLR magnitude covering 102 lakes, Eloranta et al. (2017) found that the density and biomass of brown trout *increased* with WLR magnitude, especially in large and complex shaped reservoirs. This result was somewhat counterintuitive, but sheds light on some important factors related to fish and WLR.

First, in large and complex reservoirs, the trout might find enough prey and suitable habitats even though the littoral is impaired. This, however, is only the case if trout is the only fish species in the reservoir (allopatric populations of trout). In sympatric populations (i.e., more species present), trout biomass and density decreased with WLR magnitude, indicating that trout – being a littoral species –is an inferior competitor if the littoral habitat is reduced by WLR. It is well known that species like whitefish and char are better adapted to feeding on zooplankton in the pelagic than trout. Although density increased with WLR in allopatric populations, the condition factor (as a scaling of fish quality) of the fish decreased. Hence, there were more fish, but the fish was thinner. This may indicate changes in prey availability and preference with WLR magnitude.

In reservoirs, the timing and magnitude of WLR may enhance shore erosion, which may increase turbidity and reduce light levels. Such effects are modified by geology, where fine substrates or clay can cause higher increases in turbidity than bedrock (Hirsch et al. 2017). There are examples, e.g. from the Ringedal reservoir in Hardanger (western Norway), that a large drawdown in summer may cause strong increase in turbidity, low light levels, and subsequent reduction in pelagic production that eventually led to reduced growth and survival of brown trout (Borgstrøm et al. 1992). Several alpine reservoirs have turbid water due to resuspension of silt from the sediment (Hirsch et al. 2017), which will influence pelagic primary productivity.

Successful spawning and recruitment are dependent of access to spawning grounds, suitable spawning substrate and no draining of the substrate where the eggs are laid. As different species spawn at different depths, areas, and at different times of the year, effects of WLR on recruitment is highly species dependent. Arctic char, for example, spawns at relatively shallow depths in late autumn. In lake Møsvatn (an alpine reservoir in eastern/central Norway), reduced recruitment of char was linked to changes in the draining pattern of the lake, with earlier emptying of the magazine in the spring. If the lake level is lowered below the depths of the spawning grounds before the young char can migrate to deeper waters, mortality may increase significantly (Brabrand 2011). Low water levels in spring can also reduce recruitment of the autumn-spawning whitefish (*Coregonus lavaretus*), as seen in lake Osensjøen – a hydropower reservoir in south-eastern Norway (Linløkken & Sandlund 2015). The low levels in spring did, however, not influence the recruitment of vendace (*Coregonus albula*), most likely because the vendace spawns deeper than the whitefish.

Undoubtedly, general responses of fish to WLR are complex and may be hard to find. Hence, also pointed out by Hirsch et al. (2017), assessments of the effects of WLR and other HYMO impacts on fish should be case/lake-specific, as local differences in biotic factors (e.g. species composition of fish and prey) and abiotic factors (e.g. basin morphometry, size, hydrology and water chemistry) may modify the response to of fish to HYMO.

5 Evaluation of the classification system and its suitability

5.1 Evaluation of the suitability of the classification system

Chapter 2.1 of this report presents a set of criteria to evaluate the suitability of the classification system that was established before the testing started. The results from testing of the system have been evaluated against these criteria and has formed the basis for proposing a new and revised version of the hydromorphological classification system (Chapter 7).

Table 5.1. Defined criteria of suitability of the hydromorphological classification system (version 1) and the evaluation based on the testing.

Criteria	**Evaluation**
The classification system should include parameters that are considered being important descriptors of hydromorphological alterations	All the parameters should ideally be included in the system as they all describe important hydromorphological properties of lakes and reservoirs. The changes in retention time should maybe be included in the next version of the classification system, as it deems to be an important descriptor of physical changes due to regulation.
The parameters should to a limited extent overlap each other	The system as proposed in Bakken et al. (2018) was considered including 'all possible relevant parameters' (gross list), making the system very extensive, with a risk of overlap between parameters. A goal for a new system has been to propose a 'net list' of parameters, reducing the number of parameters. This would also hopefully reduce the risk of overlap between parameters. There is, however, most likely a correlation between some parameters. If this is an undesired situation, this effect can be reduced by adjustments in the weighting procedure.
The class borders should cover the range of hydromorphological alterations, and the parameters should be reasonably sensitive to hydromorphological changes	Based on the classification of the individual parameters for each lake it appears that the results show a fairly good spread (see Table 3.1), based on the assumption that the selected case study lakes are representative for large Norwegian lakes. All parameters, except 2.16 and 2.22, parameter, produce results in at least two classes. The parameters 2.17 and 2.23 – 2.26 give results in two neighbouring classes. As such, it does not seem reasonable to make major adjustment of class borders. As the new system is based on five classes some adjustments are made. The overall classification (aggregation of individual parameters) seems to reduce the variations in the results.
The parameters must be unambiguously defined	The experiences from the project contributes to a modification of some parameters and an improved definition of them. It is important that the calculation of the classified values can be done in a robust manner. Example of parameters that were not sufficiently clearly defined in Bakken et al. (2018) were upstream and downstream barriers (Parameters 1.13, 1.14 and 3.10). Some of the parameters to be classified vary extensively in time and space within the lake (such as Parameter 2.41 and 2.50-2.54), and it is a scientific

	challenge to define how their representative value should be defined or calculated. These parameters are also very time-consuming to calculate.
The parameters should have an ecological relevance	All alterations in hydromorphological conditions are considered having some sort of ecological impact. As the relationships between hydromorphological alterations and ecological response are not very clear (see Chapter 4), it is difficult to select a limited set of hydromorphological parameters that should be included based on ecological relevance or importance only. It is also a fundamental discussion if the hydromorphological classification shall be developed based on the concept of being a proxy of an ecological assessment, or if hydromorphology should be assessed as a completely independent quality element.
It should be data and/or tools available (today or in the near future) to analyse/calculate the given parameters for a classification	The selection of parameters in the new and updated version of the classification system has been made based on the requirement that it should be possible to do a hydromorphological classification with use of tools that can handle multiple lakes within the same work process. It should not be needed to carry out site visits to do a classification and extensive literature search for each individual lake.
It should be possible to calculate the parameters with reasonable resources	It appears that 30 parameters as defined in the first version of the classification system, are too many to be included in an operational system, and the new system that is proposed (in Chapter 7) includes a reduced number of parameters. With a high a number of parameters, the importance of each individual parameter will also be very limited as they are aggregated into one overall classified hydromorphological alteration value for a lake in the end. Parameters that were very time-consuming to calculate were mostly left out of the new system. There are parameters that require extensive manual work. This can be due to extensive manual search in literature for data, poor quality of the available data or simply lack of tools to analyse the data. Example of parameters hampered by such a situation are for example parameters related to the configuration of the lake(s) before regulation and barriers in the river systems.

5.2 Discussion on substrate characteristics and physical & chemical processes

5.2.1 Parameters describing substrate characteristics within the lake (2.40 – 2.41)

The purpose of the parameter Removed or added gravel and sediments (2.40) is to assess if sand, gravel or other fractions of the sediments have been removed, e.g. for the purpose of taking out building materials from the lake or improve the conditions for boats and transportation. Sand can also be added to the shoreline of lakes in order to improve the conditions for recreation and swimming. It is probably a fairly low number of lakes in Norway where this has happened, and when this has happened the volume excavated is probably low. The next challenge during classification is that data on these hydromorphological alterations are difficult to find and extensive manual work would be needed.

Figure 5.1. Sand ready to be distributed on the beach of Tunevannet, Østfold, for the purpose of improving the conditions for recreation and bathing.

The parameter 2.41 Porosity of substrate was originally included based on the experiences from rivers, where substrate conditions can change over time due to hydropower regulations and reduced floods. This can then reduce the shelter for biota and the number of suitable areas for spawning (Forseth & Harby, 2014). It is not given that the substrate plays a similarly important role in lakes, and it is often more difficult to measure the substrate qualities in lakes. Furthermore, as it is the changes from before regulation that forms parameter 2.41, it is unrealistic that reliable assessments of substrate quality can be made for thousands of lakes with reasonable resources invested. As such, it should be considered to leave this parameter out except for those cases where these hydromorphological alterations are considered significant and important.

Figure 5.2. Inspecting the substrate along the shore of Jonsvannet, close to Trondheim, through the ice.

5.2.2 Parameters describing physical & chemical processes within the lake (2.50 – 2.53)

All the parameters regarding changes in water velocity, water temperature, ice conditions and clarity are very difficult or very time-consuming to calculate, but are fairly simple to measure or observe (for one lake). There are also some scientific challenges with respect to selecting a representative location (spatial aspect) and period of the year to represent the hydromorphological changes (time).

In monitoring as well as during a classification it is a challenge to select a representative location in the lake and the most representative time, or how measurements/model results from a set of locations should be aggregated in time and space. A large lake will probably experience practically no changes in water velocities if the measurements are made far from the introduced change (e.g. an intake to a hydropower plant), while the changes can be significant close to the inlet. The changes can also be more pronounced in some periods of the year than in others.

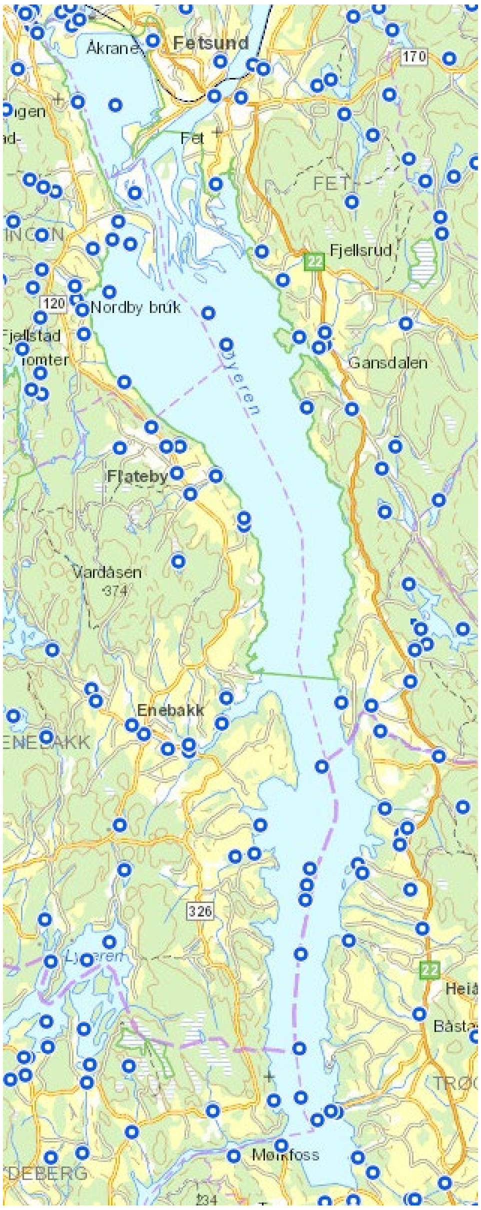


Figure 5.3. Lake Øyeren has a large number of monitoring locations registered in Vannmiljø database (www.vannmiljo.no), which holds biological, chemical and physical monitoring data. Several of the locations (shown with blue rings) also have monitoring data from different depths.

The modelling tools presented and described in Bakken et al. (2018) could be useful in case input data is available and sufficient resources can be invested to configure a model. MyLake is a 1-D model (Saloranta & Andersen 2007), while CE-QUAL-W2 is a 2-D model and the GEMSS is a 3-D Model, the latter developed by ERM's Surface water Modelling Group in Pennsylvania (http://www.ermsmg.com). All these models can simulate hydrodynamic effects in the lake. For the practical use of the classification system, a 1-D model is probably the best solution, as the time to set up and calibrate a model is shorter, to the cost of lost details. A 1-D model would probably produce results of sufficient quality for screening purposes, while more complex tools might be needed in more complex cases where more details are required.

The data availability is always a major concern when a model should be configured. A lake model would need a variety of data input, which includes data on meteorology, hydrology (inflow and outflow of the lake) and the operation of the hydropower plant, if the lake is affected by this. The bathymetry must also be given, and normally also data for calibration. From the calibrated model, scenarios of the situation prior to the hydromorphological alterations can be simulated. It can, however, be a challenge to find reliable data for all lakes and reservoirs in Norway. In particular, bathymetric data and data for calibration will be difficult to obtain.

Figure 5.4. Jonsvannet is normally ice-covered in February. Jonsvannet is regulated for the purpose of drinking water supply to Trondheim.

Several of these parameters are difficult to calculate. Water temperature changes are in many cases a very important parameter to assess when ecological impacts downstream the lake is assessed, There is, however, limited water temperature data available in the majority of the lakes. In the Vannmiljø-database (www.vannmiljo.no) scattered measurements are available. We would encourage the authorities and the hydropower companies to start regular, continuous monitoring of this parameter.

5.3 Missing data or data of poor quality

An important and time-consuming part of the classification has been to control the quality of the data. The first step was to check if the data series (volume and water level) were complete and logical. For the calculation of the parameters it was important to have entire years, because gaps or wrong data distort the results. Thus, incomplete years were deleted from the dataset.

Another step was to adjust the reference level (datum) of the water level time series. The water level time series from NVE refers to meter above sea level. Thus, the series shows a 'water level' of 950 m, when the lake is located 900 m above sea level and the actual water level is 50 m. The classification has to be based on the actual water level, which refers to the bottom of the lake. Therefore, all water level time series had to be recalculated. Another problem that might appear is the change of datum during the observation period.

It can also be the case that the water level and volume data from the same lake do not correspond correctly, e.g. that the regulation introduces an increase in water level while the volume appears to be reduced, or vice versa (Figure 5.5).

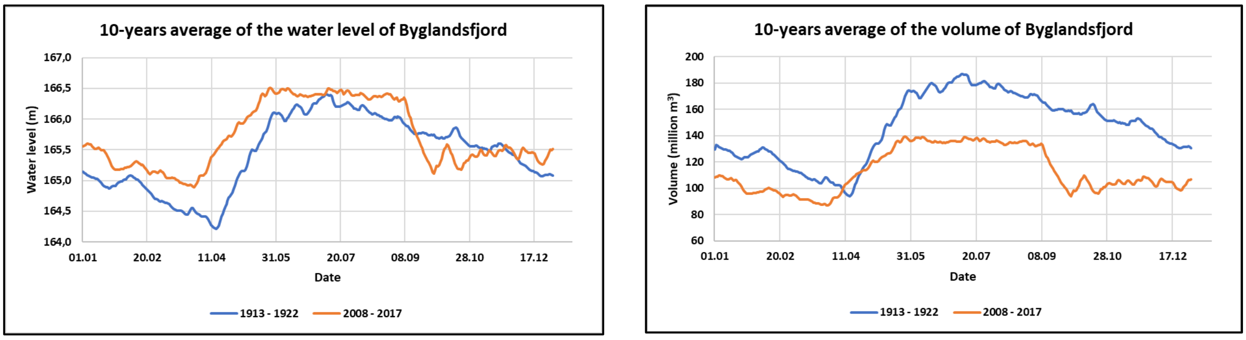


Figure 5.5. Water level time series of Byglandsfjorden before and after regulation (left) and the same volume time series (right).

By studying the full time series of volume of Byglandsfjorden, something happened in the measurements in the shift between year 1999 and year 2000. It is not clear the reason for this shift. For the purpose of the classification of Byglandsfjorden, a practical solution was selected by using an earlier period (up to year 2000) for the classification of parameters based on volume.

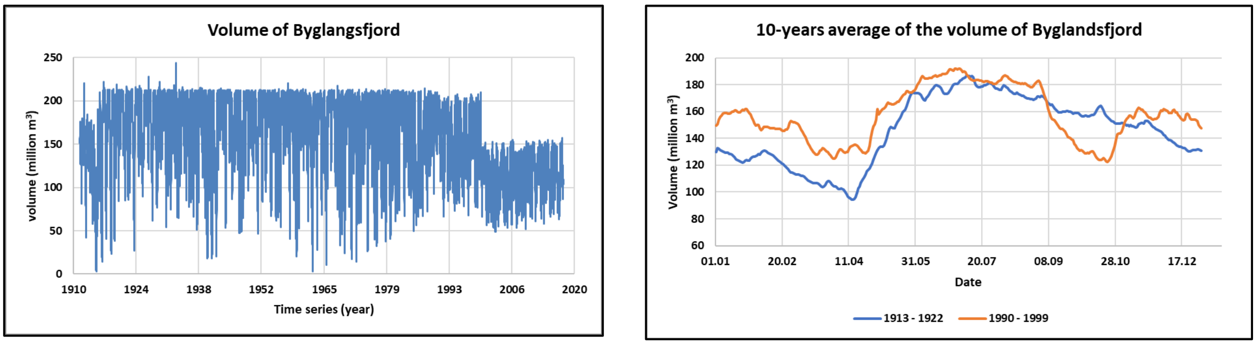


Figure 5.6. The graph to the left shows the full time series of volume of Byglandsfjorden, while the graph to the right shows the volume of the lake before and after regulation when the data for the situation after regulation is based on data in the period 1990-1999.

These types of problems might occur for several of the parameters to be calculated. Water level data is very central in the calculation of many parameters and a 'key stone' in how the classification system is defined, and it must in particular be controlled prior to use.

The overall classification should be made with care in those cases where parameters are calculated based on uncertain data input or data are missing, which in practise will happen for almost all lakes. The sensitivity of the weighing procedures to the overall results is analysed and discussed in Chapter 3.3, and how this is supposed to be handled in future classifications is discussed in Chapter 7.4.

5.4 Hydrological data and bathymetry

Hydrological data and data on the bathymetry of the lakes are very central in performing a classification. If water level data is not available, water level and volume changes in the lake can be derived from inflow/outflow data if the bathymetry is available. Several parameters are further related to the effect of the water level changes, such as dewatered areas and losses of littoral zone. In total, 10 of the 20 tested parameters are based on either water level or water volume changes. Neither water level series or the bathymetry were available for Krøderen, Limingen and Røsvatn. For these lakes 12 of the parameters could not be calculated (see Table 3.1). Therefore, these are the primary data to compile when the system is applied in the future.

If data on water level before and after regulation are available from monitoring data, the process of calculating the hydrological changes is quite straight-forward. If these data are missing, the process is a bit more challenging. In order to calculate the water level fluctuation in the lake a water balance of the lake must be established. In the unregulated situation the inflow of water must be known, which can be taken from HYPE-simulations (Schönfelder et al. 2017). The outflow of the lake must also be estimated. The outflow is a function of the shape of the outlet. A narrow outlet will hold the water back in the lake, while water flow more easily out of the lake with a wide outlet with a low threshold. An example of a lake with a narrow outlet is Selbusjøen where 'Trongfoss' controls the outflow of Selbusjøen with the effect that water level of Selbusjøen increases more rapidly than if the outlet structure was wider. As such, 'Trongfoss' has saved Trondheim from flood damages while the areas around Selbusjøen has historically experienced severe flood damages.

A set of different formulas are available for calculation of the outflow responses, based on the width of the outlet, the depth and an outlet/conveyance coefficient. The application of the formula would require detailed data on the geometry of the outlet. This is usually not available, which reduces the possibilities to calculate the outflow precisely. In addition, it is also needed to have data on the relation between volume and water level of the lake. This can be derived from bathymetric maps. If bathymetric maps are not publicly available, the hydropower companies can possibly be contacted as they would normally have volume-water level curves for their reservoirs.

The evaporation of the lake surfaces can also be calculated by use of a hydrological model (such as HYPE), or separately outside a model tool. There exists a set of different evaporation formulas that can be applied, e.g. based on variant of Penman-Monteith equations, or more simplified formulas, or apply long-term average evaporation estimates as published by NVE (Beldring et al. 2002). Data of evaporation can also be found in www.SeNorge.no.

In order to calculate the water balance in the regulated situation, also the water withdrawals for hydropower production must be known. This information is available from the hydropower companies and/or NVE, but is often confidential. HYPE holds some algorithms to calculate power production, but this is a very simplified procedure and is not expected to produce reliable results. A better approach might be to configure a hydropower simulation tool, if real data cannot be retrieved.

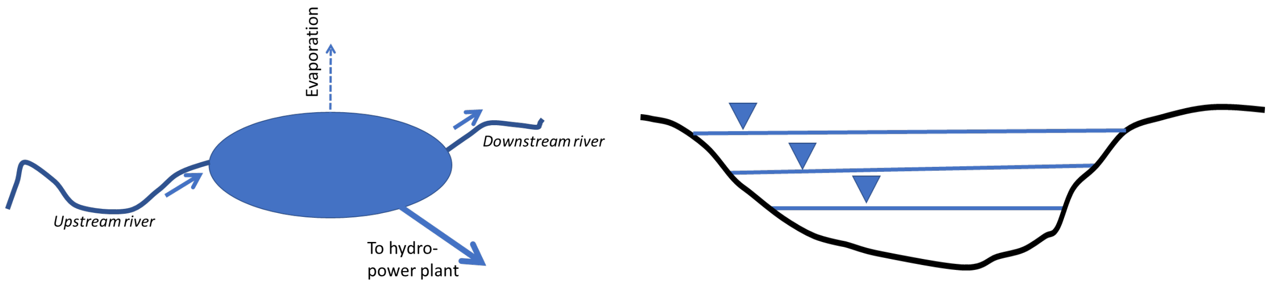


Figure 5.7. In- and outflow of a regulated lake (to the left), withdrawal for power production and evaporation fluxes, and corresponding water level changes given by the balance of these fluxes and the bathymetry (to the right).

Bathymetric maps are now available for many lakes in Norway. NVE offers fully digitized and geo-referenced bathymetric data from approximately 360 lakes in Norway in formats allowing further processing in GIS. In addition, scanned paper maps are available maps for some more lakes. The fully digitized and geo-referenced must, however, be processed before they can be used in the classification.

These maps must be processed in several steps. As they are given in contour lines (vector format), raster grids must be created. First, points along the contour lines are created. As contour lines do not cover the whole surface, and thus the points do not either, an interpolation method is required, where one method is the Kriging interpolation. It does not just predict a surface but also tells how probable the interpolated values are. The main part of Kriging is the semi-variogram, shown in Figure 5.8 for the test lake Årdalsvatn. It calculates the spatial autocorrelation, which means it shows how similar an object is compared to other objects. The idea is that the closer (spatially) the objects are to each other, the more similar the objects are. The calculation of the semi-variogram requires adjusting certain settings. The main settings are the cell size and the maximum distance between the objects. It is important to set the distance correct in order to cover the entire lake. These settings are unique for each lake. Each point represents the comparison of two data points, in this case the points on the contour lines. The x-axis shows the spatial distance and the y-axis shows the variance between the objects. The lower the variance the more similar their values are. At a certain distance the variance almost stops increasing, which means the points are no longer correlated. The next step is to fit a function to the points. This function can be adjusted in order to maximise the determination. Thus, the variables of the function are adapted. Afterwards, the tool calculates the grid based on the previous settings.

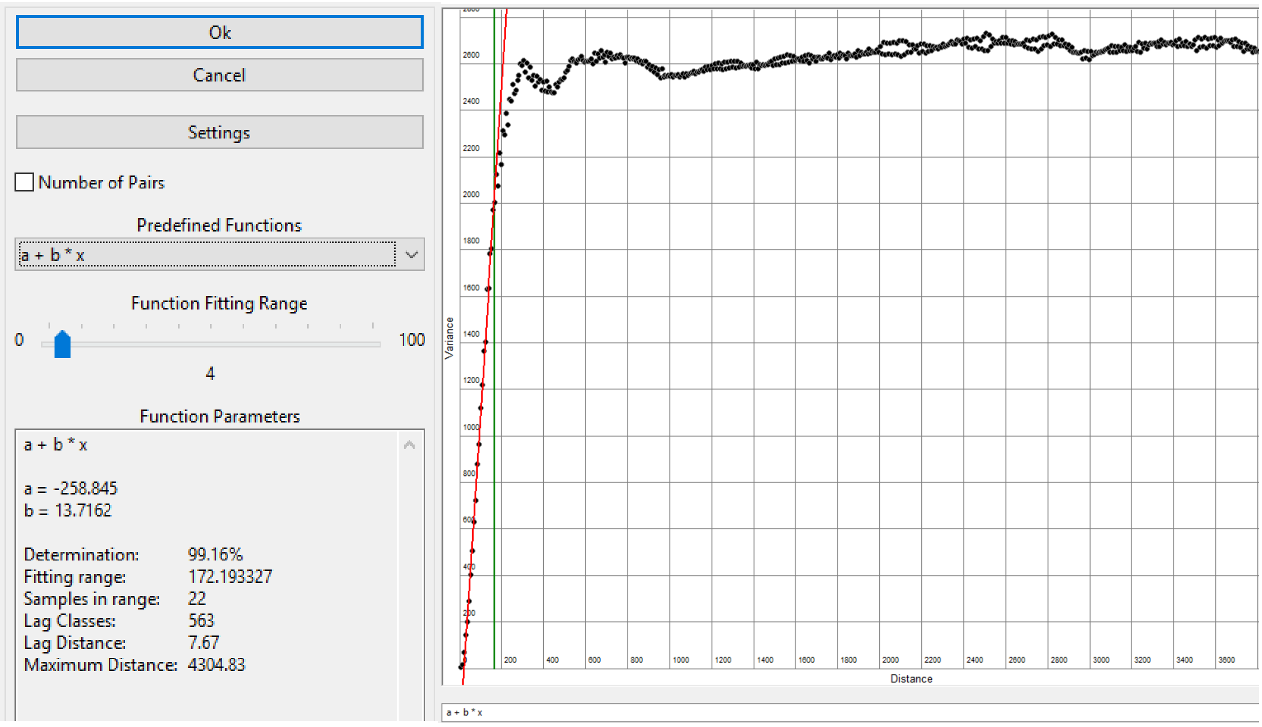


Figure 5.8. Semi-variogram of Kriging interpolation, on the left-hand side the fitting of the curve can be adjusted, the right-hand side shows the data points and how good the adjustments fit.

The resulting bathymetric map of Selbusjøen, calculated based on the procedure described above, can be seen in Figure 2.8.

5.5 Alterations from undisturbed lakes versus degree of regulation

Some of the parameters in the classification system are defined as describing the hydromorphological alteration from undisturbed conditions to 'typical situations after regulations', which is in line with the concept of classification of natural water bodies in the EU WFD. Other parameters are designed in such a way that they rather classify the degree of hydromorphological alterations, with the highest and lowest regulated water level (HRWL/LRWL) as the basis. These parameters rather assess the 'degree of regulation' than hydromorphological changes from pristine conditions. This a more fundamental discussion about the formulation of the classification system, i.e. if those parameters describing the degree of regulation should be included or not, which is not yet decided upon.

Table 5.2. The table identifies which parameters that are calculated by comparing the present hydromorphological conditions with natural state and which parameters that are calculated with the HRWL and LRWL as the basis, i.e. the degree of regulation.

Area considered	No	Parameter	Comparison with natural	Degree of regulation
Upstream changes	1.10	Hydrology: Change in annual inflow	X	
	1.11	Hydrology: Changes in periodicity (inflow)	X	
	1.12	Change in water temperature of inflowing water	X	
	1.13	Barriers affecting availability of upstream habitat	X	
	1.14	Sediment changes due to upstream barriers	X	
Flow/volume of water and water level of lake/reservoir (hydrology)	2.10	Water level changes		X
	2.11	Total volume change of lake	X	
	2.12	Seasonal change: Summer	X	
	2.13	Seasonal change: Fall	X	
	2.14	Seasonal change: Winter	X	
	2.15	Seasonal change: Spring	X	
	2.16	Short term water level variations (days)	X	X
	2.17	Short term water level variations (weeks)	X	X
	2.18	Annual maximum flood level	X	
Processes along the shoreline of the lake/reservoir (shoreline morphology)	2.20	Dewatered areas		X
	2.21	Relative lake level fluctuation		X
	2.22	Dewatered littoral zone versus total littoral zone (ratio)		X
	2.23	Shoreline development (dimensionless number)		X
	2.24	Loss in lateral connectivity along the shoreline (due to e.g. embankment/erosion protection)	X	
	2.25	Riparian zone changes	X	
	2.26	Erosion introduced by changes in flow pattern/filling/water level variations	X	
Fragmentation & barriers within lake & reservoir (habitat connectivity)	2.30	Connection/de-connection of lakes due to regulation/water level changes	X	
	2.31	Man-made infrastructure/barriers within lakes/ reservoirs and barrier effect due to water level changes	X	X
Processes within the lake related to substrate of lake & reservoir	2.40	Removed or added gravel, rocks, sand and other sediments	X	
	2.41	Porosity of substrate	X	
Physical and chemical processes in the water of the lake & reservoir	2.50	Flow velocity changes due to changes in inflow/outflow	X	
	2.51	Water temperature	X	
	2.52	Ice conditions (surface, shore ice)	X	
	2.53	Water clarity	X	
Downstream changes	3.10	Barrier effects (hindering migration between lake/reservoir and downstream areas)	X	

Based on the experience in this project it is much faster to calculate those parameters that describe the 'degree of regulation' than those that are based on comparing with the present situation with the situation before regulation. We also think that they are calculated with higher certainty. One of the main reasons for the scientific challenge of comparing the present situation with the situation before regulation is the availability of historical data. As some hydropower projects are more the 100 years old, it can be that data simply does not exist, unless they can be modelled.

The parameters 2.16 *Short term water level variations (days)* and 2.17 *Short term water level variations (weeks)* could have been interpreted as a description of the degree of regulation. As the natural water level changes are considered being very slow compared to water level variations we can observe in regulated lakes, we consider the natural variations as negligible, and simply compare today's water level variations with zero fluctuations. Similarly, for the parameters 2.25 and 2.25 we assume that there was no embankment and that the riparian zone completely filled the areas around the lake, unless the lake is located above the tree-line.

5.6 The HYMO classification system compared to the identification of HMWBs

This chapter aims at comparing the criteria for designating lakes to heavily-modified water bodies (HMWBs) with the hydromorphological classification system proposed in Bakken et al. (2018) and the proposed new system in Chapter 7 (parameters and class borders).

According to the report by Direktoratsgruppen for gjennomføringen av vannforskriften (2018), heavily modified water bodies are designated based on the process illustrated in Figure 5.9.

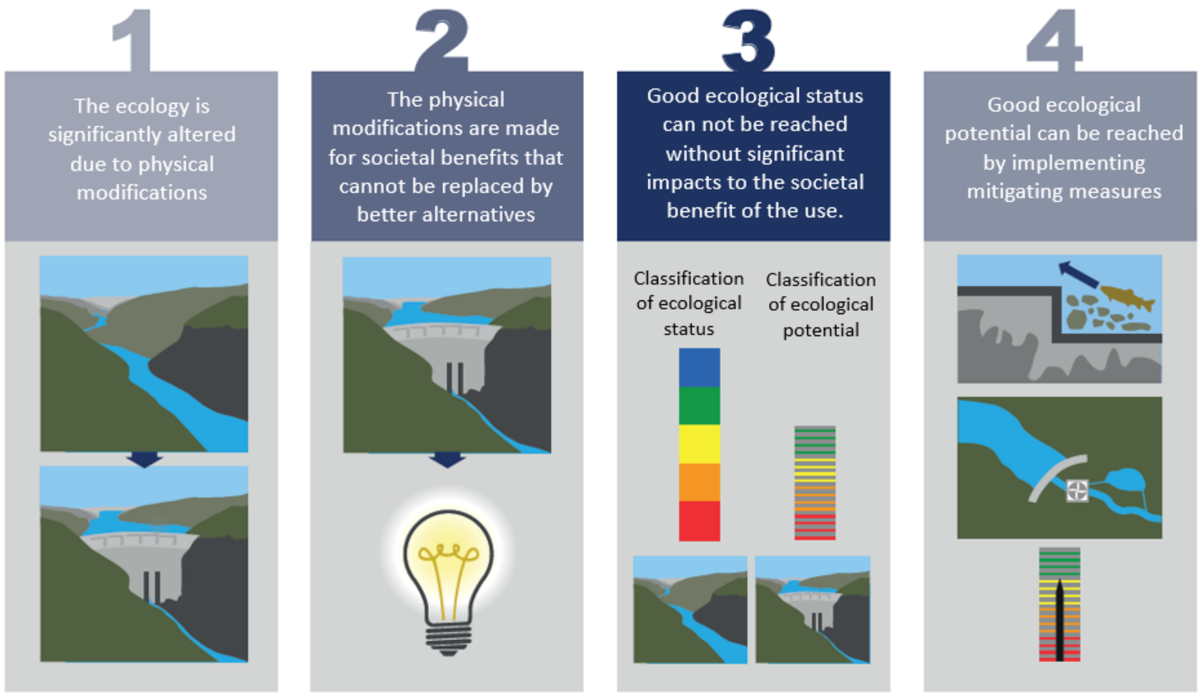


Figure 5.9. The figure illustrates the designation of heavily-modified water bodies and the achievement of good ecological potential (GEP) (translated from Direktoratsgruppen for gjennomføringen av vannforskriften (2018)).

Criteria to designate a water body as heavily modified are as follows:

- The water body cannot reach good ecological status, or it has shifted water body type, e.g. from river to lake.
- The reasons good ecological status cannot be reached are that the hydromorphological alterations have been introduced for the purpose of societal benefits.
- The effects of the hydromorphological alterations cannot be mitigated without significant negative impacts on the societal benefits of the present use.
- The societal benefits cannot be achieved by other means that are socio-economic viable or environmentally better.

Table 5.3 presents those criteria applied when the designation of heavily modified water bodies was made.

Table 5.3. Indicative physical criteria to assess the degree of hydromorphological alteration in lakes, and assessment criteria for the designation of heavily modified water-bodies (lakes) (translated from Direktoratsgruppen for gjennomføringen av vannforskriften (2018)).

Criteria of alterations	**ID**	**Indicative criteria for designation of HMWBs**
Damming of rivers/narrowing of rivers, change of water body type	A	Rivers that are significantly dammed or transformed into lakes with a surface area >0.5 km^2. This includes damming where the water level is elevated more than 5 meters compared to the annual flood level. This includes also lakes that are transformed into rivers.
Changes in wetland areas	B	Artificial modification of the water level (in lake or river) with more than 50 cm.
Regulation of lakes and reservoirs	C1	Lakes that are dammed with an elevated water level greater than 10 meters compared to the natural state (independent of regulation height)
	C2	Lakes with a regulation height larger than 3 meters between HRWL and LRWL.
	C3	Lakes with a change in theoretical retention time with a factor larger than 5. This criterion is first of all relevant for lowland lakes. The lake can change character from oligotrophic to eutrophic, or vice versa. The retention time is defined as the lake volume divided on the annual, average inflow.
	C4	Salmon rivers that have changed its turbidity from clear (turbidity < 0.5 FTU) to turbid (turbidity > 2.0 FTU).
	C5	Non-humic lakes that due to increased load of clay/silt have reduced secchi depth with 2 meters or more during the Summer, and that the secchi depth is less than 4 meters.

Some of the criteria defined in Table 5.3 match to some extent parameters that are defined in Bakken et al. (2018) or the revised system proposed in Chapter 7. In the following we have tried to compare and discuss those criteria and parameters that are related to each other. Some of the criteria presented in Table 5.3 do not have an equivalent in a parameter in the (old or new) hydromorphological classification systems.

Table 5.4. Criteria defined in Table 5.3 and how they possibly relate to hydromorphological parameters and their defined class borders.

Criteria	Relates to
A	This criterion relates to some extent to parameter 2.30 (Connection/de-connection of lakes due to regulation/water level changes) in Bakken et al. (2018). This criterion and the parameter touch the same problem, as lakes/river are dramatically changed, possibly transformed into a different water body type. Parameter 2.30 is qualitatively defined, as the large variety of hydropower projects has made it difficult to define a quantitatively parameter covering this change.
B	Criteria B has defined a conservative (small) level of change qualifying for a HMWB and it covers a specific type of lakes (wetlands). The hydromorphological classification systems proposed do not use typology, and the classification system is not designed to capture lake types of special concern (e.g. wetlands). For this reason, we would not recommend that our hydromorphological classification system is applied to wetlands.
C1	The hydromorphological classification systems presented do not include a specific parameter covering elevating the water level, but rather how the fluctuations are changed due to the regulation. Criterion C1 can hence not be compared directly with one specific hydromorphological parameter, but is to some extent related to parameters P-200, P-205 and P-206 (see Chapter 7).
C2	C2 relates directly to P-200 (see Chapter 7). P-200 | Water level changes | <2 meters | 2-3 meters | 3-10 meters | 10-50 meters | >50 meters C2 defines a heavily modified water body if the regulations height is greater than 3 meters. Comparing this to our proposal for a hydromorphological classification system where the class border between slightly and moderately modified is 3 meters, it appears that the it is too simple to qualify as a HMWB compared to our proposal (i.e. lakes with a larger regulation than 3 meters should not automatically qualify as a HMWB, according or system). The arrow indicates where the criterion for designation of HMWB is set compared to our proposed hydromorphological classification system (version presented in Chapter 7).
C3	The retention time is a new parameter in the system proposed in Chapter 7. P-202 | Change in retention time | <5 % change in retention time | 5-20 % change in retention time | 20-50 % change in retention time | 50-100 % change in retention time | >100 % change in retention time Our proposed class borders are stricter than criterion C3, as a retention time that is five times longer because of the hydromorphological alterations will be far into the class 'severely modified'. As retention time is defined as the lake volume divided on the average inflow, either an increase of volume with a factor of 5, or reduction on inflow to 20% of the original (or some combination of these) will qualify for being a HMWB. From our point of view, C3 appears to allow a very large alteration before the water body is a HMWB. The arrow indicates where the criterion for designation of HMWB is set compared to our proposed hydromorphological classification system (version presented in Chapter 7).

C4	C4 relates to the effect a hydromorphological alteration might have on the downstream river hosting salmon population. Parameter 2.53 in Bakken et al. (2018) relates to changes in clarity, but described as changes in secchi depth, and not FTU, within the lake itself, and not the effect in the downstream water body.
C5	C5 relates to parameter 2.53 in Bakken et al. (2018). C5 is, however, defined for a specific lake type, while parameter 2.53 does not differentiate on lake types (no typology in our hydromorphological classification systems). In Bakken et al. (2018) this parameter is defined as relative change to natural state, while C5 is defined in absolute numbers. This difference in approach is reasonable, but also makes the criteria not directly comparable. Based on our evaluation we found parameter 2.53 difficult to apply for a large number of lakes and is for this reason left out of the revised system proposed in Chapter 7.

6 International perspectives on classification of hydromorphological alterations

6.1 Purpose and overall reflections

An international workshop on hydromorphological classification of lakes and reservoirs was held in Trondheim in October 2019 for the purpose of comparing hydromorphological classification approaches applied in selected European countries, where experts from Sweden, Finland, Germany/Luxemburg, France, Italy and Norway participated. In the following paragraphs, key information, that is considered relevant for the development of a Norwegian classification system, is reported. The information provided in this chapter is to a large extent based on presentations given during the workshop. The presentations given can be distributed on request to the principal author of this report. It should be underlined that the goal is not to develop an identical classification system for all states implementing the EU WFD, but rather harmonising them and ensure that applying them will imply a similar level of environmental standard.

As the number of lakes and reservoirs and the availability of data varies between countries, different approaches will be expected. France, Italy and Germany have some hundred lakes to classify while Sweden, Finland and Norway have thousands of lakes. A smaller number of lakes makes manual processing of data and even field work more acceptable, while countries with a large number of lakes would need to make more use of automatic procedures.

We would also refer to Bakken et al. (2018) where the relevance of the following systems was evaluated with respect to their suitability for Norway, i.e. Lake Habitat Survey, Lake MImAS - Morphological Impact Assessment Tool and GLAHF - Great Lakes Aquatic Habitat Framework.

6.2 Sweden

Information in this chapter is provided by Katharina Vartia and Johan Kling, HaV.

The Swedish system is probably the approach that is most similar to what we have tested and proposed to improve (see Chapter 7). The Swedish system divides hydromorphology into three main hydromorphological elements, i.e. connectivity, hydrological regime and morphological status (Figure 6.1).

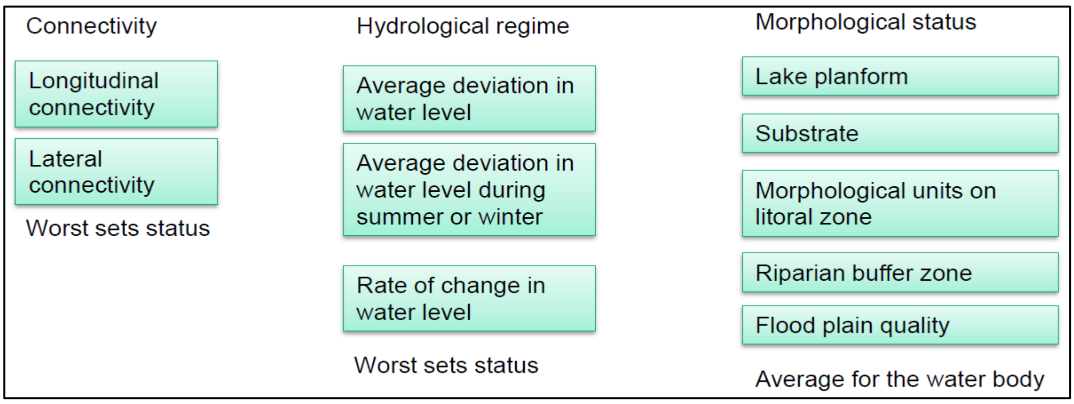


Figure 6.1. Overall division of hydromorphological elements and parameters.

The green boxes in Figure 6.1 represent parameters where quantitative values define the class borders. Examples of these parameters and classes are given in Table 6.1 and Table 6.2.

Table 6.1. The table presents the class borders for annual water level fluctuations in lakes and corresponding status class. The first column refers to status class (High, Good, Moderate, Bad and Poor, from top to bottom), class numbers are in the second column, and the column to the very right describes the changes in water level compared to the average mean water level (translated from HVMFS 2019).

Status	Class	Water level variations in lakes
High	5	The average deviations in water level fluctuations compared to unregulated conditions are less than 0.05 meters
Good	4	The average deviations in water level fluctuations compared to unregulated conditions are in the range 0.05 – 0.25 meters
Moderate	3	The average deviations in water level fluctuations compared to unregulated conditions are in the range 0.25 – 1.00 meters
Bad	2	The average deviations in water level fluctuations compared to unregulated conditions are in the range 1 - 3 meters
Poor	1	The average deviations in water level fluctuations compared to unregulated conditions are greater than 3 meters

Table 6.2. The table presents the class borders for deviations in water level from the unregulated status during winter and summer. The first column refers to status class (High, Good, Moderate, Bad and Poor, from top to bottom), class numbers are in the second column, and the column to the very right describes the changes in water level compared to the unregulated situation summer and winter (translated HVMFS 2019[2]).

Status	Class	Water level variations in lakes during summer and winter
High	5	The average deviations in water level fluctuations compared to unregulated conditions are less than 0.05 meters during summer and winter
Good	4	The average deviations in water level fluctuations compared to unregulated conditions are in the range 0.05 – 0.25 meters
Moderate	3	The average deviations in water level fluctuations compared to unregulated conditions are in the range 0.25 – 1.00 meters
Bad	2	The average deviations in water level fluctuations compared to unregulated conditions are in the range 1 - 3 meters
Poor	1	The average deviations in water level fluctuations compared to unregulated conditions are greater than 1-3 meters

During the development of the system several problems and challenges have been encountered, including those listed below (based on information provided by Johan Kling and Katharina Vartia, HaV).

Connectivity

- Reference condition is a major issue. Many lakes are affected by fish stocking.
- Connectivity between lake and rivers usually binary.
- Connectivity along littoral zone requires more research.

[2] NOTE: It might be an error in the last row of the table (this is directly translated from the original document).

Hydrological regime

- Deviation estimated in the same way as rivers using modelling techniques.
- Good correlation with macrophytes, but present macrophyte index only developed for eutrophication.
- Link to fish status needs further development.
- Regulation during winter has a major effect on benthic fauna on the littoral zone (freezing). This is not picked up in the index.
- Water regulation in impoundments affect also physical-chemical status. Difficult to separate from hydromorphology.

Morphological status

- Some of the parameters can be assessed by desktop studies, others require field data.
- Hydromorphological alterations are less common in lakes compared to rivers.
- Significant morphological impact usually associated with eutrophication and/or acidification. Biological methods cannot separate the pressures.
- Morphological alteration usually decreases with distance from.

Sweden uses typology, based on region of Sweden (southern and northern), altitude (in northern; <200 meters, 200-800 meters and >800 meters), average depth, alkalinity and concentration of humic substances.

6.3 Finland

Information in this chapter is provided by Seppo Hellsten, SYKE.

Artificial water level fluctuations are the main cause of hydromorphological alterations in Finland. The typical annual pattern is that the water levels are lowered during the winter period, spring flood is often smaller and delayed, while water levels during the summer period are higher and quite stable. Short-term regulation might exist, but normally doesn't impact the lakes significantly. Water level drawdowns in the winter are considered being the key factor and the main concern.

Proper water levels for the cabin owners have been important for defining requirements/restrictions on water level regulations in Finland. The water regulations (HRWL minus LRWL) are usually not very large, rather are the smaller regulations/oscillations more typical.

The water level draw-down during winter has been applied as criteria to define regulated lakes as heavily modified water bodies. A water body is defined heavily modified if the water level alterations are:

- greater than 3 m, or at least half of the average depth or
- decreases the water covered area to at least half of the regular size

The following parameters are used to define the hydromorphological status in lakes:

- Average winter draw down (m), or average winter draw down compared with the average depth (%), or change in water covered area (%)
- Raising or decreasing the mean water level (m)
- The proportion of constructed shore line of the lakes shore line (%)
- The effects of bridges and embankments
- Migration barriers

The full classification system with class borders is presented in Table 6.3.

Table 6.3. Hydromorphological classification parameters and class borders.

	Average winter draw down[1] (m)	Average winter draw down compared with the average depth (%) or average change in water covered area (%)[2]	Raising or decreasing mean water level (m) Average depth		The proportion of constructed shore line of the lakes shore line (%)	The effects of bridges and embankments	Migration barriers[3]
			<1.2 m	>1.2 m			
Very high (4 points)	> 3.0	>50	>1	>1.5	>50	Case-specific evaluation	Migration of fish completely prevented
High (3 points)	>1.5-3	>30-50	>0.5-1	>1-1.5	>20-50	Case-specific evaluation	Migration of fish almost completely prevented
Moderate (2 points)	>1.0-1.5	>10-30	0.1– 0.5	0.5-1	10-20	Case-specific evaluation	Migration of fish partly prevented or only some species are able to migrate
Slight (1 point)	0.5- 1.0	1- 10	< 0.1	< 0.5	<10	Case-specific evaluation	Only migration of some species is prevented
No change (0 points)	< 0.5	<1	0	0	<5	Case-specific evaluation	All fish and the rest of aquatic fauna can migrate

Footnotes to the table:

1) The water depth at the time of the ice cover formation - the lowest water level during the period of ice cover. Calculate average e.g. from years 1995-2005.

2) Both factors shall be estimated. Points shall however be given for only one of the factors.

3) Can be evaluated in several discharge situations if necessary. Also the impacts of the migration barrier on the fish stocks can be taken into account.

The points given in the column to the left in Table 6.3 are then summed to give the overall score (Figure 6.2).

Level of hydro-morphological change	Changes in the hydro-morphological status	HyMo-points
0	No change	0 – 1
1	Slight change	2 – 3
2	Quite significant change	4 – 5
3	Significant change	6 – 9
4	Very significant change	10 -

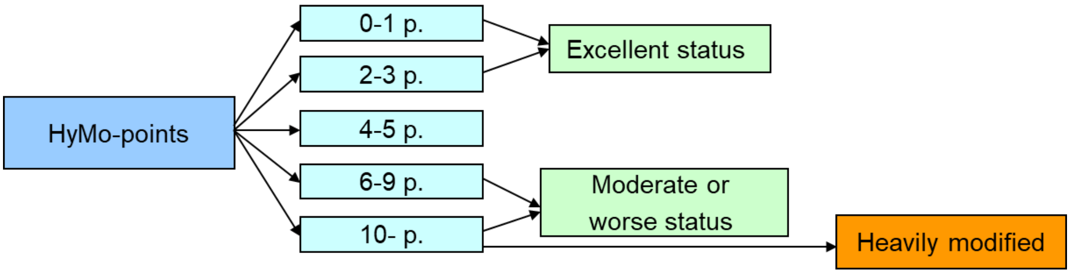


Figure 6.2. The figure shows the aggregation of the score of the individual hydromorphological parameters into an overall score.

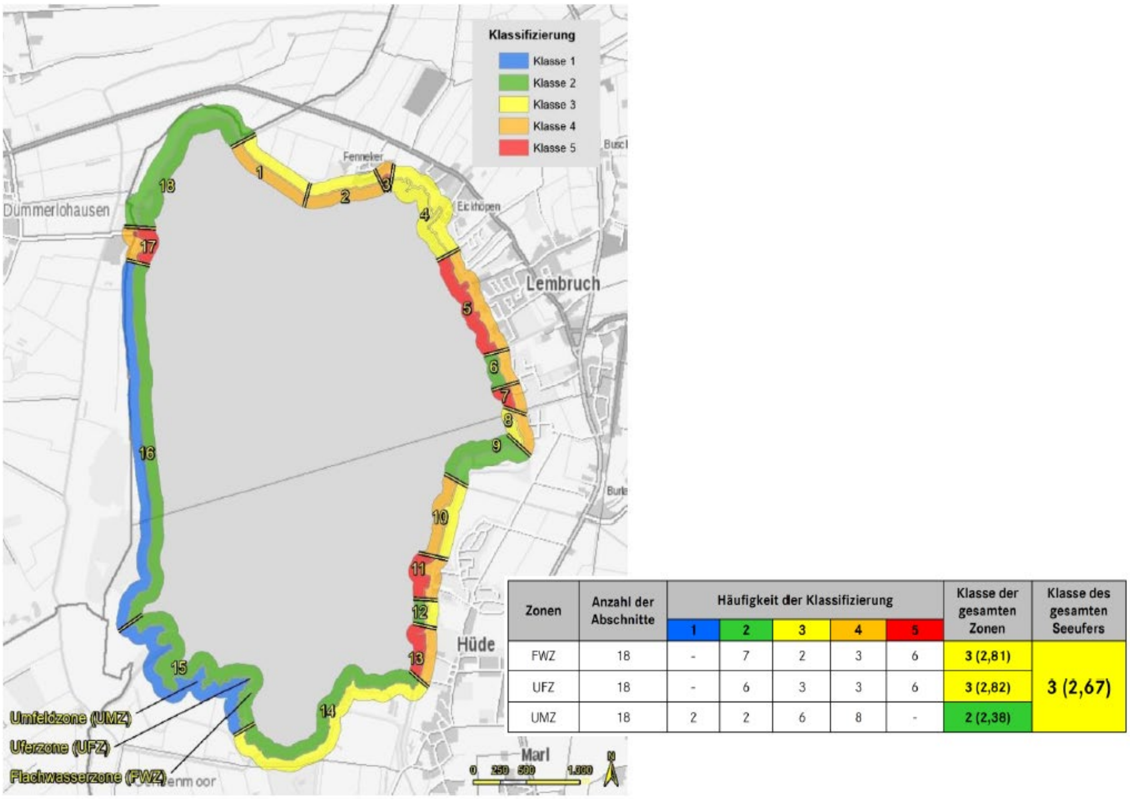
It is worthwhile noting that the poorest classification status (≥10 points) will lead to the definition of a heavily modified water body. The classification system proposed in Chapter 7 is not defined in such a way. A poor hydromorphological classification does not lead a water body to be heavily modified.

6.4 Germany and Luxemburg

Information in this chapter is provided by Georg Lamberty, Planungsbüro Zumbroich.

The hydromorphological system applied in Germany and Luxemburg focusses on morphological status of lakes and reservoirs but covers also hydrology. The application of the system is based on visual assessment of the morphological conditions. Aerial photos, drones and site visits can be used to do the assessment, and a combination of these techniques and approaches is often needed to cover areas with extensive riparian vegetation. For the use of drones, 20 kms of shoreline can typically be covered in two flying days. Challenges related to obtaining permits for flying drones exist. As the number of lakes in Germany is small compared to Scandinavia, more efforts can be invested in each lake. The results of a morphological classification are visualized in Figure 6.3.

The classification approach applied in Germany and Luxemburg does not include changes outside the lake that might impact the lake, nor does it relate to reference conditions.



Zonen	Anzahl der Abschnitte	Häufigkeit der Klassifizierung					Klasse der gesamten Zonen	Klasse des gesamten Seeufers
		1	2	3	4	5		
FWZ	18	-	7	2	3	6	3 (2,81)	3 (2,67)
UFZ	18	-	6	3	3	6	3 (2,82)	
UMZ	18	2	2	6	8	-	2 (2,38)	

Figure 6.3. Morphological classification of Dümmer.

The hydrological part of the system is pressure-based, i.e. 'if no pressures are found, the water body is ok'. Typical hydrological pressure groups are:

- Land use / changes in basin
- Water abstraction
- Water discharge
- Water works (e.g. hydropower stations)
- Changes in floodplain

The parameter retention time and its class borders are given in Table 6.4.

Table 6.4. The parameter retention time and its class borders. This is the same as parameter 202 in the revised system proposed in Chapter 7.

Intervals (G/L)	Color coding	Intervals in system proposed in Chapter 7
0 % - < 5 %	1	0 % - < 5 %
5 % - < 10 %	2	5 % - < 20 %
10 % - < 25 %	3	20 % - < 50 %
25 % - < 50 %	4	50 % - < 100 %
≥ 50 %	5	≥ 100 %

The class borders proposed in the Norwegian system are comparable, but not as strict as the system used in Germany/Luxemburg.

6.5 France

Information in this chapter is provided by Christine Argillier, IRSTEA.

France has developed the LAKe Hydromorphological Conditions index (LAKHYC index) for the hydromorphological classifiation of lakes and reservoir (see Figure 6.4). The method applies 22 parameters/EQR values, which are aggregated into 6 values, i.e. water fluxes, residence time and hydrogeology (Hydrology) and substrate, shore zone and depth (Morphology) in the end.

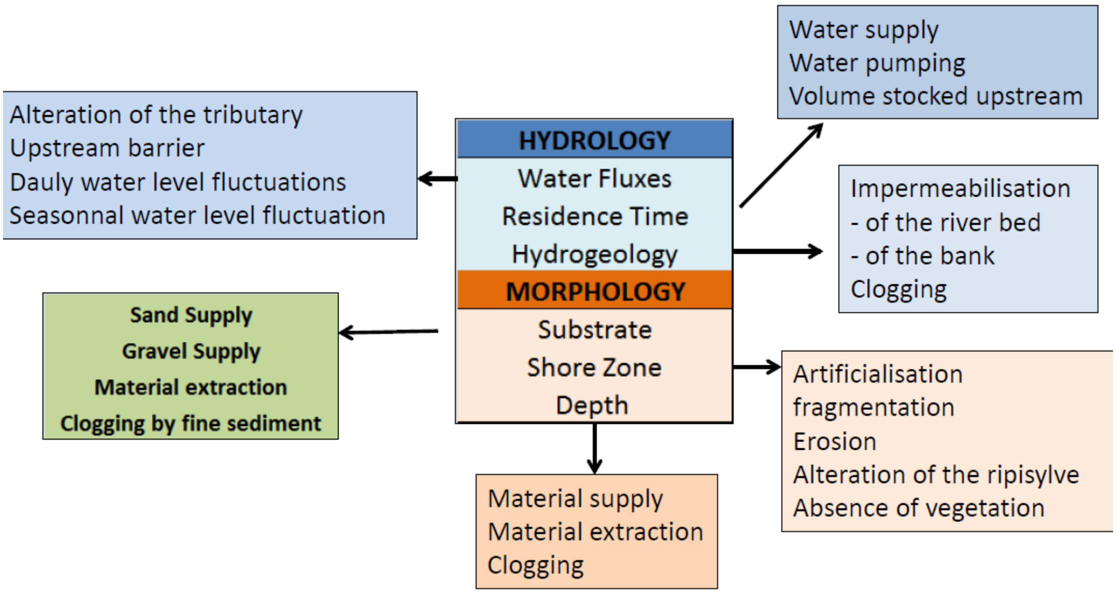


Figure 6.4. Overview of the design of the LACHYC index.

The method has been applied to around 200 lakes in France. Future work on the method should:

- Check calculation of some of the metrics
- Test the usefulness of all the metrics (redundancy, range of variation, etc.)
- Evaluate associated uncertainties (operator bias)
- Draw the link between hydromorphological conditions and biota

6.6 Italy

Information in this chapter is provided by Martina Bussettini, ISPRA.

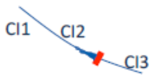
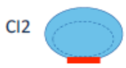
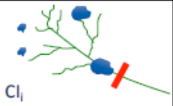
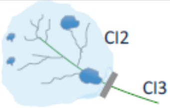
Italy seems to be delayed compared to most of the other countries presented during the workshop. Italy has developed an extensive system for typology of lakes, based on altitude, chemical composition of the bed rock, lake origin and conductivity (Table 6.5).

Table 6.5. Definition of typology in Italy.

DESCRITTORE		INTERVALLO DEI VALORI
Localizzazione Geografica	Ecoregione Alpina	Lat. ≥ 44°00' N
	Ecoregione Mediterranea	Lat. < 44°00' N
Descrittori Morfometrici	Quota (m s.l.m.)	< 800
		≥ 800
		≥ 2000
	Profundita media/massima (m)	< 15
		≥ 15 / ≥ 120
	Superficie (km^2)	≥ 100
Descrittori geologici	Composizione prevalente substrato geologico	Substrato dominante calcareo Talk ≥ 0.8 meq/l
		Substrato dominante siliceo Talk < 0.8 meq/l
	Origine vulcanica	SI
		NO
Descrittori chimico-fisici	Conducibilita (µS/cm 20°C)	< 2500
		≥ 2500
	Stratificazione termica	laghi/invasi polimittici
		laghi/invasi stratificati

A number of the Italian lakes have undergone major changes due to human use. Table 6.6 shows different types of transformations. Reservoirs have been created as rivers are blocked by the construction of dams and forming 'ponded rivers', lakes have been regulated forming reservoirs larger than the original lake, and dams have connected a number of smaller ponds into larger reservoirs.

Table 6.6. Overview of different variants of transformation into the present variety of reservoirs, due to major human interventions.

before	*after*	*From/to*	*DM 131/08*	*Def WFD*	*Def WFD WISE*
		CI2 is HMWB from CI river to CI lake	CI2 "reservoir"	HMWB RW (LW)	Yes, it is a reservoir and the water body was originally a river
		CI2 is HMWB from CI river to CI river		HMWB RW	The water body is not a reservoir
		CI2 is HMWB from CI lake to CI lake	CI2 "reservoir"	HMWB LW	Yes, it is a reservoir and the water body was originally a lake
		CI2 is HMWB from Σ CI$_i$ lake to CI lake	CI2 "reservoir"	HMWB LW	Unclear, it is a reservoir but originally included chained rivers and lakes
		CI1 is AWB Creation lake ex novo	CI2 "reservoir"	AWB LW	
		CI1 is AWB Creation canal ex novo		AWB RW	

Water level variations are also in Italy a key parameter, but also the more extensive Lake Habitat survey (see presentation in Bakken et al. 2018) is used and adapted for vegetation for hydromorphological classification.

7 Revised hydromorphological classification system for lakes and reservoirs

Before a revised hydromorphological classification is proposed and presented, we would underline the purpose of having such a classification system in place. A hydromorphological classification system should be used to:

- Identify the main physical and ecological impacts related to hydromorphological alterations, causing deviations from the overall goals of the EU WFD.
- Describe the severity of the physical and ecological impacts related to hydromorphological alterations
- Indicate what set of measures should be introduced in order to improve the physical and ecological impacts in the most efficient manner

The hydromorphological factors included in the classification system can be considered those factors that together describe the physical habitat in lakes and reservoirs. An alternation in one of the hydromorphological will hence change the physical habitat of lakes and reservoirs, to a small or large degree.

7.1 Parameters and class borders of proposed, revised classification system

Based on the experiences from the testing and evaluation of the system in Bakken et al. (2018) a revised hydromorphological classification system for lakes and reservoirs is proposed. Key characteristics of the revised system are;

- The system will make use of a five-class system, being more consistent with the majority of the classification systems already in place to support the implementation of the EU WFD.
- The number of parameters is reduced from 30 to 18 parameters. The reduction is made as the testing revealed challenges in finding data and/or tools to support the classification of many lakes with reasonable efforts.
- A system for weighting is proposed, which was not included in Bakken et al. (2018)).
- The relative number of parameters between hydrology, morphology and continuity (barriers, fragmentation) is changed, in the favour of more hydrological parameters. The reason for this is that the parameters defined to describe alterations in morphological and continuity are generally more time-consuming to calculate than hydrologic parameters, or data is not available.

(light red)	Changes upstream, affecting the lake/reservoir under consideration	(green)	Hydrological change
(light green)	Changes directly at the lake/reservoir under consideration	(brown)	Morphological change
(light blue)	Changes downstream, affecting the lake/reservoir under consideration	(grey)	Barrier, fragmentation

Figure 7.1. The figure explains the colour coding used in the Tables (7.2-7.4), where the colour codes to the left refer to geographic location compared to the lakes assessed (light blue is not used in the new system proposed) and the colour codes to the right refer to type of hydromorphological alteration. Green cells refer to hydrological alterations, brown are morphological alterations and grey are barriers and fragmentation.

Table 7.1. Generalised five-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
2		Slightly modified
3		Moderately modified
4		Extensively modified
5		Severely modified

Furthermore, a procedure for screening of lakes is proposed in Chapter 7.2. The aim of the screening procedure is to reduce the number of lakes that would need to undergo full classification. The screening procedure will sort out those lakes that are clearly slightly modified or near natural (e.g. mountain lakes with no or limited human intervention) and no further hydromorphological classification needed. The procedure will also sort of those lakes that are extensively or severely modified.

It has been decided that typology should not be introduced for the hydromorphological classification of lakes and reservoirs. The arguments behind this decision are that for a hydromorphological classification the alterations in hydromorphology would be equally dramatic independent of lake type, i.e. altitude, size and ecology. This is also in line with the proposed classification system for rivers (Harby et al. 2019), and it is considered important that these systems are consistent. If typology is introduced at a later stage, one approach could be that one specific lake type would be assessed by only a sub-set of the proposed parameters, alternatively that all are used for all lakes (independent of typology), but the importance is adjusted according to the lake type.

Table 7.2. The table presents the revised hydromorphological classification system. The columns describe the following; Parameter number (light red = upstream areas, light green = within the lake/reservoir), name of the parameters, the unit of each parameter, the metric for change, if the parameters describe changes from unregulated situation or the degree of modifications and what type of hydromorphological quality elements (green = hydrology, brown = morphology, grey = barrier/fragmentation). The numbers in the column to the very right indicate assumed importance (3=high, 2=medium, 1=low).

No	Parameter	Unit	Metric for change	Natural vs degree of regulation		HYMO element (Importance)
				Natural	Degree of reg.	
100	Change in annual inflow	%	Change in annual inflow from the unregulated conditions, expressed by degree of regulation	X		(3)
101	Upstream barriers affecting sediment processes	%	Percentage of upstream areas (river reaches) blocked due to man-made barriers, compared to a river without encroachments	X		(1)
200	Water level changes	Meter	Highest regulated water level (HRWL) - Lowest regulated water level (LRWL)	X	X	(3)
201	Total volume change	%	Change in volume of lake compared to the natural conditions, in percentage (%)	X		(3)
202	Change in retention time	%	Change in retention time of lake compared to the natural conditions, in percentage (%)	X		(2)
203	Change in date of filling	Days	No. of days changed start of filling compared to the date in the natural condition	X		(2)
204	Change in date of emptying	Days	No. of days changed in start of emptying compared to the date in the natural condition	X		(2)
205	Water level change at filling date	%	Relative deviation at filling date, given as deviation between natural water level and actual water level at this date, divided on max depth	X		(3)
206	Water level change at emptying date	%	Relative deviation at emptying date, given as deviation between natural water level and actual water level at this date, divided on max depth	X		(3)
207	Short term water level variations (days)	Meter/ day	Water level changes, given as water level change in meters per day	X	X	(2)
208	Short term water level variations (weeks)	Meter/ week	Water level changes, given as water level change in meters per week	X	X	(2)
210	Dewatered areas	%	Dewatered areas due to regulation, i.e. dewatered areas at lowest level compared to total area at highest level (measured horizontally)		X	(3)
211	Relative lake level fluctuation	%	Relative water level variations, defined as HRWL – LRWL divided on mean depth		X	(1)
212	Dewatered littoral zone versus total littoral zone (ratio)	%	Percentage of the littoral zone affected by the regulation (measured horizontally)		X	(3)
213	Loss in lateral connectivity along the shoreline	%	Percentage of the shoreline affected by embankments or other types of erosion protection	X		(3)
214	Riparian zone changes	%	Percentage of riparian vegetation along the shoreline affected by hydromorphological alterations	X		(3)
220	Change in substrate qualities	%	Changes in extent of areas of given substrate qualities	X		(1)

Change in retention time is a new parameter from the classification system proposed in Bakken et al. (2018). Retention time is the mean time period the water stays in the lake before it leaves the lake and is defined as the volume of the lake divided on the mean annual inflow. An increase in volume or a decrease in inflow will increase the retention time.

The parameters defined are dominated by hydrological parameters. They were also dominating in the previous version of the system. The reason for this is that hydrological parameters are easier to calculate based on existing data sources, while morphological and continuity (barriers and fragmentation) often needs manual work. As soon as hydrological data (observed or modelled) is available from before and after regulation, a set of relevant hydrological parameters can be derived. The hydrological parameters (parameter 100, 200-208) can be calculated by use of hydrological models, while the parameters 210 and 212 can be calculated with digital bathymetric maps, if available.

Table 7.3. Proposed new hydromorphological classification system and the corresponding class borders, following a five-class system. All parameters refer to changes in the hydromorphological state from natural conditions or degree of hydromorphological alterations.

No	Parameter	Near-natural	Slightly modified	Moderately modified	Extensively modified	Severely modified
100	Change in annual inflow	<5 % regulation upstream	5-20 % regulation upstream	20-50% regulation upstream	50-90% regulation upstream	>90% regulation upstream
101	Upstream barriers affecting sediment processes	<5 % reduction in distance to natural upstream barrier	5-10 % reduction in distance to natural upstream barrier	10-50 % reduction in distance to natural upstream barrier	50-90 % reduction in distance to natural upstream barrier	>90 % reduction in distance to natural upstream barrier
200	Water level changes	<2 meters	2-3 meters	3-10 meters	10-50 meters	>50 meters
201	Total volume change	<5 % change from natural volume	5-10 % change from natural volume	10-30 % change from natural volume	30-70 % change from natural volume	>70 % change from natural volume
202	Change in retention time	<5 % change in retention time	5-20 % change in retention time	20-50 % change in retention time	50-100 % change in retention time	>100 % change in retention time
203	Change in date of filling	<3 days change compared to filling by starting date	3-10 days change compared to filling by starting date	10-20 days change compared to filling by starting date	20-70 days change compared to filling by starting date	>70 days change compared to filling by starting date
204	Change in date of emptying	<3 days change compared to emptying by starting date	3-10 days change compared to emptying by starting date	10-20 days change compared to emptying by starting date	20-70 days change compared to emptying by starting date	>70 days change compared to emptying by starting date
205	Water level change at filling date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
206	Water level change at emptying date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
207	Short term water level variations (days)	<0.1 meters change during one day (90-percentile day during a year)	0.1-0.5 meters change during one day (90-percentile day during a year)	0.5-1 meter during one day (90-percentile day during a year)	1-2 meters during one day (90-percentile day during a year)	>2 meters during one day (90-percentile day during a year)
208	Short term water level variations (weeks)	<0.3 meter within a week (90-percentile of a week during a year)	0.3-1 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)	3-5 meters during one week (90-percentile week during a year)	>5 meters during one week (90-percentile week during a year)
210	Dewatered areas	<5 % dewatered compared to natural surface area	5-10 % dewatered compared to natural surface area	10-40 % dewatered compared to natural surface area	40-90 % dewatered compared to natural surface area	>90 % dewatered compared to natural surface area
211	Relative lake level fluctuation	<5 % in relative lake level fluctuations	5-50 % in relative lake level fluctuations	50-100 % in relative lake level fluctuations	100-150 % in relative lake level fluctuations	>150 % in relative lake level fluctuations
212	Dewatered littoral zone versus total littoral zone (ratio)	<5 % affected by dewatering	5-10 % affected by dewatering	10-40 % affected by dewatering	40-90 % affected by dewatering	>90 % affected by dewatering
213	Loss in lateral connectivity along the shoreline	<5 % of shoreline affected	5-20 % of shoreline affected	20-50 % of shoreline affected	50-90 % of shoreline affected	>90 % of shoreline affected
214	Riparian zone changes	<5 % of riparian vegetation affected (measured as % of shoreline)	5-20 % of riparian vegetation affected (measured as % of shoreline)	20-50 % of riparian vegetation affected (measured as % of shoreline)	50-90 % of riparian vegetation affected (measured as % of shoreline)	>90 % of riparian vegetation affected (measured as % of shoreline)
220	Change in substrate qualities	<5 % spawning substrate lost	5-10 % spawning substrate lost	10-40 % spawning substrate lost	30-90 % spawning substrate lost	>90 % spawning substrate lost

Table 7.4. Proposed new hydromorphological classification system where the calculation procedure of each parameter is briefly explained.

No	Parameter	Calculation procedure
100	Change in annual inflow	This parameter is calculated by summing all upstream reservoir volumes and divided on the average annual inflow of the lake to be classified. The reservoir volume of the lake to be classified should not be included.
101	Upstream barriers affecting sediment processes	This parameter is calculated by measuring the distance to the closest man-made barrier upstream blocking sediments and divide this on the distance to the nearest upstream natural barrier blocking sediments (the situation without the man-made barrier).
200	Water level changes	This is simply calculated from Highest regulated water level (HRWL) - Lowest regulated water level (LRWL)
201	Total volume change	This parameter is calculated from calculating the volume of the lake before regulation and the same volume after regulation, i.e. divide the 'old' volume on the 'new' volume.
202	Change in retention time	Retention time is calculated by dividing the volume of the water flowing into the lake and divide this on the total volume. The change in retention time is calculated by dividing the 'new' retention time on the 'old' retention time, giving a percentage change (%)
203	Change in date of filling	This parameter assesses the change in number of days when filling starts. In order to do so a timeseries of water level (or volume) of the lake before regulation must be compared to the similar timeseries after regulation, and then identify the dates of filling.
204	Change in date of emptying	This parameter assesses the change in number of days when emptying starts. In order to do so a timeseries of water level (or volume) of the lake before regulation must be compared to the similar timeseries after regulation, and then identify the dates of emptying.
205	Water level change at filling date	This parameter corresponds to parameter 203 and two timeseries of water level form the basis for the calculation. Instead of date of filling, the water level at the date of filling is used and comparted to the natural water level at the same date.
206	Water level change at emptying date	This parameter corresponds to parameter 204 and two timeseries of water level form the basis for the calculation. Instead of date of emptying, the water level at the date of emptying is used and comparted to the natural water level at the same date.
207	Short term water level variations (days)	This parameter is calculated based on a timeseries of water level data where water level increases and water level decreases are identified on daily basis. The representative value should be calculated as the 90-percentile of the daily water level changes, i.e. the increase and decrease that is exceeded in 10% of the identified events. It is assumed that the variation is negligible in the situation prior to regulation.
208	Short term water level variations (weeks)	This parameter is calculated based on a timeseries of water level data where water level increases and water level decreases are identified on weekly basis. The representative value should be calculated as the 90-percentile of the weekly water level changes, i.e. the increase and decrease that is exceeded in 10% of the identified events. It is assumed that the variation is negligible in the situation prior to regulation.
210	Dewatered areas	This parameter assesses how large areas that are dewatered due to regulations, i.e. how large areas of the lake that is dried out when the regulation is at its lowest level. The parameter is a ratio between dewatered area and total water-covered area when the lake is at its highest level. This number can be calculated based on bathymetric maps that are processed in GIS. As such, the horizonal area of the lake bottom should/must be used.
211	Relative lake level fluctuation	This parameter is calculated by subtracting LRWL from HRWL and divide this difference on mean depth (when filled) of the lake. In contrast to parameter 200, this parameter will indicate how large the regulation height is when calculating it relative to the depth.
212	Dewatered littoral zone versus total littoral zone (ratio)	This parameter is analogue to parameter 210, but is calculated based on the littoral zone only. The extent of the littoral zone is calculated based on the secchi depth, as the secchi depth determine how deep the light penetrates. The classified value can be found by processing a bathymetric map in a GIS. Similar to parameter 210, the horizontal extent should/must be calculated.
213	Loss in lateral connectivity along the shoreline	This parameter is simply calculated by observing how large parts of the shoreline that is changed due to embankment or some other type of erosion protection. The number is calculated as a distance (km) of such protection, divided on the total shore length of the lake, giving a value in percent (%).
214	Riparian zone changes	This parameter is simply calculated by observing how large parts of the areas close to the lake that does not holds riparian vegetation and comparing this to the situation prior to the human intervention. It is assumed that the lake had riparian vegetation along the lake before human intervention, if the lake is located below the tree-line. The number is calculated as a distance (km) where the vegetation is removed, divided on the total shore length of the lake, giving a value in percent (%).
220	Change in substrate qualities	This parameter is the fraction of the total areas holding substrate of desired qualities and how that has changed since before the human intervention started. As such, the parameter itself is simple to calculate as soon as the data is available. The present state must probably be assessed by on-side mapping and the historic changes assessed by expert judgement.

7.2 Proposed approach for aggregation/weighting

The feedback from the experts participating in the international workshop in October, 2019, was clear with respect to weighting of hydromorphological parameters. The experts recommended the following regarding aggregation/weighting of parameters:

1. Three hydromorphological classification values: The overall types of hydromorphological alterations (Hydrological change, Morphological change and Barrier, fragmentation) should be aggregated individually and shall not be further aggregated into one total lake score. Based on our testing, reported in Chapter 3.3, a variant of '**1c**: Group importance' is a viable option, but applied separately for each type of alteration. In this weighting method all parameters within each type are included and given weight according to given importance. Applying such a variant justifies the effort to calculate all of them. As Morphological change and Barrier, fragmentation contain few parameters compared to hydrological alterations, it should be notified the number of parameters the weighted results are based on.

2. Exclusion of uncertainty: The uncertainty/confidence level shall not affect the hydromorphological classification. In order to keep the information about uncertainty/confidence level each parameter or parameter group should be flagged with the given level of certainty for the classification. In this way parameters that have a high uncertainty are equally impactful on the lake score, disregarding that this impact is based on uncertain data.

7.3 Procedure for screening of lakes

It is clearly a very extensive management task to do a full hydromorphological classification of all lakes in Norway, which is more than 6400 lakes and reservoirs. At the same time, we know that several of the lakes to undergo such a classification are to a very little extent affected by hydromorphological changes, such as mountain lakes. In the other end, we know that some lakes are extensively changed, in particular due to hydropower regulations. In order to try to reduce the number of lakes that would need to undergo detailed assessments, we propose a screening system that would filter out lakes that are within these two groups. Figure 7.2 illustrates such a system, based on a few parameters that should be easy to find for all lakes, supporting a rapid assessment.

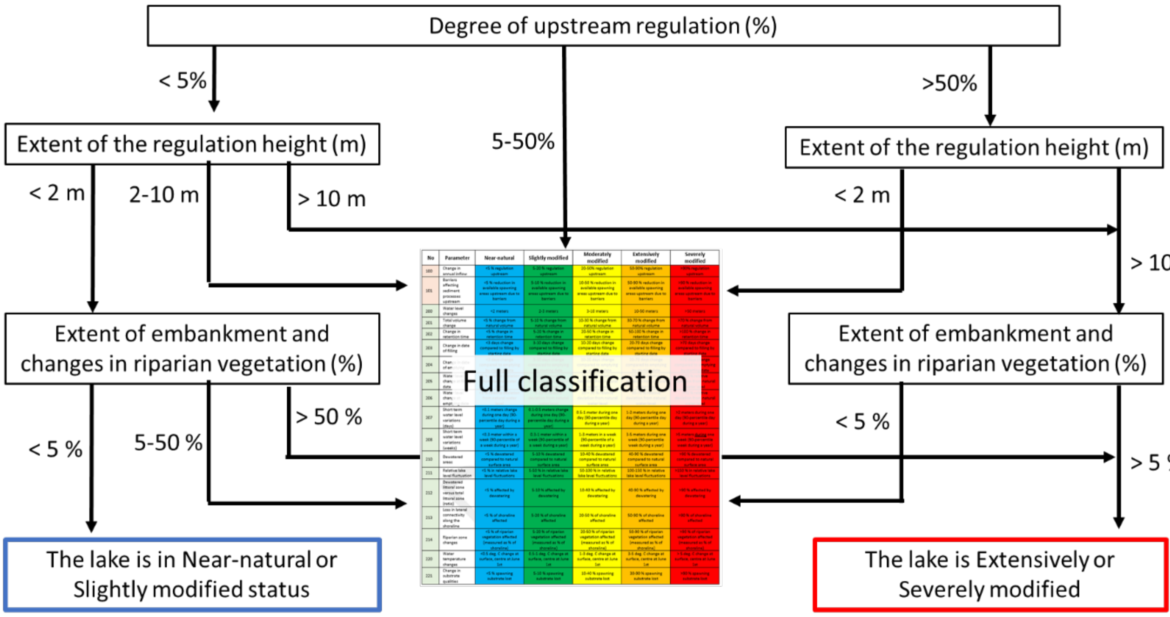


Figure 7.2. Outline of a procedure to screen if a lake is clearly is Near-natural or slightly modified status, if it is Extensively or severely modified, or if a full classification is needed. This procedure will allow a first sorting of lakes and will reduce the number of lakes where a comprehensive hydromorphological classification must be carried out.

The proposed parameters for such a screening procedure are;

Upstream regulation (%): This parameter is used to assess if the upstream regulation is so extensive that it must affect the lake that is considered. This parameter is calculated by summing all upstream reservoir volumes and divided on the average annual inflow of the lake to be classified. The reservoir volume of the lake to be classified should not be included.

Regulation of the lake (meter): This parameter is simply calculated by subtracting LRWL from HRWL.

Embankment and riparian vegetation (%): This parameter is a combination of the changes along the shoreline due to embankment and changes in riparian vegetation. Percentage change in embankment and percentage change in riparian vegetation should be summed in order to be used for screening purposes.

The previous characterisation of water bodies contains important pressure information useful for such a screening exercise, which makes data collection and compilation much less extensive.

We would underline that this procedure has not be tested and it is unknown how many lakes that would be sorted out for no further hydromorphological classification.

7.4 Existing and new data sources

When a national hydromorphological classification is started we would draw the attention to the extensive work already carried out during the work of characterisation (‘karakterisering’). In this work all water bodies have been characterised with respect to pressures. This information is stored in the Vann-Nett database and should definitely be re-used during a hydromorphological classification, hence reducing the needed work.

Quality assurance of measurements: The project showed that data must be carefully quality checked before use. Time series can have shifts, e.g. due to changes in measurement techniques, reference level or other reasons, gaps or errors. As calculation of water level variations is central, a consistent representation (datum) of the elevation must be established when combining different data sources.

Hydrology and bathymetry: Hydrological data and a bathymetric representation of the lakes are core data in carrying out the classification with use of the proposed system. If a correct water balance is established for the situation before and after regulation, several hydrological parameters can be calculated fairly easy. In order to establish this water balance, information about the inflow, evaporation rates, the hydropower production and controlled releases must be known. Furthermore, the outflow from the lakes before regulation must be known, in order to find the corresponding water level variations. Information about the bathymetry of the lake must be available, as well as the geometry of the outlet.

Bathymetry of the lake is also the basis for calculating parameters such as dewatered areas and how large parts of the littoral zone that are dewatered when the water level drops. As such, a more complete set of bathymetric maps to be processed within a GIS would be very useful for a classification of all lakes in Norway.

New monitoring to be established: Water level fluctuations and changes in water temperatures are important hydromorphological factors effecting the ecology and are also very simple to monitor. For this reason, we recommend that monitoring of water level and water temperature is established in more lakes, for the purpose of implementing the EU WFD, and as a basis to increase the knowledge of physical, chemical and biological processes in Norwegian lakes.

Prospects of new monitoring techniques: New monitoring data can potentially be useful in a national classification of lakes. Satellites can monitor surface areas of the lakes, and from this water levels can be calculated, at least in periods of the year without snow and ice. Drones can be useful in mapping of hydromorphological alterations along the shoreline by photogrammetry and can also be equipped with green LIDAR that can map the shoreline in detail, and possibly also the most shallow areas of the lakes. Use of single and multiple beam echosounders are also promising techniques in mapping of substrate characteristics.

A more extensive description about data sources and new measurement techniques is given in Bakken et al. (2018).

7.5 Classification in relation to identification of mitigating measures

Hydromorphological classification scores can be the basis for selecting the best mitigating measures of the problem at hand. In order to do so, it will in many cases be necessary to study the scoring value of each individual parameter, as looking at the scoring aggregated to types of hydromorphological alterations (i.e. hydrological change, morphological change and barrier, fragmentation) will mask important information about the alterations.

The possible set of mitigating measures for lakes are generally fewer than those that are available for impacted rivers. Stocking of fish is probably the most common measure in Norwegian reservoirs, but this is not a recommended measure, according to the philosophy of the EU WFD. Joint Research Centre (2016) published a review of possible measures in reservoirs that briefly is presented in Table 7.5. Some of the measures described in this table are formulated in such a way that they appear to be used as measures to improve the ecological status in water bodies affected by the water storage/reservoir or related infrastructure, and not within the reservoir. We have, however, decided to interpret the scope of the measure a bit wider than stated in the description of the measures, in such a way that the given measures can also be applied also directly within the lake or reservoir.

In Table 7.6, the hydromorphological parameters are coupled with potential measures to mitigate alterations for of each of the parameters.

Table 7.5. Full wording and corresponding abbreviation of mitigation measures for three key types of mitigation of impacts from water storage. This includes measures both within the reservoir/lake and also measures aimed at improving the status in water bodies affected by water storage. Those measures considered most relevant within the lake or reservoir are given in *Italic* and on light grey background (adapted from Joint Research Centre, 2016).

	Code	Measure (short)	Measure (full wording)
Sediment alteration	M-S1	Mechanical break-up of bed armouring	Mechanical break-up of bed armouring
	M-S2	Removal of sediment	Mechanical removal of accumulations of sediment (e.g. to reform pools)
	M-S3	Re-introduce sediment (intake structures)	Re-introduce sediment downstream of river intake structures (e.g. through sluice gate; passively by weir design; by returning dredging downstream)
	M-S4	Re-introduce sediment (reservoirs)	*Re-introduce sediment downstream of water storage reservoirs (including by actively introducing sediment or passively via a constructed bypass channel)*
	M-S5	Restore lateral erosion processes	Restore lateral erosion processes in river (e.g. by removing engineering) to enhance local sediment supply
	M-S6	Introduce mobilising flows	Introduce flows sufficient to mobilise sediment (flush fine sediment to mitigate colmation and/or to mobilise coarse sediment)
	M-S7	Fish stocking	*Fish stocking[3] where interruption of sediment transport means bed characteristics are unsuitable for spawning and/or for juvenile fish*
Ponded rivers (impoundments)	M-I1	Bypass channel	Create an artificial bypass channel to provide some flowing water habitat
	M-I2	Reduce storage level	*Reduce storage level (e.g. by raising bed or lowering dam) to increase flowing water habitat*
	M-I3	In-channel habitat improvements	In-channel habitat improvements
	M-I4	Lateral reconnection	*Lateral reconnection e.g. tributaries, floodplain features such as oxbows*
Lake level alteration	M-L1	Reduce abstraction	*Limit level variation by reducing abstraction during ecologically sensitive periods*
	M-L2	Increased inflows	*Limit level variation by balancing abstraction with increased inflows (e.g. by transfers from another reservoir etc) during ecologically sensitive periods*
	M-L3	Create embayment(s)	*Limit level variations in part(s) of the reservoir by creating a separate area (embayment) in which levels are maintained*
	M-L4	Manage shore/shallow habitats	*Manage shore/shallow habitats e.g. control erosion, plant overgrowth. Re-naturalisation of lake shore or artificial habitats.*
	M-L5	Connectivity to tributaries	*Maintain connectivity between reservoir and tributaries for fish movement*

[3] Fish stocking may be a strategy to compensate various impacts of water storage on fish populations of selected fish species, and/or to optimise fishing. However, as the majority of EU countries are not considering this as an alternative to reach Good Ecological Potential (GEP), this mitigation measure is handled separate from other measures.

	M-L6	Artificial floating islands	*Create artificial floating islands with associated shore/shallow habitats that follow level variations*
	M-L7	Fish stocking	*Fish stocking[2] to compensate for lost spawning/rearing habitat*
Physico-chemical alteration	M-P1	Flexible intake	*Flexible intake (i.e. floating intake able to take water from surface layer of reservoir)*
	M-P2	Multiple intakes	*Multiple intakes at different heights that can be alternated as reservoir levels rise and fall*
	M-P3	Manage reservoir level	Manage reservoir levels so that water from surface layers provides the river flow mitigation during ecologically sensitive periods

Table 7.6. Hydromorphological parameters and those mitigating measures that can be introduced to improve the ecological status of the water bodies affected by hydromorphological pressures. We would underline that the proposed measure should be read indicative as the selection of measures is very case-specific.

No	Parameter	Measure Code
100	Change in annual inflow	M-L1 / M-L2 /
101	Upstream barriers affecting sediment processes	M-S4
200	Water level changes	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
201	Total volume change	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
202	Change in retention time	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
203	Change in date of filling	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
204	Change in date of emptying	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
205	Water level change at filling date	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
206	Water level change at emptying date	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
207	Short term water level variations (days)	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
208	Short term water level variations (weeks)	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
210	Dewatered areas	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3 / M-L4
211	Relative lake level fluctuation	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3
212	Dewatered littoral zone versus total littoral zone (ratio)	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3 / M-L4 / M-L6
213	Loss in lateral connectivity along the shoreline	M-L1 / M-L2 / M-I2 / M-L1 / M-L2 / M-L3 / M-L5
214	Riparian zone changes	M-L4
220	Change in substrate qualities	M-S4

We would underline that the selecting of measures is case-specific and a variety of different aspects should be evaluated before a specific set of measures is proposed, such as;

- present use causing hydromorphological alterations (e.g. hydropower production),
- reduced societal benefits the measures might imply,
- positive ecological effect of the measure, and
- certainty of the effect as well as the costs of implementing the measures.

If win-win solutions between environmental effects and the human use of the water-body can be found, such measures should, of course, be prioritised.

8 Conclusions

The first version of a hydromorphological classification system has been tested with the following conclusions:

- The tested system includes a comprehensive list of parameters that seems to describe the most important hydromorphological processes and alterations in Norwegian lakes and reservoirs.
- All parameters are considered having an ecological relevance, whereas the direct ecological response to single factors or combined changes in the hydromorphological conditions are difficult to assess.
- The classification results of the test lakes show a reasonable spread in their results, in particular when evaluating the individual parameters. When aggregating all the parameters into an overall score, the spread is reduced.
- Testing revealed that data is not available to calculate all parameters in all case-study lakes, even though they are considered being among the best monitored lakes in Norway. As several lakes were regulated 100 years ago, it can be difficult to find reliable data on the situation before they were regulated. Some of the parameters would also need extensive manual work to calculate, even when data was present.
- For practical use in a large number of lakes and reservoirs, using the full parameter set is then consider being impossible due to missing data, or too labour-intensive. We would, however, draw the attention to the work already carried out during the characterisation as a full, future hydromorphological classification could extensively benefit from this.
- ‘Unregulated lakes’ can be dramatically changed hydrologically due to major changes upstream. This is the case for lakes in the middle and lower part of all catchments with larger reservoirs in the upstream parts.
- Detailed quality checking of data is needed prior to classification.

We propose a revised hydromorphological classification system for lakes and reservoirs with the following characteristics:

- The revised hydromorphological classification system uses five classes instead of three, in order to be more consistent with how classification systems are defined for other quality elements.
- It contains a reduced set of parameters, going from a system holding 30 parameters, to a system with 17 hydromorphological parameters.
- The majority of the parameters can be calculated based on hydrological data (water balance of the lake before and after regulation) and bathymetric maps (to be processed in GIS).
- The revised system is dominated by hydrological parameters, as parameters describing morphology and continuity are generally more work-intensive (or very difficult) to calculate.
- The hydromorphological parameters are aggregated into the three main types of hydromorphological alterations, i.e. hydrological change, morphological change and barrier/ fragmentation. The weight of each parameter is given according to importance during aggregation. Uncertainty of the parameter scores should not be accounted for in the weighting, but indicated beside the classified values when registered in the WFD database.
- The application of the revised classification system requires expert knowledge on hydrology, hydrological modelling and use of GIS. As such, it appears rational if a national classification is carried out by a few dedicated experts (e.g. by NVE or a consultant/researcher).

Fundamental questions that need further work are:

- Should the hydromorphological classification system be based on a description of the hydromorphological alterations and the severity of these, without considering the ecological response they might introduce? Or should the selection of parameters and class borders be defined based on to what extent the hydromorphological alteration cause an ecological response, as such being a proxy for ecological status? The parameters defined in the system proposed in Chapter 7 are selected as they are important for hydro-morphology alone, but they are also considered being ecological relevant, and at the same time suitable for use in all lakes with reasonable efforts.

  It is important to recall that the EU WFD is an ecological directive with the purpose of improving the ecological conditions in rivers, lakes and coastal areas across Europe. The purpose of classification is to compile information about the ecological status and pressures as the basis of proposing and implementing mitigating measures to improve the ecological status. It has been intense discussions in the workshop regarding these issues and a conclusion has not been drawn in this project.

- Should all the parameters be designed in such a way that they compare the present situation with the situation before any hydromorphological modifications are introduced (before regulations)? Or should we allow the inclusion of parameters that describe the degree of regulation? In the revised system it is a mix of these two fundamentally different approaches.

- Our comparison between the criteria for designating HMWBs and the hydromorphological classification system showed that even a fairly mild water level regulation (3 meters) has qualified for being a HMWB. When comparing changes in retention time, a large change is required in order to be designated as a HMWB compared to the proposed classification system. It should be discussed and clarified the role is of the hydromorphological classification system in the context of designation of HMWBs. This should also be further compared with the criteria applied in other countries.

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