PHYSICAL ENVIRONMENTAL IMPACTS ON A HYDROPOWER RESERVOIR UNDER DIFFERENT OPERATIONAL MODES

Ana Adeva-Bustos (SINTEF), Gaia Donini (UniTN), Anna Pinneli (UniTN), Asja Alic (UniTN), Marco Tofollon (UniTN), Atle Harby (SINTEF), Knut Alfredsen (NTNU), Mauro Carolli (SINTEF), Per Øyvind Grimsby (Sira-Kvina kraftselskap)...et al.

Intro

Decarbonising the EU's energy system is crucial to reach our 2030 climate objectives and for Europe to become carbon neutral by 2050

HydroConnect

Impacts of connecting Norwegian hydropower to continental Europe and the UK

1. How can Norwegian hydropower contribute to the decarbonisation of the European power system?
2. What are the consequences on the Norwegian power system of delivering balancing services to Europe?
3. What are the implications of participating in several markets on operations and income of hydropower plants?
4. What will be the impacts of future hydropower operations on environmental conditions in reservoirs?

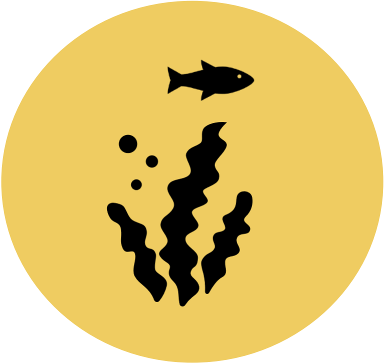
Project Leader: SINTEF Energi

Partners: NTNU, Fraunhofer IEE (Tyskland), University of Trento (Italia), Agder Energi, BKK, EnergiNorge, Hydro Energi, Lyse Produksjon og Sira-Kvina kraftselskap

Project period: 2021-2024

Type: Knowledge-building Project for Industry

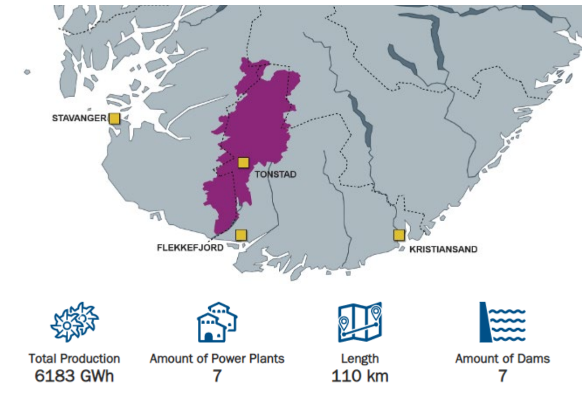
Why is it important to study these effects?

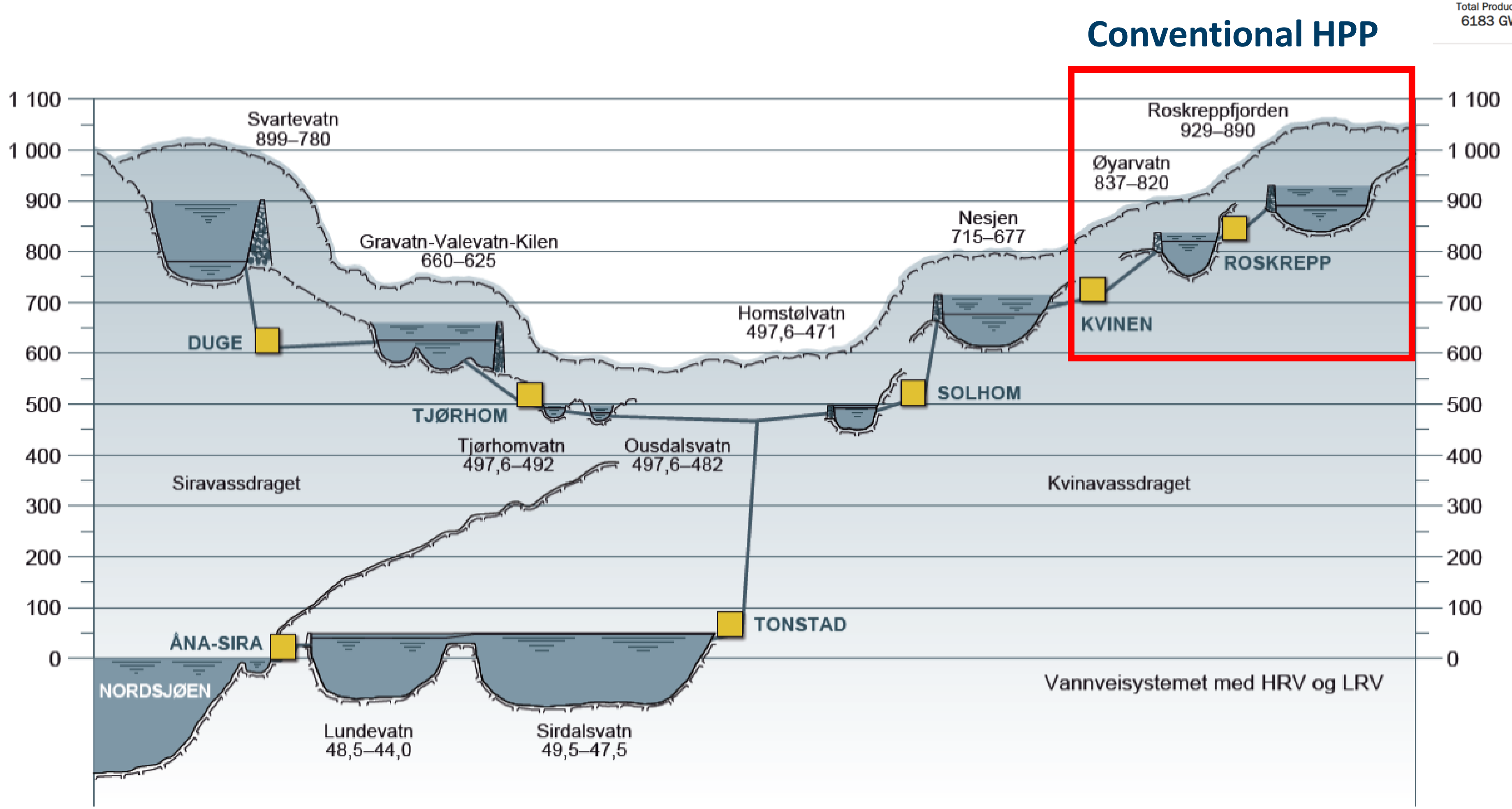


A variation in the thermal cycle of the lake can alter its **physicochemical processes**, and **biological activity** both at the lake and downstream.

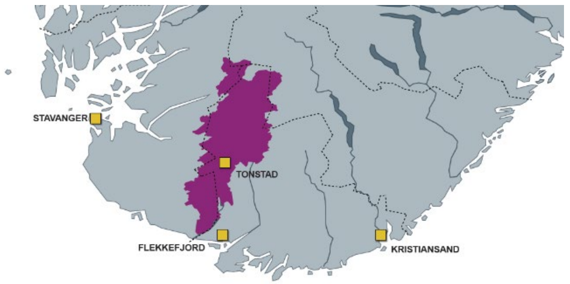
A stable ice cover ensures a safe lake crossing for **animals** and **humans.**

Sira-Kvina system





Sira-Kvina system

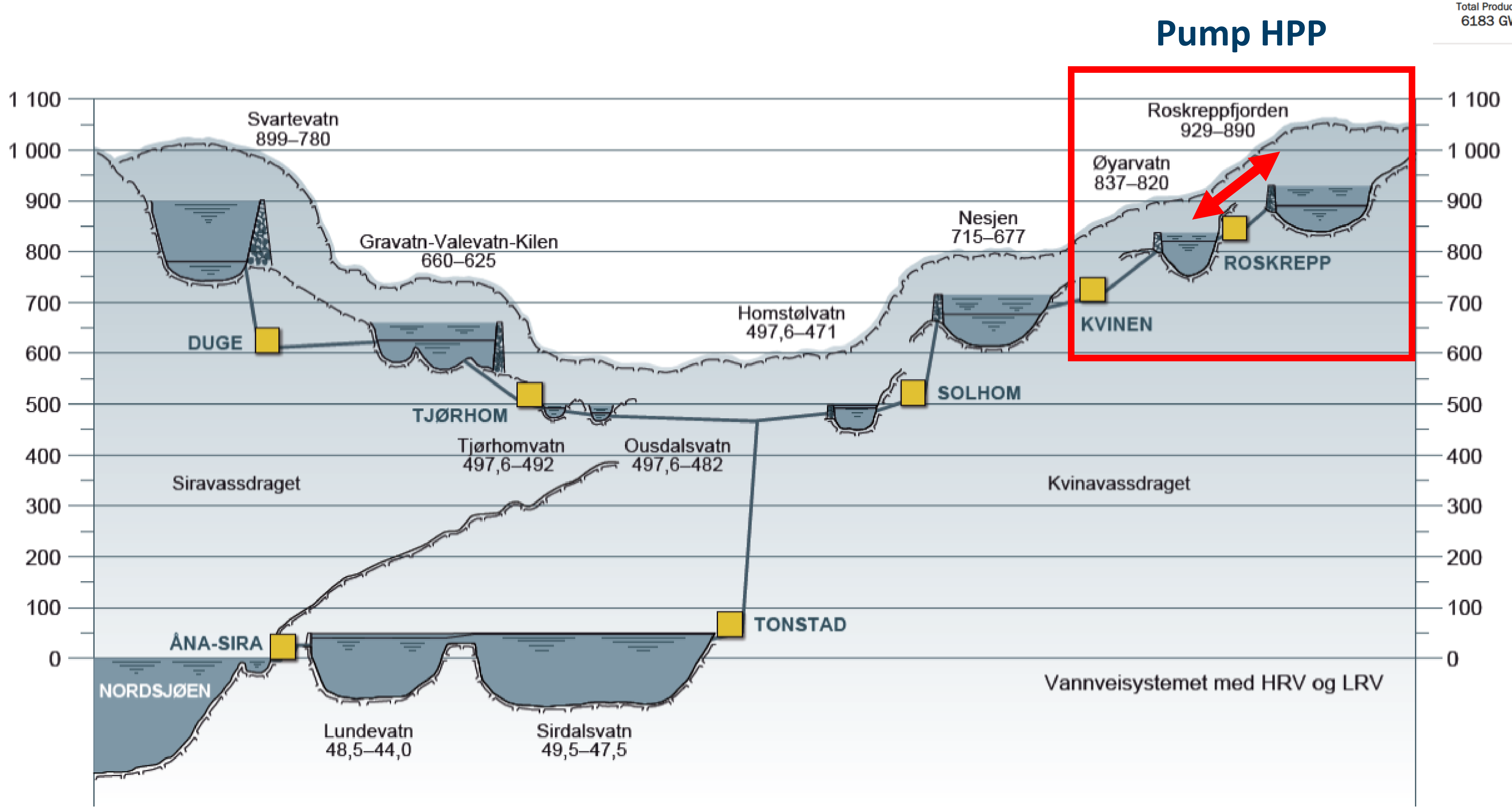


Total Production
6183 GWh

Amount of Power Plants
7

Length
110 km

Amount of Dams
7



Focus of todays presentation

Hydromorphological impacts on the littoral zone

- water level fluctuations
- Dewatering indices

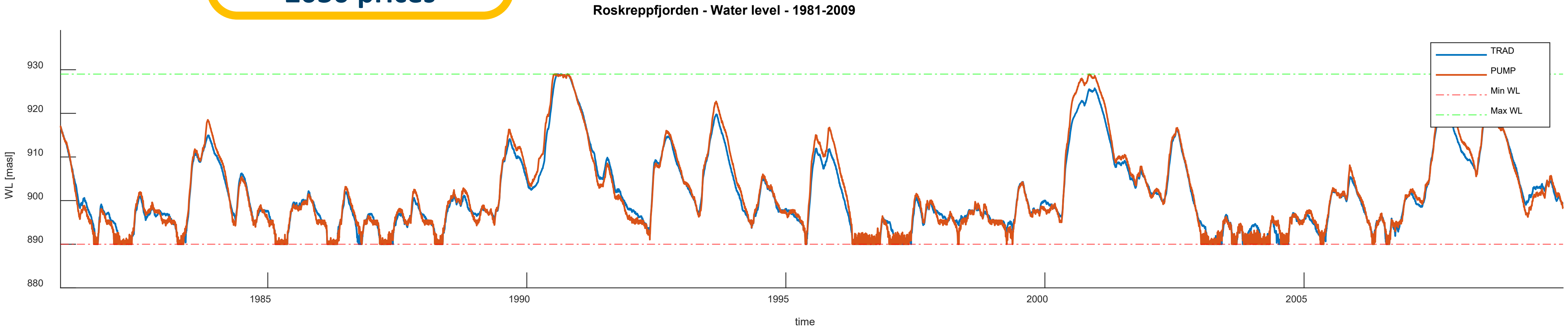
Effects on water temperature

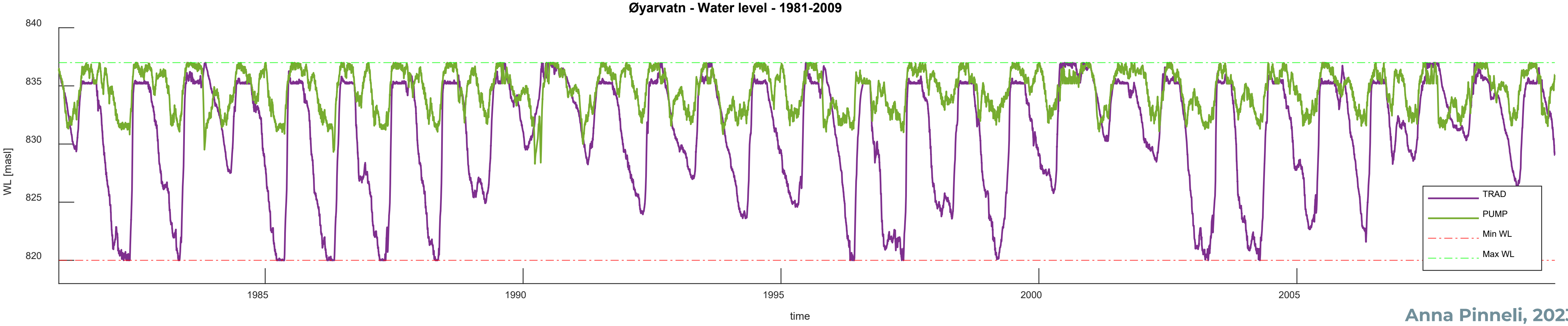
- Stratification
- Ice cover

Water level variation

Medium-term optimization scheduling model

2030 prices



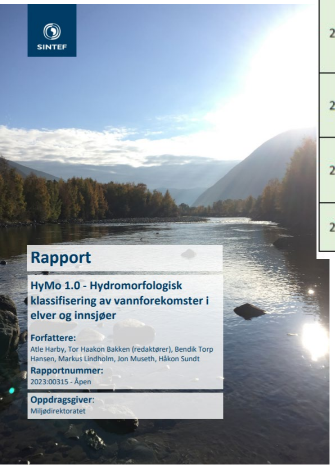


Anna Pinneli, 2023

Hymo classification

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

HYMO classification



17 hydromorphological parameters

Easy classifications for lakes and reservoirs

Daily detailed-level

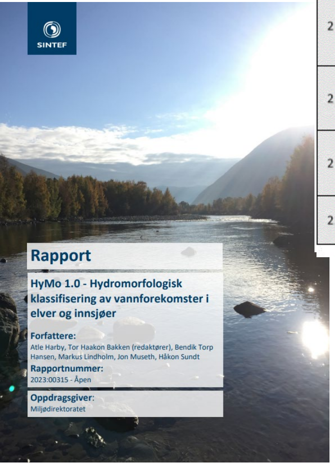
Hymo classification

SINTEF

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
	Change in date	<3 days change	3-10 days change	10-20 days change	20-70 days change	>70 days change
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

No.	Parameter	N.N.	S.M.	M.M.	E.M.	Se.M
P.207	Short term WL variations (days)	< 0.1 m	0.1 – 0.5 m	0.5 – 1 m	1 – 2 m	> 2 m
P.210	Dewatered Area	< 5 %	5 – 10 %	10 – 30 %	30 – 70 %	> 70 %
P.212	Dewatered Littoral Zone VS Total Littoral Zone	< 5 %	5 – 10 %	10 – 40 %	40 – 90 %	> 90 %

HYMO classification



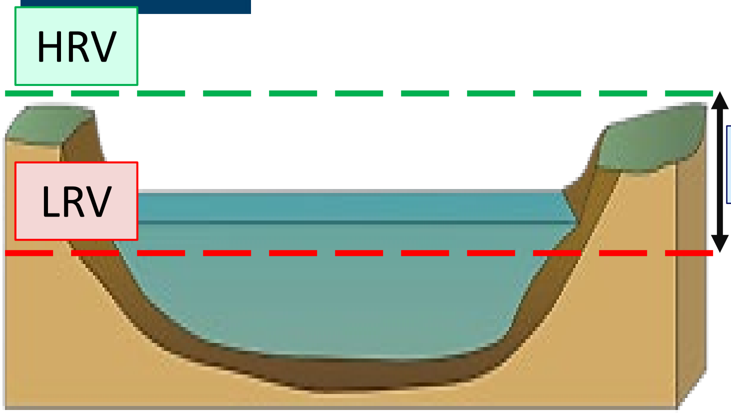
17 hydromorphological parameters

Easy classifications for lakes and reservoirs

Daily detailed-level

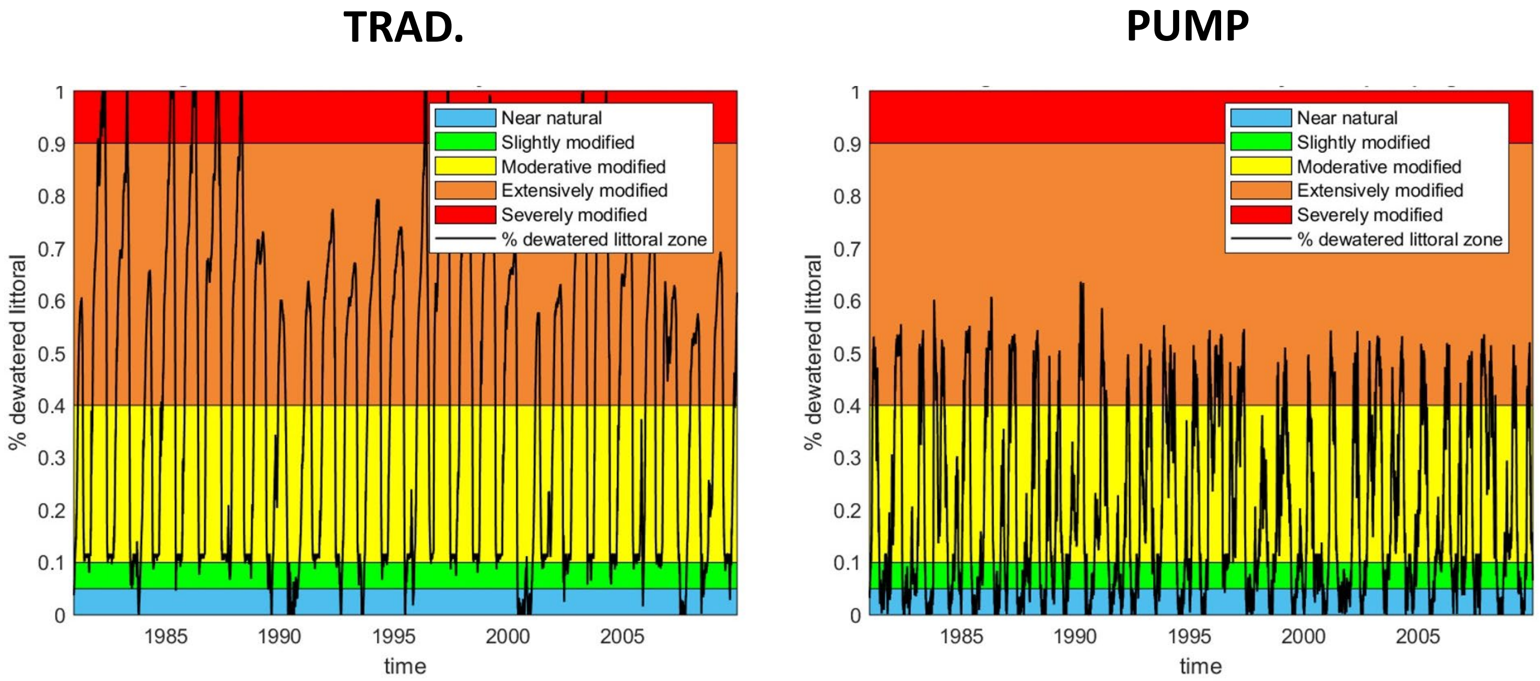
Anna Pinneli, 2023

Dewatered littoral zone (Hymo)



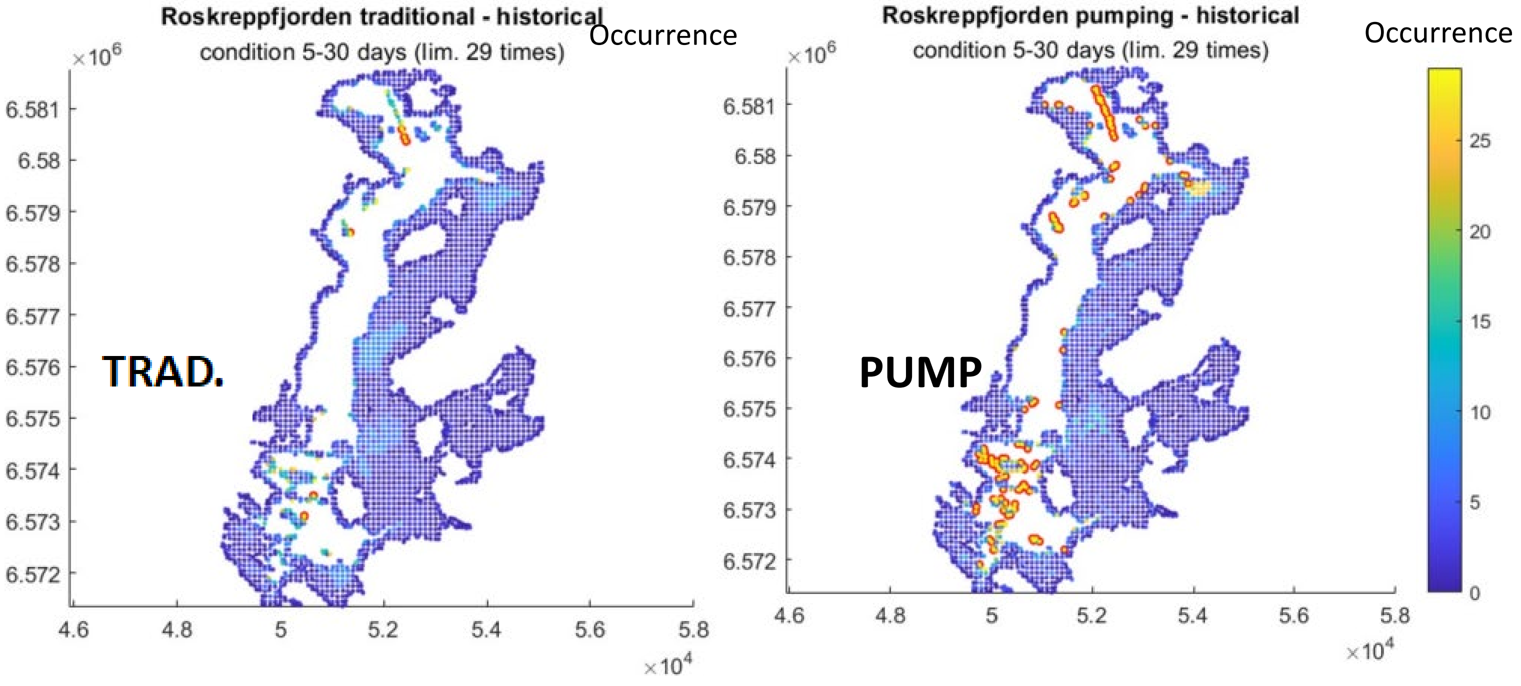
Parameter	N.N.	S.M.	M.M.	E.M.	Se.M.
Dewatered Littoral Zone	< 5%	5 – 10%	10 – 40%	40 – 90%	> 90%

Øyarvatn



Anna Pinneli, 2023

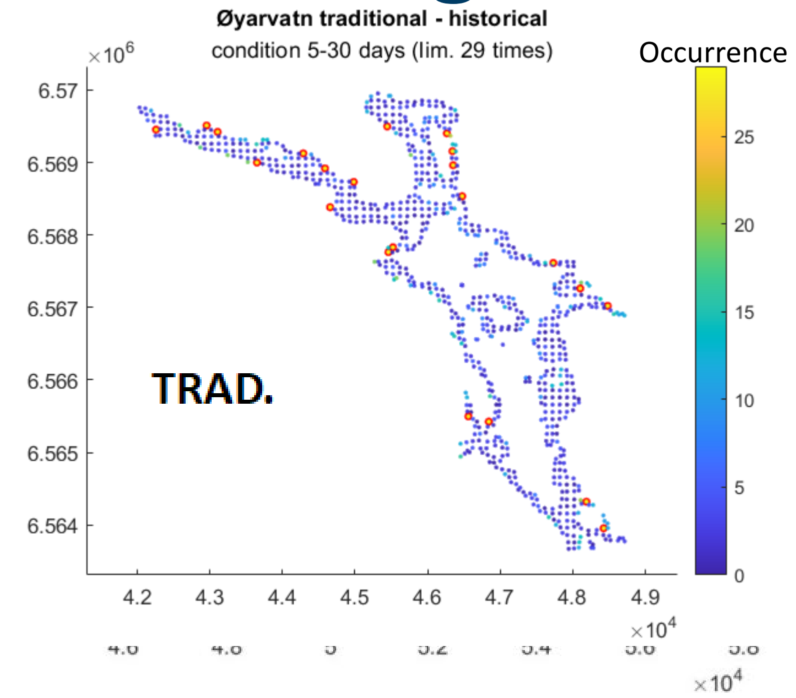
Dewatering indices (new)

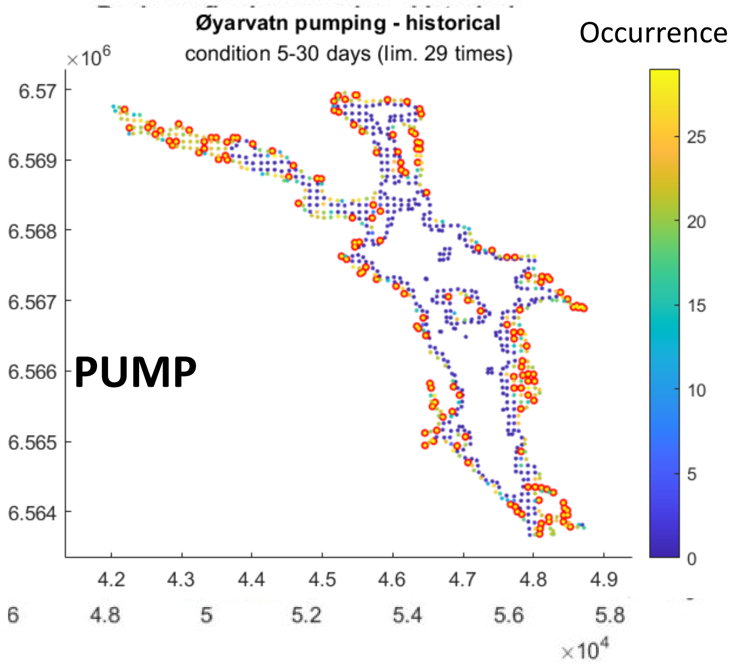


5-30 days period, potentially critical for juveniles

Anna Pinneli, 2023

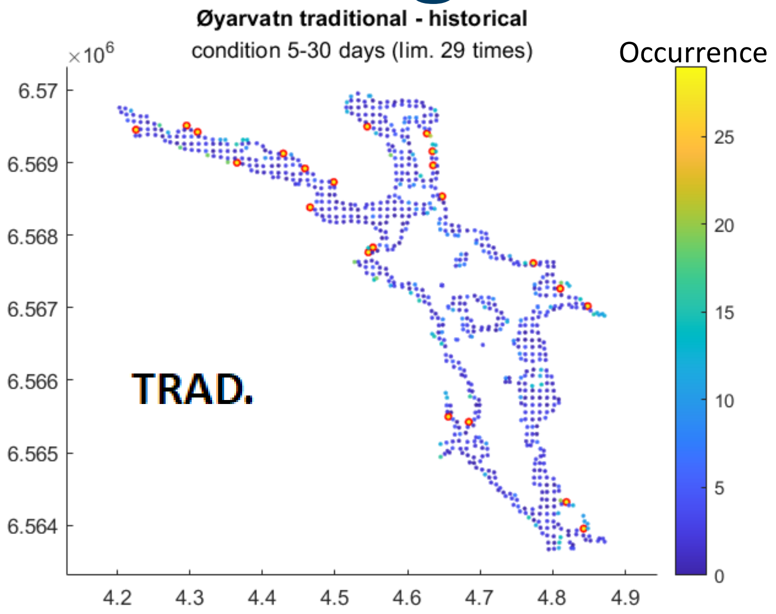
Dewatering indices (new)

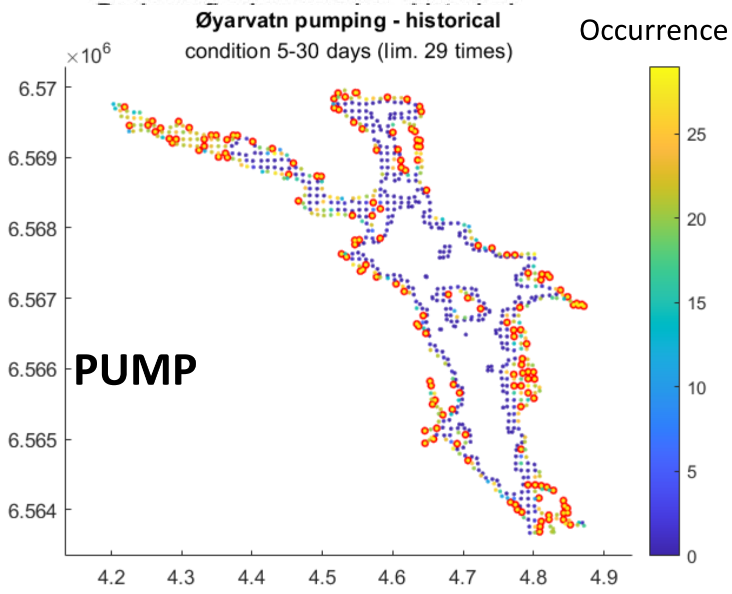




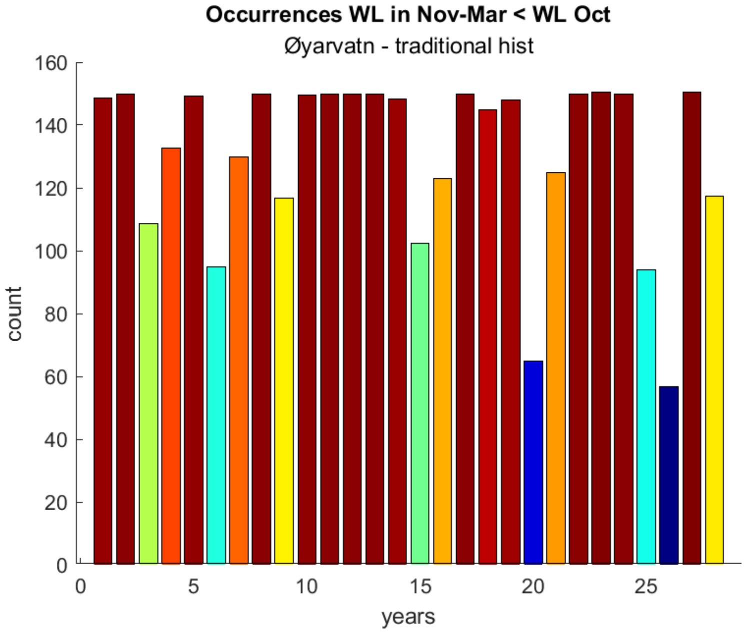
5-30 days period, potentially critical for juveniles

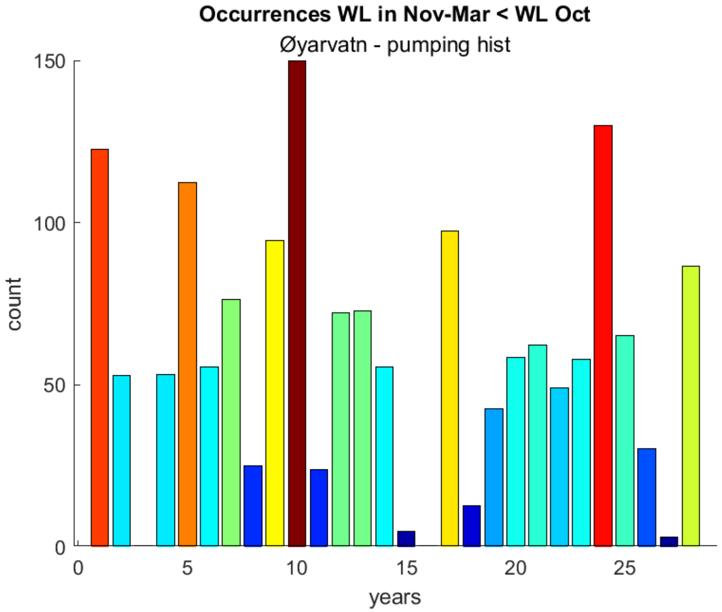
Dewatering indices (new)





5-30 days period, potentially critical for juveniles





More specific analysis in Oct and Nov-Mar period

Anna Pinneli, 2023

Hydropower Optimization model- way forward

Asja Alic (UniTN)

Environmental constraints

- State-dependent level constraint on maximum discharge

$$q_{h,k} = 0 \qquad if \quad v_{h,k} \leq V_h^{lim}$$

$$v_{h,k} \geq V_h^{lim} \quad for\ t \in [t_1, t_2]$$

- Minimum Environmental Flow

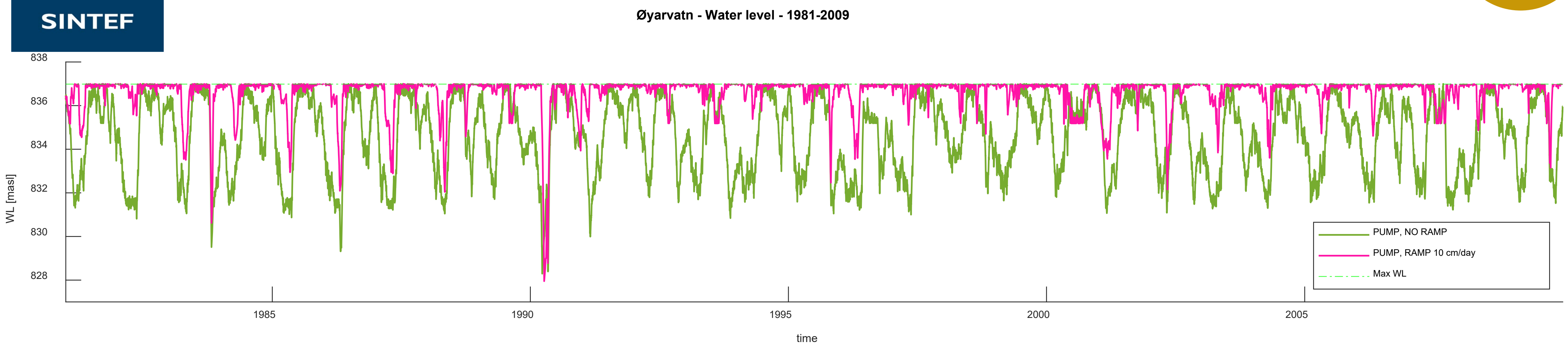
$$\boldsymbol{b_{h,k} = Q_h^{min}}$$

- Ramping constraints

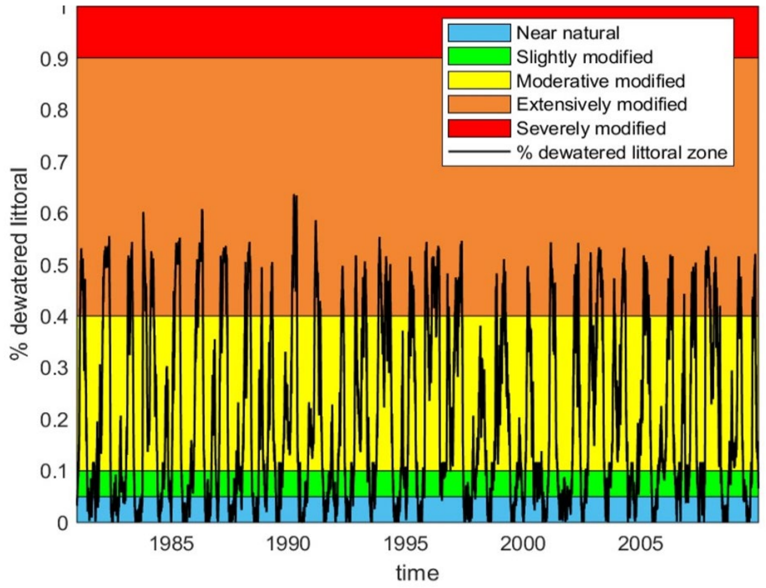
$$+\Delta^- \leq \boldsymbol{v_{h,k} - v_{h,k-1}} \leq \Delta^+$$

*Schäffer, Linn Emelie, Arild Helseth, and Magnus Korpås. "A stochastic dynamic programming model for hydropower scheduling with state-dependent maximum discharge constraints." Renewable Energy (2022)

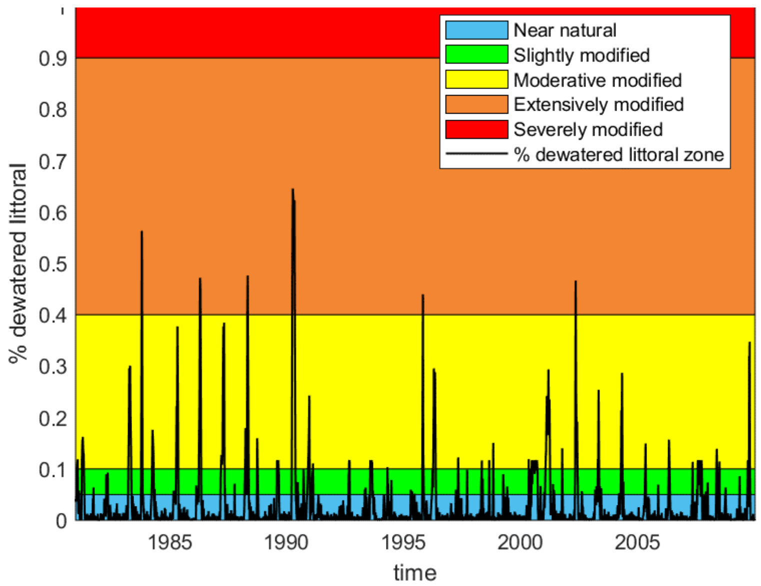
Ramping constraints- way forward…



PUMP NO RESTRICTION



PUMP WITH RESTRICTION



Anna Pinneli, 2023

Focus of todays presentation

Hydromorphological impacts on the littoral zone

water level fluctuations

Dewatering indices

Effects on water temperature

Stratification

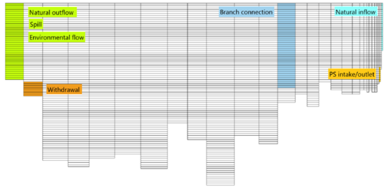
Ice cover

The model: CE-QUAL-W2

SINTEF

OPTIMAL PRICE-BASED SCHEDULING MODEL

BATHYMETRY



METEOROLOGICAL DATA

DISCHARGES

$$dQ = inflow - outflow$$

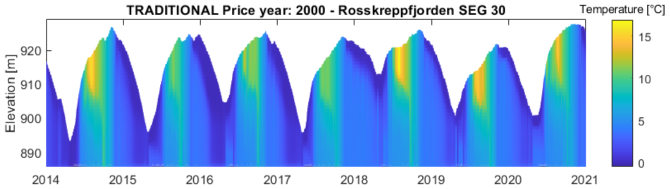
INPUT

2D Model

RANS - *Reynolds Averaged Navier Stokes*

ADE - *Advection-Diffusion Equation*

TEMPERATURE AND VELOCITY AT ANY GRID POINT

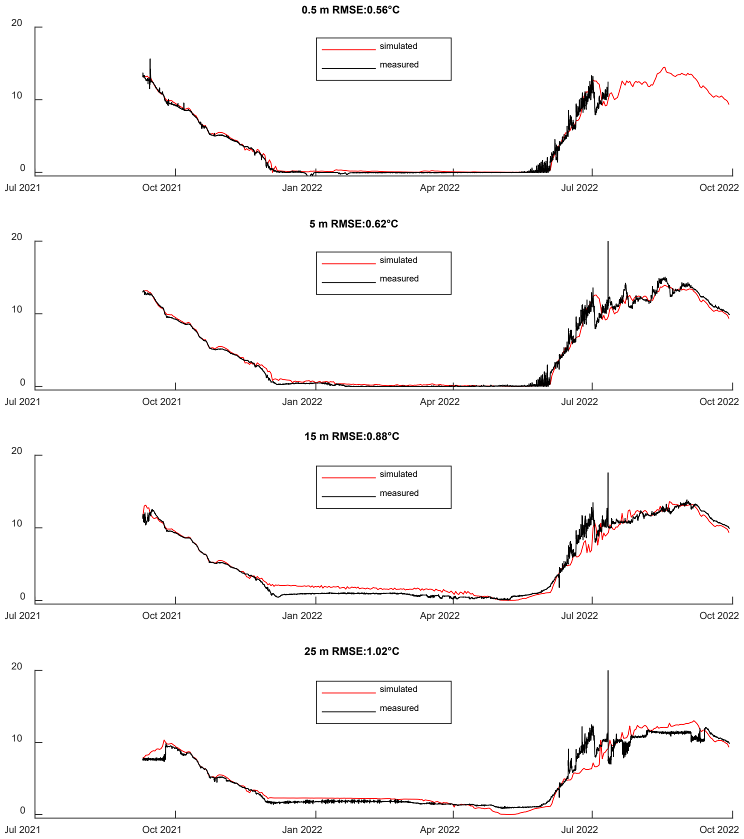


OUTPUT

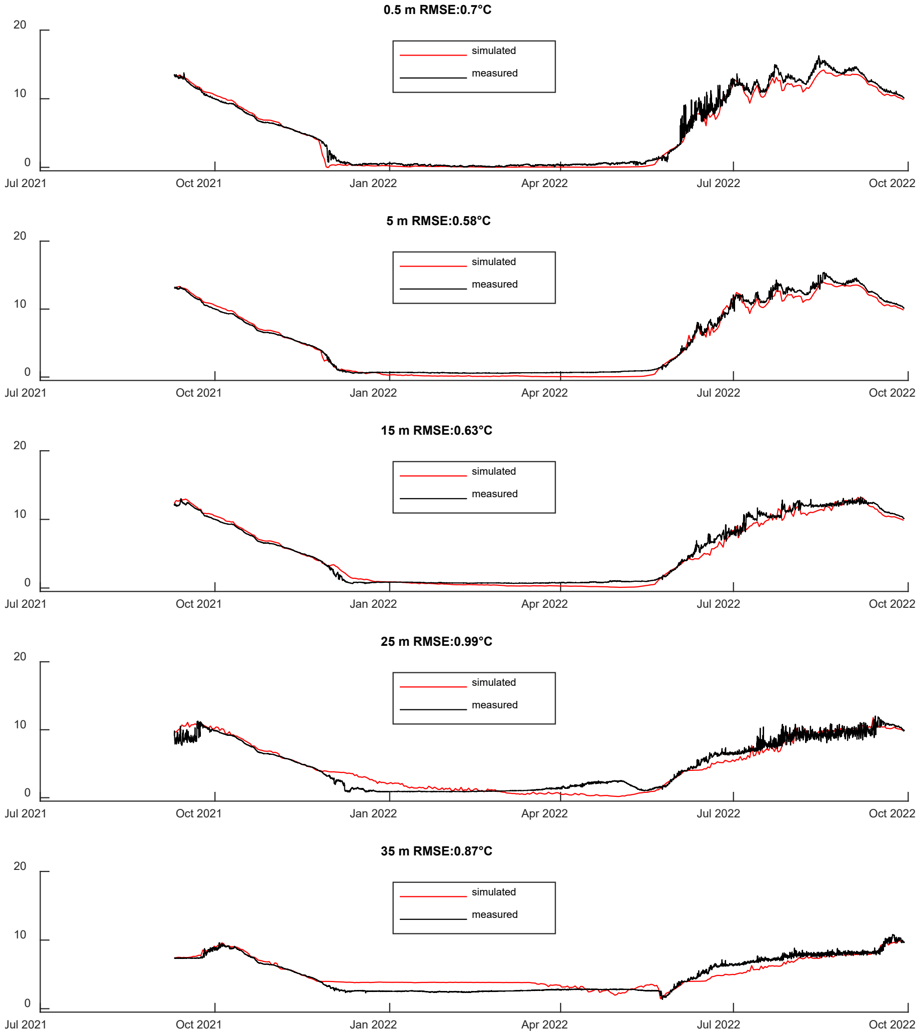
Model calibration – water temperature

Gaia Donini, 2022

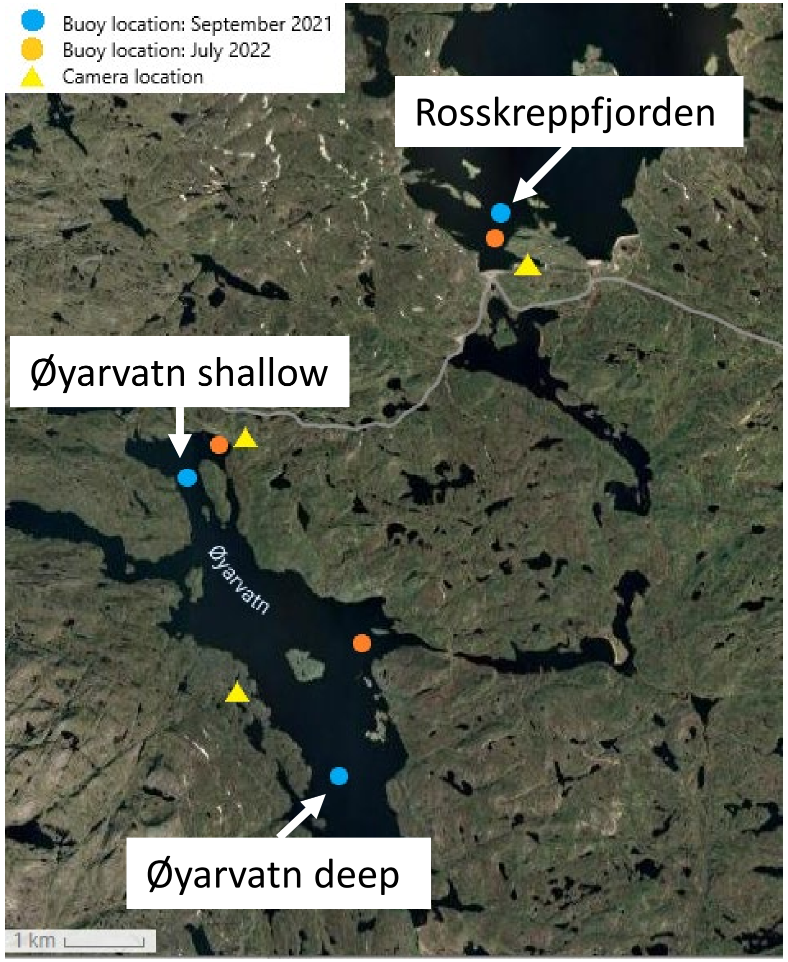
Rosskreppfjorden



Øyarvatn deep

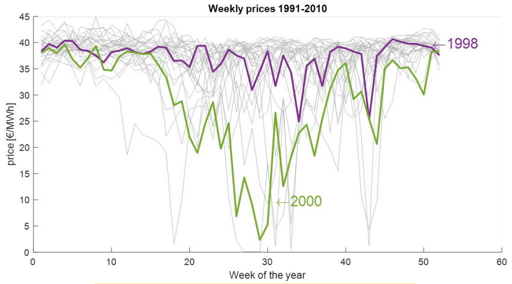


Period: 09/09/2021 14:00 - 27/09/2022 00:00

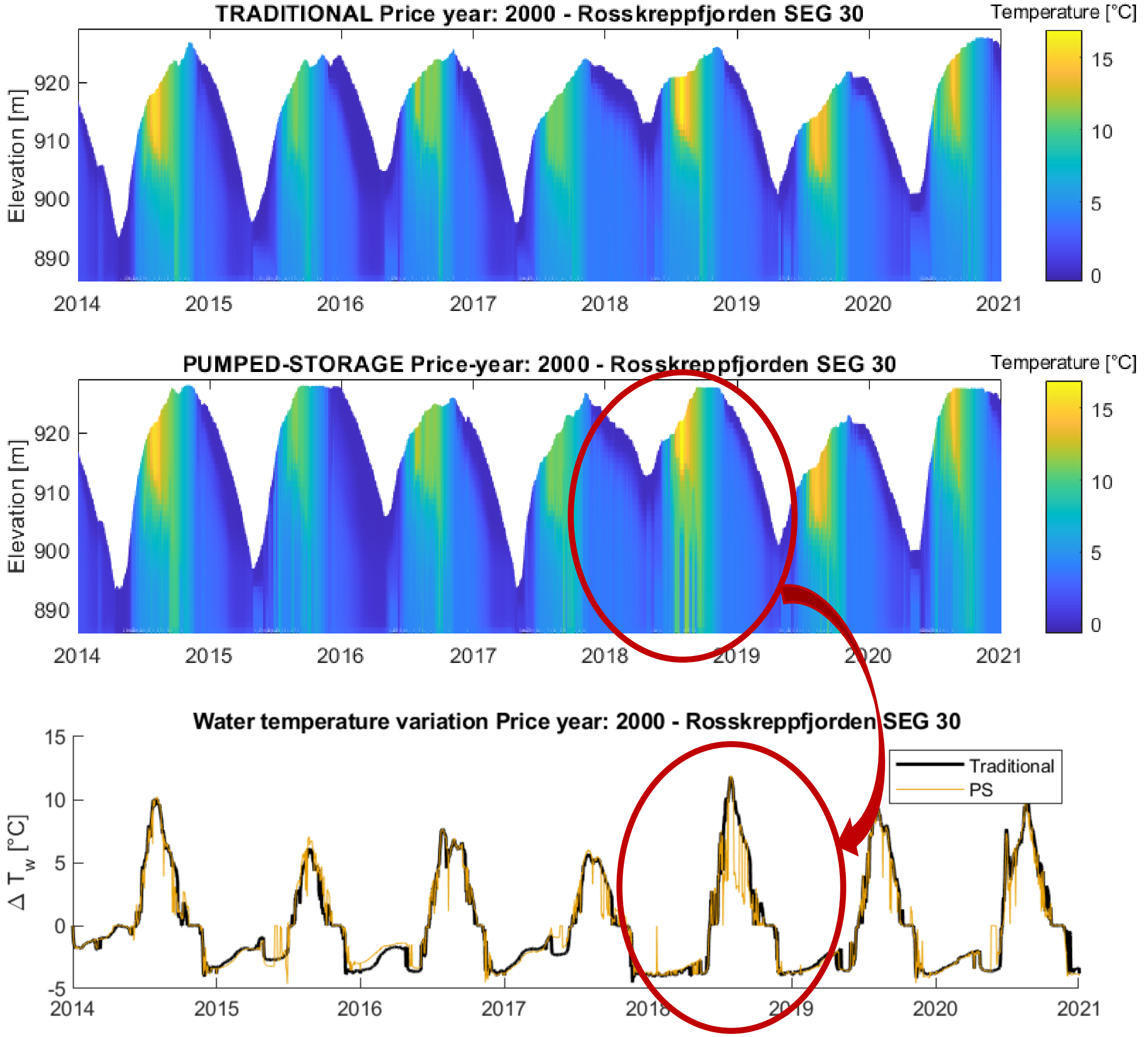


Results

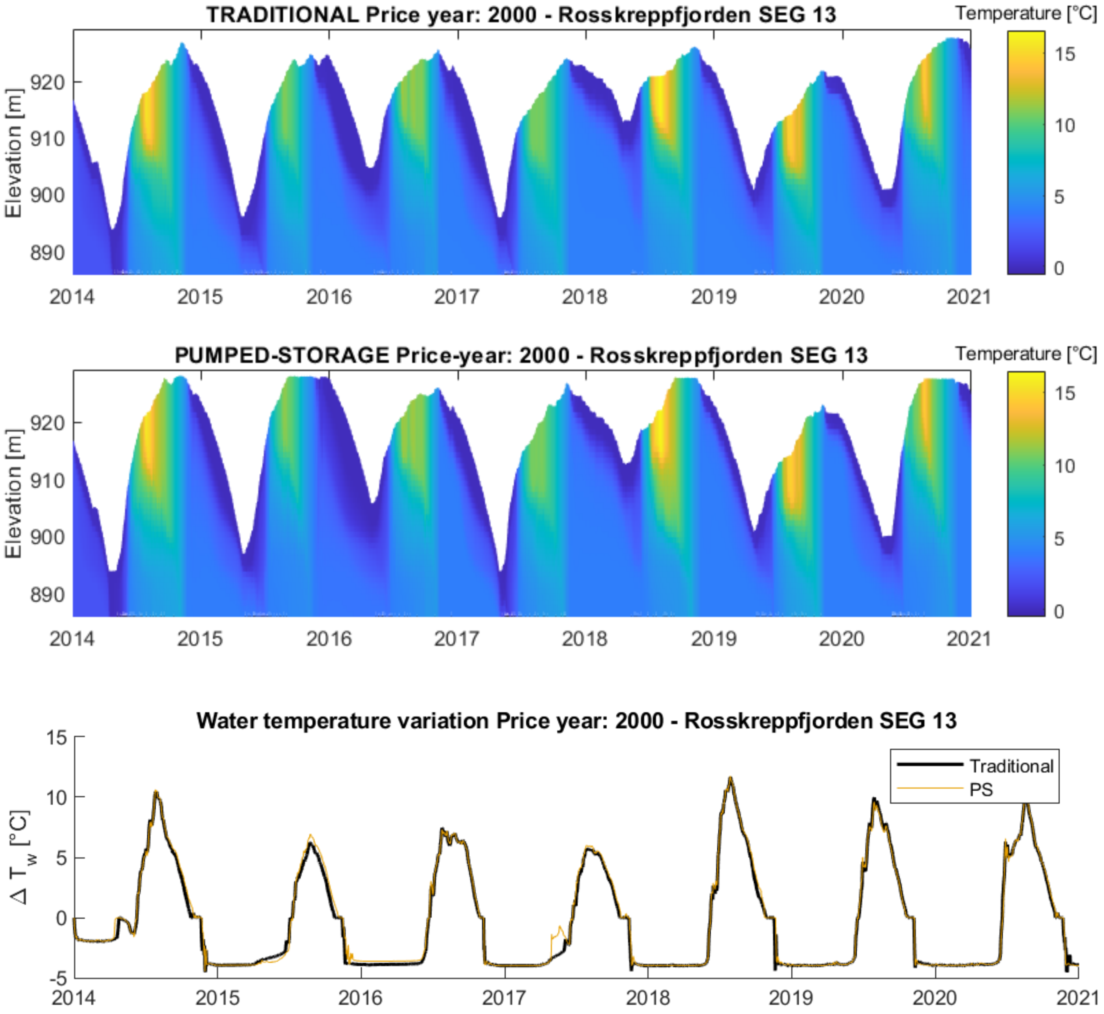
ROSSKREPPFJORDEN - 2000



INLET/OUTLET SEGMENT



MID-LAKE SEGMENT

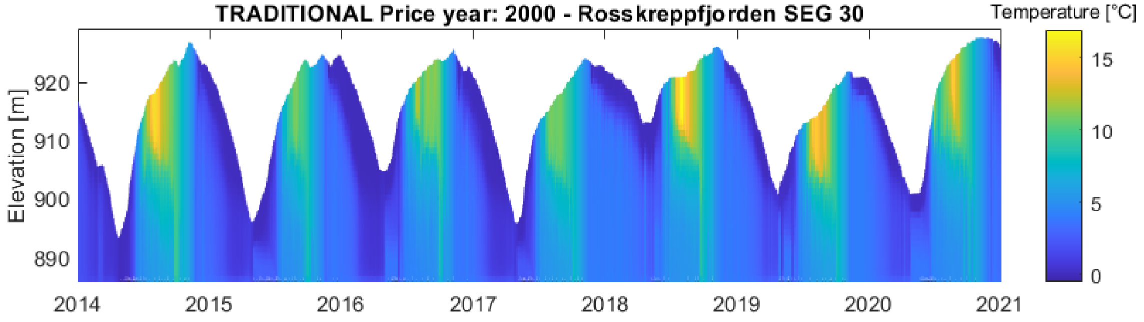


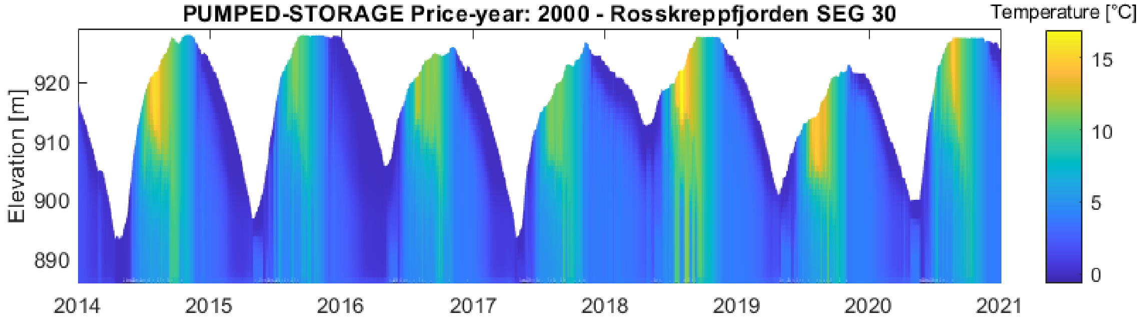
Gaia Donini, 2022

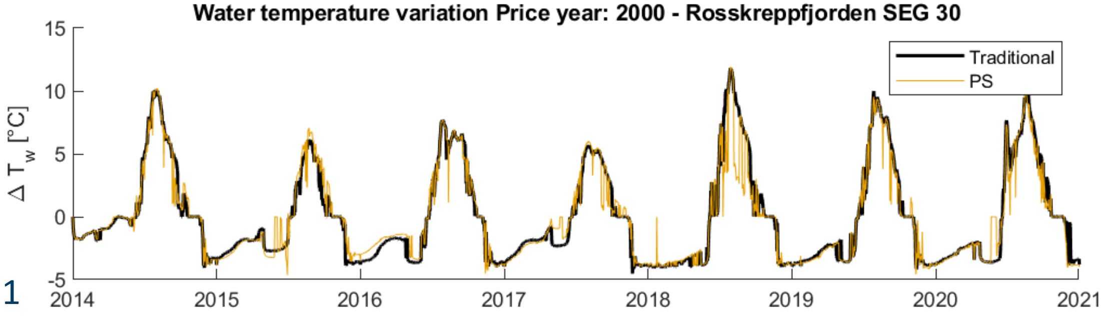
Results

ROSSKREPPFJORDEN - 2000

INLET/OUTLET SEGMENT







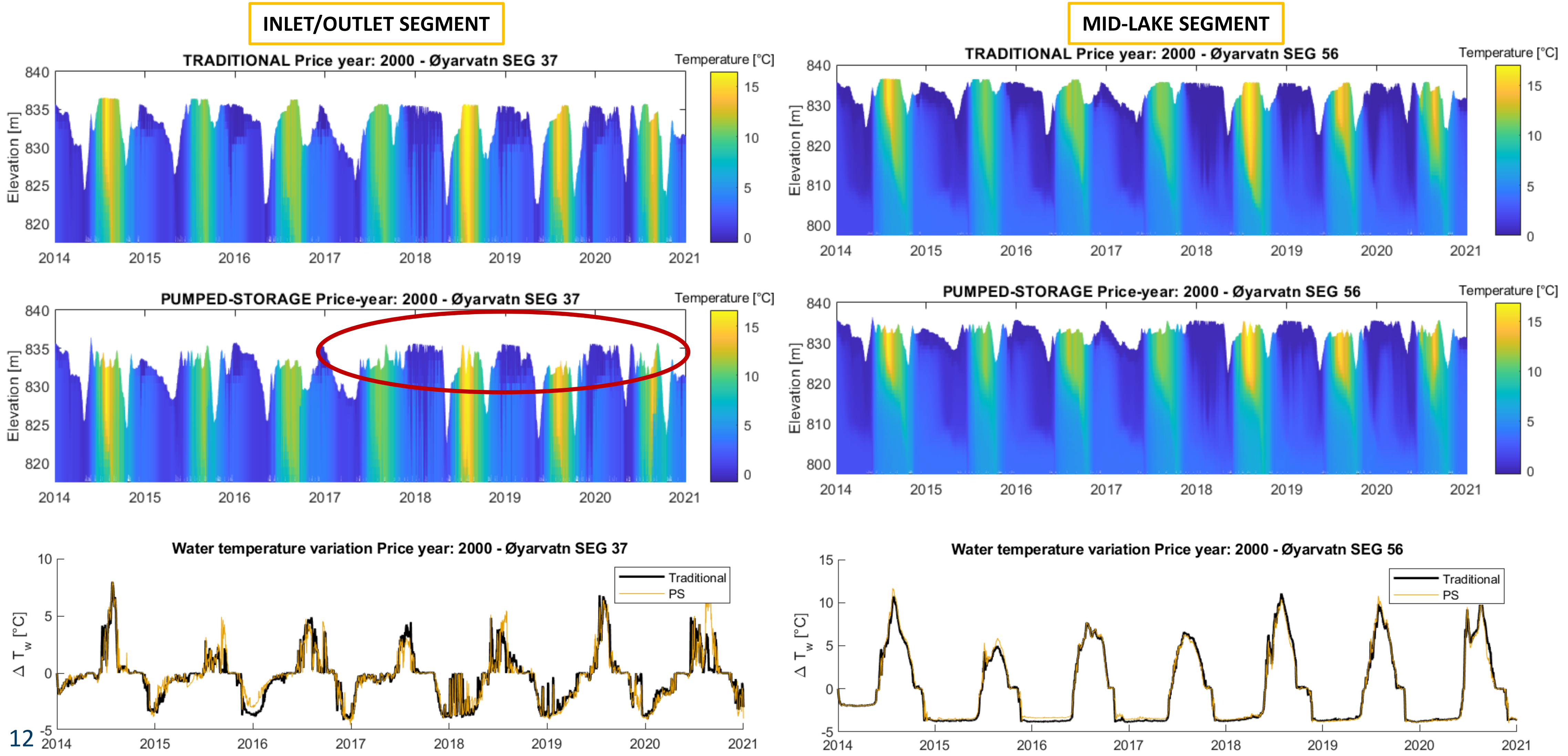
MID-LAKE SEGMENT

discontinuous
stratification

Gaia Donini, 2022

Results

ØYARVATN - 2000

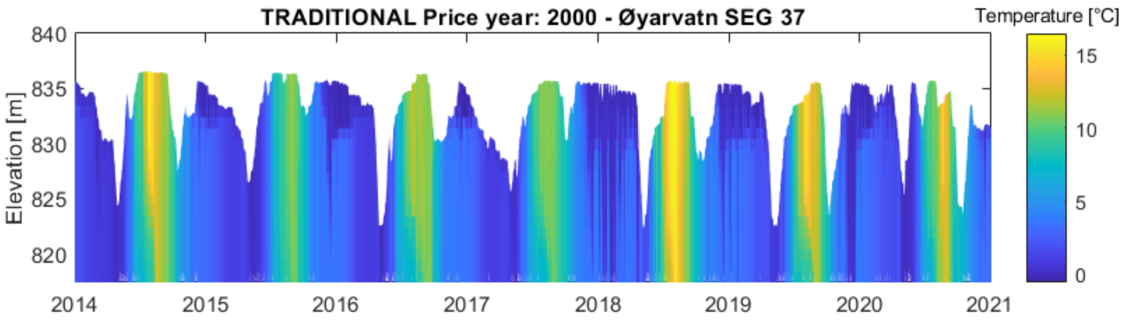


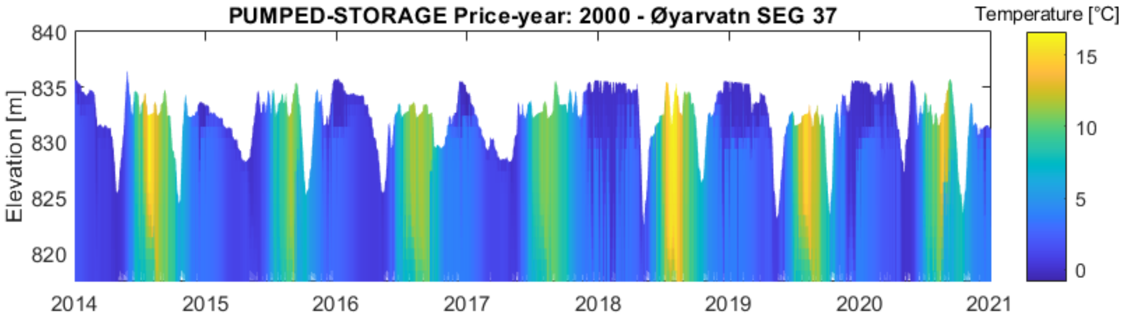
Gaia Donini, 2022

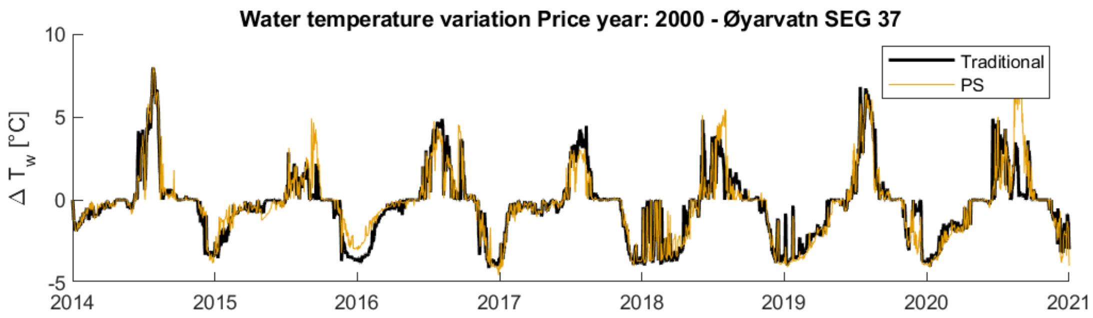
Results

ØYARVATN - 2000

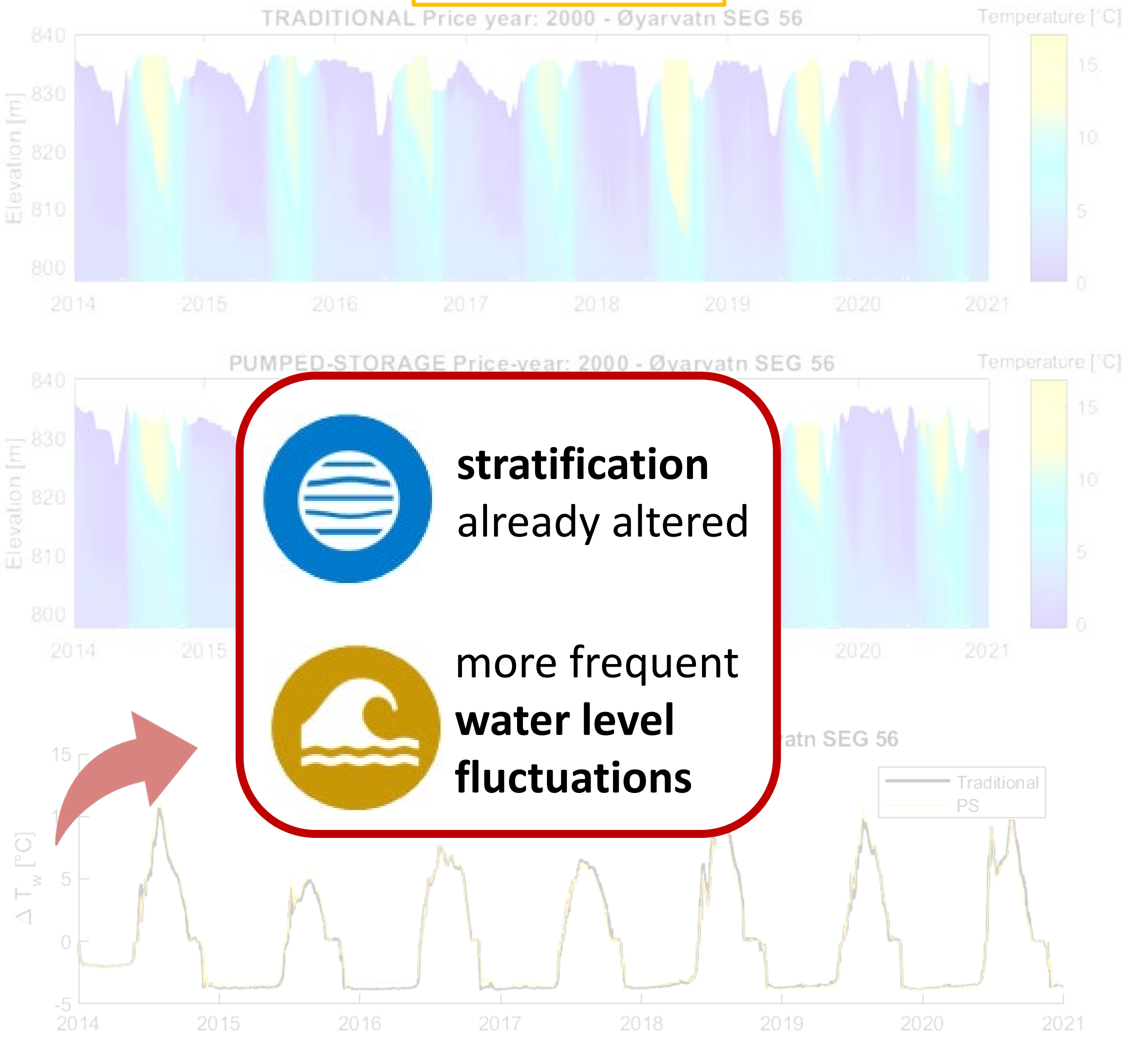
INLET/OUTLET SEGMENT







MID-LAKE SEGMENT

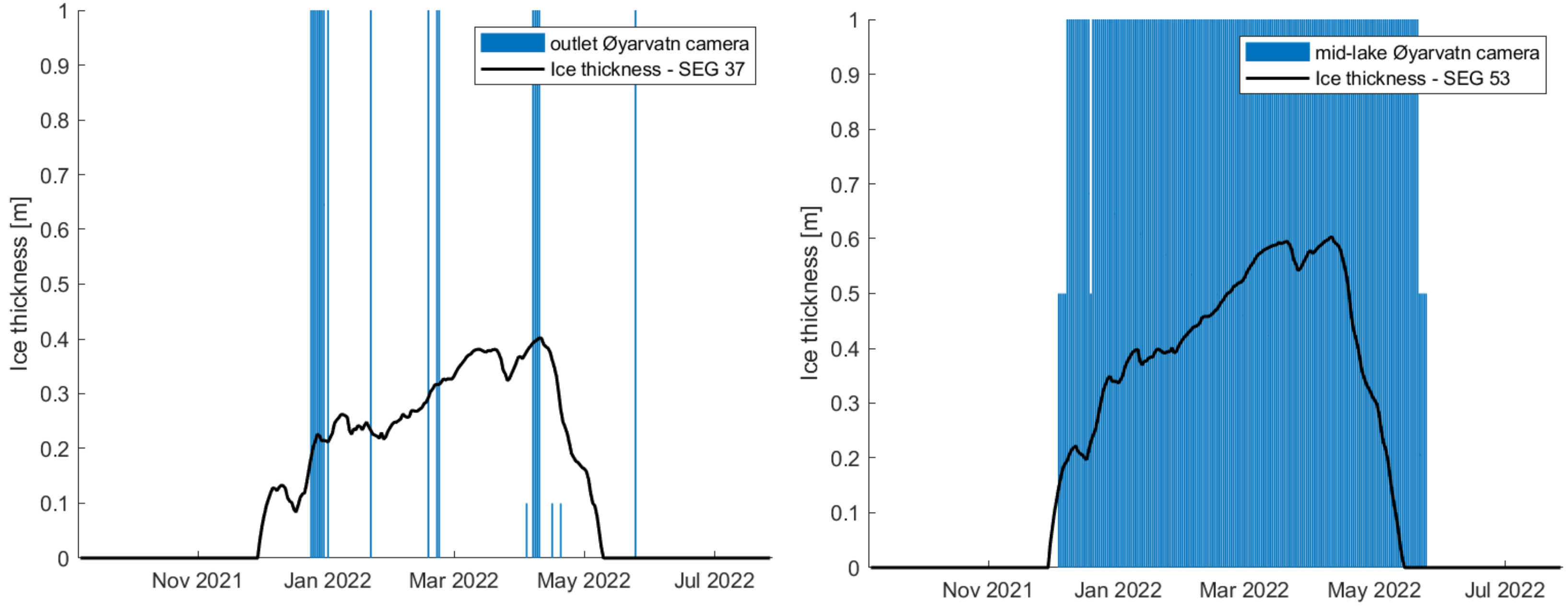


stratification already altered

more frequent **water level fluctuations**

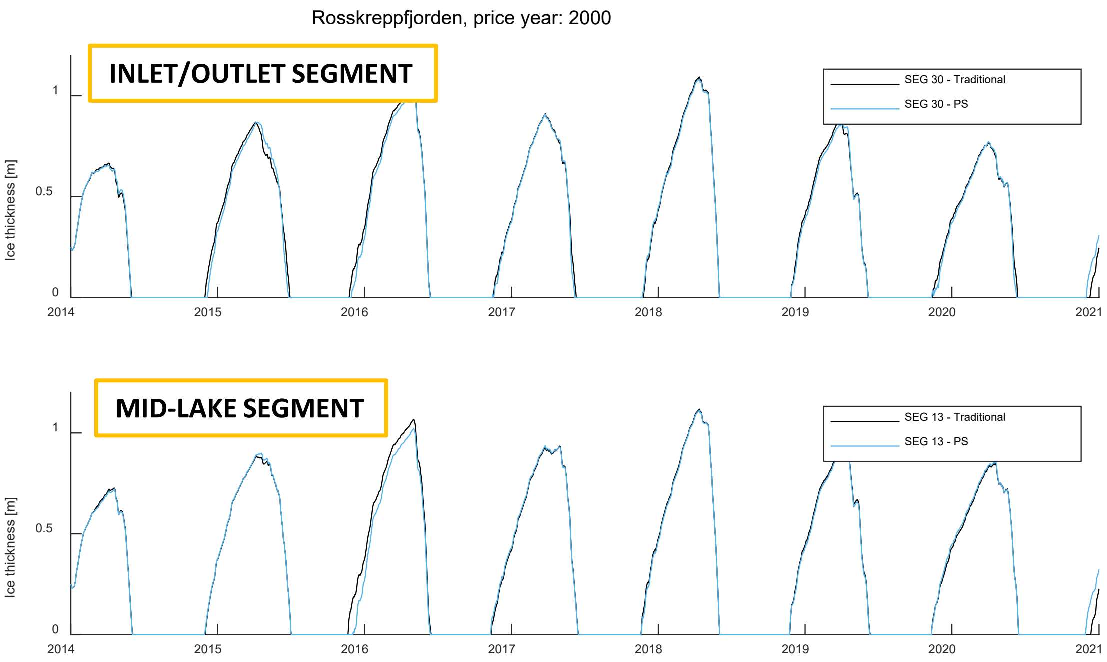
Gaia Donini, 2022

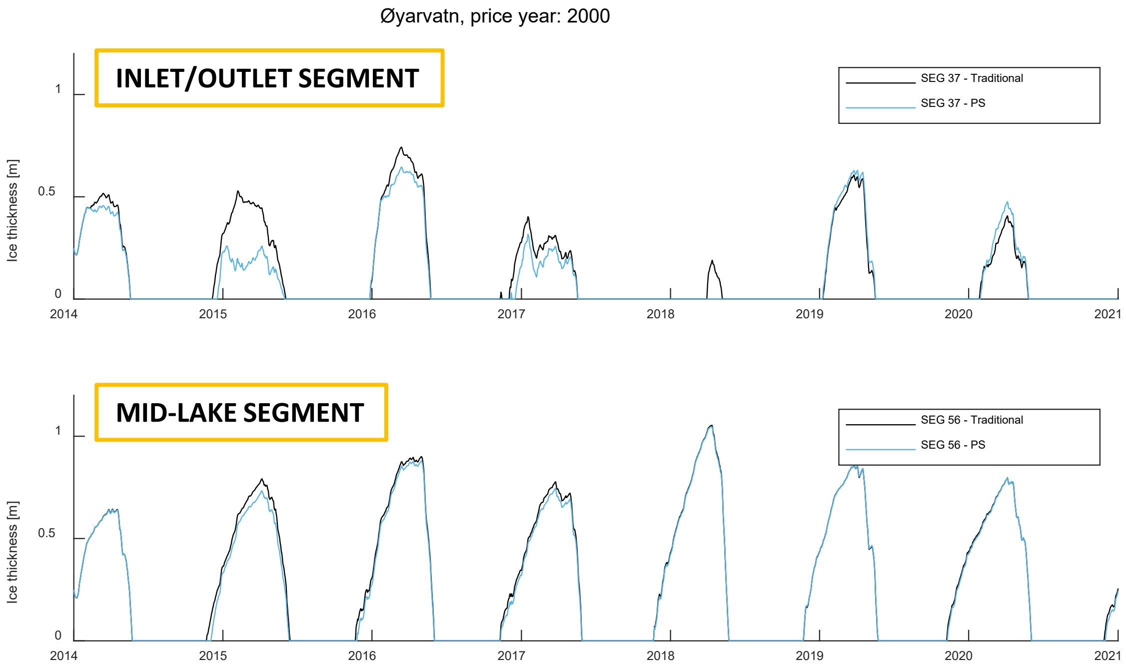
Model calibration – ice cover



Results

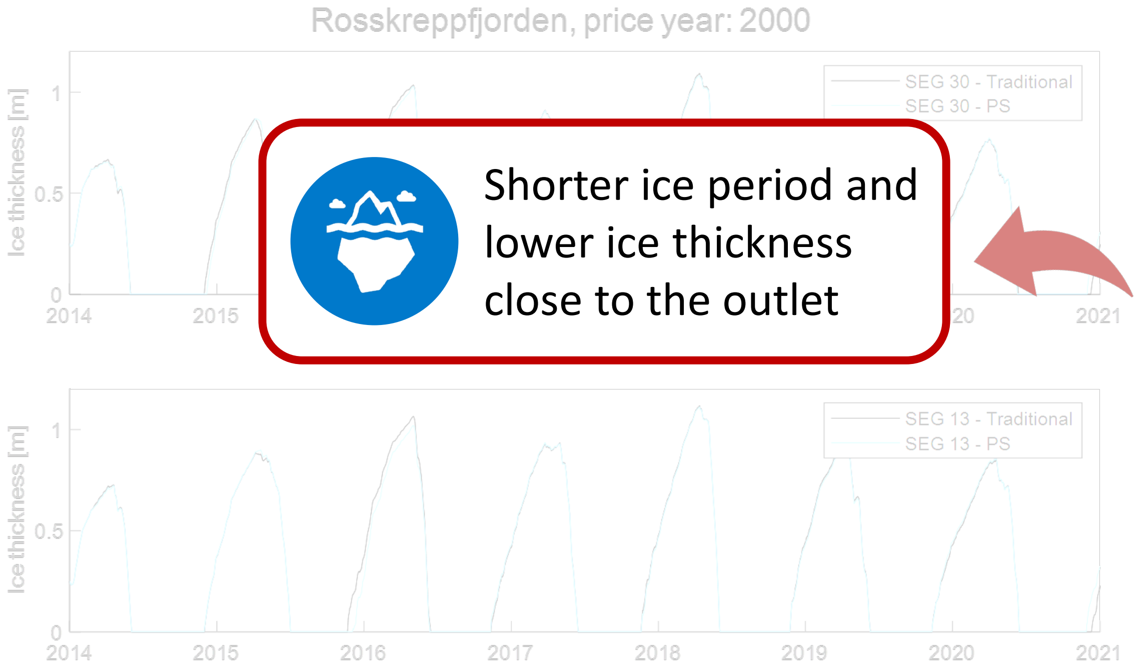
ICE COVER – PRICE YEAR:2000



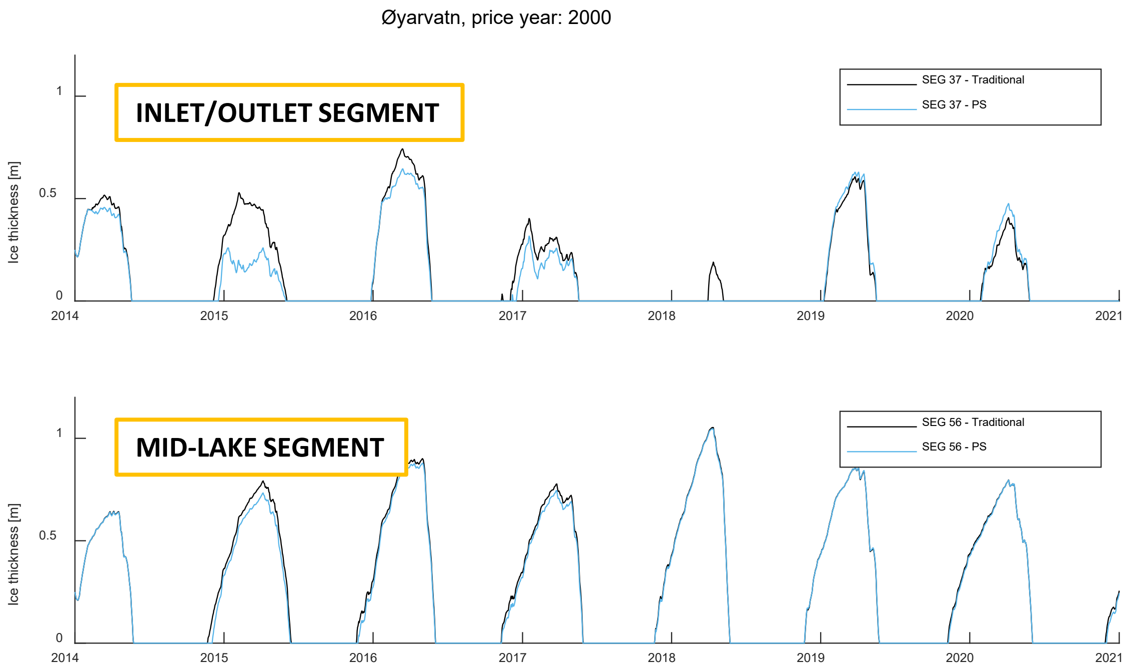


Ice cover- way forward…

ICE COVER – PRICE YEAR:2000



Shorter ice period and lower ice thickness close to the outlet



Conclusions I

The **smaller** the reservoir, the bigger the impacts along the littoral zone

High differences in **WL variation** for traditional and **pumping mode**, especially in Øyarvatn

The **dewatered zone** impacted is **lower** with **pumping** than with traditional, especially in Øyarvatn

Ramping constraints on WL variations **can help in reducing impacts** on the regulation zone, needs more investigation

Conclusions II

The **area closest to the inlet/outlet is the most altered**

In Rosskreppjorden there is a weaker and more discontinuous **stratification**

In Øyarvatn there are more frequent **water level fluctuations**

In Øyarvatn the **ice period is shorter** with **lower ice thickness** close to the outlet due to hydropower operations

References:

Gaia Donini, 2022. Modelling hydrodynamics and ice formation in a pump-storage system between two Norwegian reservoirs. Master Thesis. Modelling hydrodynamics and ice formation in a pump-storage system between two Norwegian reservoirs - SINTEF

Anna Pinneli, 2023. Analysis of environmental impacts of a pump-storage system between two Norwegian reservoirs considering climate scenarios. Master Thesis.

SINTEF

Thank you for your attention!

ana.adeva.bustos@sintef.no

Especial thanks to Gaia Donini and Anna Pinneli (University of Trento)