Ecohydraulic research within Centre for environmental design of renewable energy (CEDREN)

Atle Harby, CEDREN Director
SINTEF Energy Research
Norway
Centre for environmental design of renewable energy - CEDREN

Renewable energy respecting nature
Energi21 and The Parliament
→ 8 new research centres on environmental-friendly energy
Energy for Europe

Theoretical potential offshore wind 14 000 TWh

2006: Oil & Gas: 2500 TWh/y

Hydro power: 125 TWh/y

Subsea Transmission Network

The European energy market demands:
- Renewable energy
- Balancing Power

Effective use of energy
CCS
Bio power & heat
Balancing power from hydro
Hydropower technology for the future

Environmental design of hydropower

Impacts on birds and wildlife from wind turbines and power lines

Reconciling environmental and energy policy concerns
CEDREN will deliver

1. Knowledge about renewable and sustainable energy production
CEDREN will deliver

2. Innovation and new opportunities for renewable energy solutions
CEDREN will deliver

3. Outstanding dissemination and targeted communication of processes and results
International collaboration

- Research and education
- Authorities
- Seminars, workshops
- Together with Norwegian industry
- Case-studies

GHG issues at Bakun dam, Malaysia

Workshop Arusha

Policy brief

End-user meeting in India
Associated research partners

- SEI Stockholm Environment Institute
- Game and Fisheries Research
- BOKU
- Universität Stuttgart
- sj.e
- Heriot-Watt University
- University of Exeter

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Scientific Committee

Klaus Jorde  
KJ Consult/SJE

Silke Wieprecht  
Uni Stuttgart

Daniel Boisclair  
Univ. Montreal

Center for Environmental Design of Renewable Energy
CEDREN key figures 2011

- **Total costs:** 64.6 Mill NOK

- **110 scientists and students working**
  - SINTEF Energi 34
  - NINA 41
  - NTNU 14
  - LFI 5
  - NIVA 4
  - Uni Research 12

- **16 PhD og 4 post-doc**
Dams

- Migration barrier
- Loss of connectivity
- Less access
- Loss of biodiversity
Degraded habitat in bypassed sections
Change in downstream flow regime
Landscape effect
Impacts on wildlife
Greenhouse gas emission control
How to mitigate all this?
Flow and the environment

environment

flow
Flow and the environment
Flow and the environment

Variation important
Alternatives

1. Investigate status

Compare to other rivers

Guess

Model

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In situ study  Laboratory  Model simulation
How much water is needed?

EnviDORR
Marine River

Salmon life cycle

- Adult
- Spawning in a Redd
- Eggs
- Eyed eggs
- Alevin
- Smolt
- Parr
- Fry

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Spawning – site chosen by the female
- Substrate
- Velocity
- Depth
- Partner
Nest of salmonid

- Water current
- Water depth (cm)
- Burial depth (cm)
- Water chemistry
  - Oxygen content
- Water velocity
- Substrate composition
  - Fredle indeks
- No. egg/nest
- Egg survival
- Temperature
- Identification of species
Spawning redd for Vosso salmon (110 cm):
- grain size > 64 mm.
- depth 25-30 cm

Normal egg survival > 80 %
Large spawning fields
Small patches of spawning grounds
Small spawning site in Bjoreio
964 spawning sites surveyed in 2004-2011
+ 105 sites in 2012
Vøringsfossen – one of Norway's highest rated tourist attractions
Flow at spawning time

During winter

OBS! Notice the scale: Size of a man

Bjoreio – water diverted for power production
Egg survival and water depth 2004

Survival rate [%]

Water depth [cm]

- Trout
- Salmon
- ???

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Simple solution.....

.....move some water released in summer to winter
How much spawning area is enough?

Quantifying the effect of spawning area on sea trout production

Strong correlations between river wide juvenile density

• and the percentage river area suitable for spawning

• and the distribution of spawning grounds

• Guidelines for river restoration and mitigation.

• Presentation today, 17:00, A
Salmon life cycle

Marine

River

Eggs
Spawning in a Redd
Eyed eggs
Alevin
Smolt
Fry
Part

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“temperatures at swim-up should be > 8°C”
..and in a natural stream!

![Bar chart showing survival rates in different conditions](chart.png)

- **Low Density**
  - Early and cold: 187%
  - Medium: 170%
  - Late and warm: 118%

- **High Density**
  - Early and cold: 99%
  - Medium: 70%
  - Late and warm: 71%

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...and under peaking and stable conditions in semi-natural streams

![Graph showing survival percentages under different flow conditions](image-url)
Marine

River

Salmon life cycle

- Adult
- Smolt
- Parr
- Fry
- Spawning in a Redd
- Eggs
- Eyed eggs
- Alevin
....focus on hydropeaking
Smolt migration
River Mandal

Torbjørn Forseth, Hans-Petter Fjeldstad, Ingebrigt Uglem
Knut Alfredsen & Thibault Boissy

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Challenge:

- Safe road:
  2003: 10%
  Goal: 90%

- Wrong route:
When do the smolts arrive and which route do they choose?
Impacts of strobe lights
Smolt timing model

\[
\ln(\text{Smolts}) = \ln(\text{MeanSmoltNumber}) + \text{Const} + \beta_1 \times \text{Tempsum} + \beta_2 \times \text{Temp} + \\
\beta_3 \times \text{Tempdiff} + \beta_4 \times \text{Discharge} + \beta_5 \times \text{Dischargediff} + \beta_6 \times \ln(\text{Discharge}) + \\
\beta_7 \times \ln(\text{Temp}) + \beta_8 \times \text{Days}
\]

\[R^2 = 0.60\]

Fjeldstad et al., 2012

- Observed smolt catches
- Model predictions

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Predictions from route model
Likelihood for bypass migration

\[ \log it(\pi) = \log \left( \frac{\pi}{1-\pi} \right) = \beta_1 \times \text{Total} + \beta_2 \times \text{Share} \]

<table>
<thead>
<tr>
<th>Proportion of total discharge in bypass (%)</th>
<th>20</th>
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</table>

Fjeldstad et al., 2012

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2008:
- 96 fish tagged
- 61 migrated out from lake Mannflåvatn (64 %)
How to predict what is happening here?
How to predict what is happening here?

Climate change, ice, water temperature
Changes in key lake ice parameters
1961-90 vs 2040-71 scenario
Model verification from Timalsina et al. (in prep)

Drifting frazil ice

Ice cover

Frazil formation
**Abiotic input:**
Water temperature
Wetted area per section (discharge)

**Biological input:**
Egg deposition (per section)
Habitat quality (each year)

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The Mandal River
Water temperature

- Control scenario
- A2 scenario
- B2 scenario
Flow

![Graph showing flow discharge over weeks for different scenarios: Control, A2, and B2. The graph plots discharge (m$^{-3}$s$^{-1}$) against week number. The control scenario shows a steady decrease in discharge, while A2 and B2 scenarios have fluctuations with peaks and troughs.](image-url)
• Salmon juveniles grow faster, smoltify younger
• Increased mortality in summers due to reduction in wetted area
• Reduced recruitment and reduced production of salmon in future scenario

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Seasonal requirements

Flow (m³/s)

- Natural
- Regulated

Seasons:
- 1. jan.
- 1. feb.
- 1. mar.
- 1. apr.
- 1. mai.
- 1. jun.
- 1. jul.
- 1. aug.
- 1. sep.
- 1. okt.
- 1. nov.
- 1. des.

Events:
- Egg survival, winter habitat
- Smolt migration
- Maintain geomorphology
- Fry displacement?
- Spawning
- Habitat
- Attract spawners

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Environmental impacts of rapid and frequent flow changes

Knowledge about how, when and where rapid variations in power production may be done with acceptable impacts on the ecosystem.

Physical processes  Biological processes  Mitigation
• Hydropower operation with rapid flow fluctuations
• Physical effects of highly unsteady flow
• Environmental effects of highly unsteady flow
Numerical approach

Example Nidelva River 4km upstream of Trondheim

- Hydropower peaking scenario
- Inflow decreases from 150m$^3$/s to 50m$^3$/s
- Simulation with Star CCM+ (7.600.000 cells)

→ slowing down
→ wetted area decreasing
→ main streamline shifting sideways
Physical experiments

PIV – Particle Image Velocimetry
Artificial streambed
Highly unsteady discharge
3D Hydraulic model simulation and results validation

**Star CCM+:**
- Commercial 3D code based on the Reynolds-averaged Navier-Stokes equations, k-epsilon turbulence model
- Free water surface calculation by “Volume of Fluid” Method

**Discretization**
- 850,000 cells on rectangular mesh
- 0.35 x 0.35 x 0.175 m

**Analysis**
- Steady Flow at 2, 10, 16 and 20 m³/s
- Unsteady Flow Analysis

**Verification**
- Observed vs simulated velocity profiles and water lines
3D Hydraulic model simulation and results validation

Steady simulation Results:

Measured vs simulated water line at 10.58 m³/s

Measured vs simulated water line at 20.63 m³/s

Measured velocities

Simulated velocities

Depth averaged velocities (20 m³/s)
3D Hydraulic model simulation and results validation

*Unsteady Simulation Results:*
Effects on bentic macro-invertebrates

Hydropeaking operation → Modification of the habitat

Effect on
- biomass
- abundance
- behaviour
- life cycle

Qualifying and quantifying this impact to define locally adapted mitigation measures
Modeling the suitability for benthic macro-invertebrates in Surna River

- One site upstream power plant
- One site downstream power plant (affected by hydropeaking)
Suitability for *Limnius spp.* at the site affected by hydropeaking

\[ Q = 53 \text{ m}^3/\text{s} \]

- Frequent drops in water level down to 15.4 m³/s
  \[ \rightarrow \text{decrease in suitable habitat} \]

Included parameters:
- Water depth
- Substrate type
- FST-number
Fish: Experimental setup in Ims
Results: Winter

Flow fluctuations had no effect on body fat
Fish surviving stranding - experimental setup in Ims
Results: Winter

Survivors of stranding had significantly less body mass.
Growth of fish in peaking environment - experimental setup in Paltamo (Finland)
Results: Winter

- **Fork length, winter end**
- **Body weight, winter end**
- **Body fat, winter end**

Each graph compares the changes in fork length, body weight, and body fat between 'peaking' and 'stable' treatments.
Results: Summer

Significant effects on:

- body weight → control fish 2.56 g (= 10.3%) heavier;
- body fat → control fish have 0.25 g (= 16.6%) more body fat
Nest digging within an hour after a typical hydropeaking event.

Presence of salmon at the spawning ground affected by variability in water discharge.

Take home message: Salmon are affected by hydropeaking events but relatively quickly return to the spawning ground.

Range in water discharge

Salmon spawning behavior

Nest digging within an hour after a typical hydropeaking event.
Linking Population and Habitat Model

Effects of hydropeaking on the Atlantic salmon populations...

Engineers’ view
Hydraulic Habitat Models

Biologists’ view
Population Models

...on large temporal and/or spatial scales
Linking Population and Habitat Model

Hydraulic Habitat Model

CASiMiR stranding

multivariate fuzzy hydraulic habitat

Population Model

IB-salmon

mechanistic ecological population dynamic
Linkage concept

1. identification of characteristic reaches
2. if necessary 1D simulation to account for attenuation
3. assignment to 50m sequences

<table>
<thead>
<tr>
<th>River Sequence Number</th>
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<td>1</td>
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</table>

60% 40%

IB-salmon

CASiMiR stranding
Linking Population and Habitat Model

CASiMiR stranding

Week factor

Age dependent stranding risk

IB-salmon

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Hydropeaking in Europe

Legend
- EFI+ sites with hydropeaking
- EFI+ sites

Hydropeaking EFI+sites

Number of EFI+ sites

map done by Raffaela Schiappargor, June 2011
Development of a computer-based wave detector - Observed parameters

Parameters (Increase=IC and decrease=DC)

- Duration $dt$ (min)
- Mean IC/DC $[m^3/s/min]$
- Maximum IC/DC $[m^3/s/min]$
- Total IC/DC $\Delta Q$ IC/DC $[m^3/s/event]$
Norwegian, Austrian and Reference Rivers
Sum \( dQ_{IC} \) – Events 2008 (m\(^3/s\)) \((n=500)\)

Sum of discharge fluctuations; Increase-Events (m\(^3/s\)) 2008

- Arithm. Mean
- NOR: 5500
- AUT – hp: 16950
- AUT – Ref: 2350

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Hydro storage – a renewable battery
Norwegian hydropower

Natural lakes used as reservoirs

Multi-year reservoirs
Norway

- Hundreds of large reservoirs
- 20 reservoirs with more than 100 Mm³ both up- and downstream
Simulated wind production in the North Sea area in 2030 – 100 000 MW installed capacity

80 000 MW
January - March

7 x 24 h
July - September

7 x 24 h
The technical potential
The technical potential

\(~20\ 000\ MW\) in southern Norway possible - including \(~10\ 000\ MW\) pump turbines
Environmental impacts
Threatening biodiversity?

Impacts on fish?
Unsafe ice conditions?
Detailed simulations of PSP with outlet into Suldalsvatn

Simulations with GEMSS
10 m depth in summer - today

Hylen HPP

Kvilldal HPP

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10 m depth in summer – with PSP Production phase

Hylen HPP

Kvilldal HPP

CEDREN
Centre for Environmental Design of Renewable Energy
10 m depth in summer – with PSP Pumping phase

Hylen HPP

Kvilldal HPP
Results

- Intense vertical mixing through the water column
- Colder temperature in the downstream river Suldalslågen during summer and autumn if water comes directly from Blåsjø
- Strong currents appear next to the new power plant
Drawdown zone exposed – changed pattern?
Water level variations

Stage Holen - upper reservoir

- Simulated
- Current
- LRWL
- HRWL
Water level variations

Stage Holen - lower reservoir

- Simulated
- Current
- LRWL
- HRWL
Social acceptance
Large plants – large impacts?

Long history of conflicts

Resistance formed the environmental movement

Source: Statkraft
Small plants – small impacts?

Accumulated effects?
An extreme example from China

Small hydropower (< 50 MW):
• More than 1000 plants built
• Producing 2.5 TWh/a

XXLarge Three Gorges:
• 1 huge plant
• Producing 96 TWh/a

In order to produce the same energy output from Three Gorges project, approximately 40,000 small hydropower plants (< 50 MW) must be constructed.

What are the accumulated environmental (and social) impacts?
Results: Comparison of impacts

- Large negative
- Medium negative
- Small negative
- Insignificant
- Small positive
- Medium positive
- Large positive

Legend:
- Average larger HP-project
- Sum of 27 small

Categories:
- Water temperature
- Ice cond./Local climate
- Sediment transport/Erosion
- Landscape
- Recreation
- Nature and environment
- Hunting
- Fish
- Cultural heritage
- Nature resources
- Water quality - supply and pollution
Comments to the results

- Small-scale HP scores 'worse' (more negative/less positive) on the following topics:
  - Ice conditions/local climate
  - Recreation
  - Fish
  - Nature resources

  - Large HP scores 'worse' (more negative) in the category water temperature

  - The scores differ with only one impact level
Is salmon more important than moss?

Who to assign values/priorities to the environment?

- Researchers?
- Management authorities?
- The majority?
- Other stakeholders?
Conclusions

- Rivers are smaller, shallower and narrower at the upstream end compared to the downstream end – most of the times
- Rivers are wet – if they are not dry
- Bullet points are boring....
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