#30803

Modelling of Chemical Discharges from Atlantic Salmon Hatcheries Using Computational Fluid Dynamics

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Introduction

Formalin (aqueous formaldehyde) is widely used in salmon hatcheries for parasite and fungal control. Effluents are released into receiving waters where concentrations may temporarily exceed the Predicted No-Effect Concentration (PNEC) within the vicinity of the outfall.

Regulators and risk managers must determine:

What spatial and temporal extent of a mixing-zone is environmentally acceptable for intermittent hatchery discharges?

Generic marine dilution factors seldom reflect site-specific hydrodynamics. Although permitting incorporates environmental design criteria, demonstrating compliance requires site-specific assessment.

This study applies Computational Fluid Dynamics (CFD) to construct a scientifically defensible, worst-case mixing-zone scenario for large Norwegian flow-through hatcheries using formalin. The model was initially developed from measured data collected from smaller hatcheries and then scaled up to accommodate the operational requirements for theoretical releases from large-scale facilities where no measured data were available.

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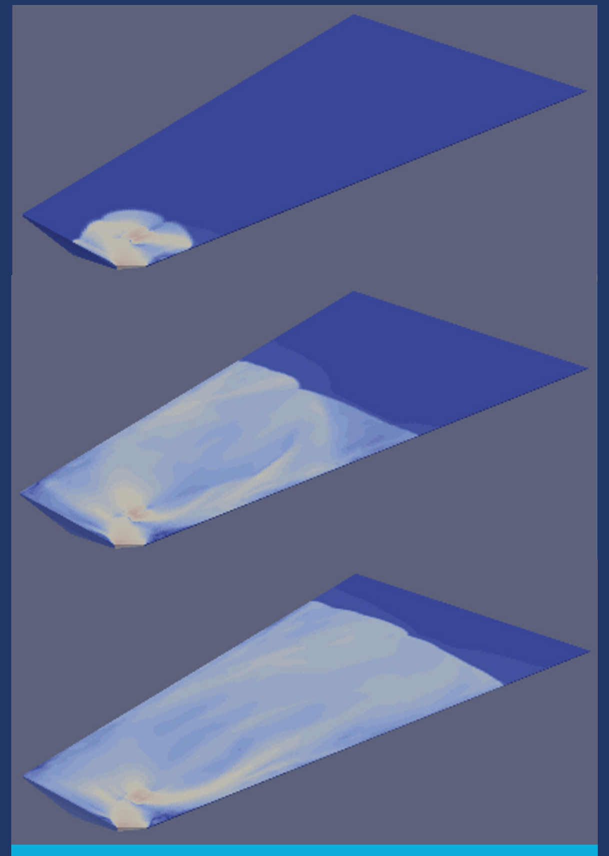


Establishment of the flowfield in the model fjord domain

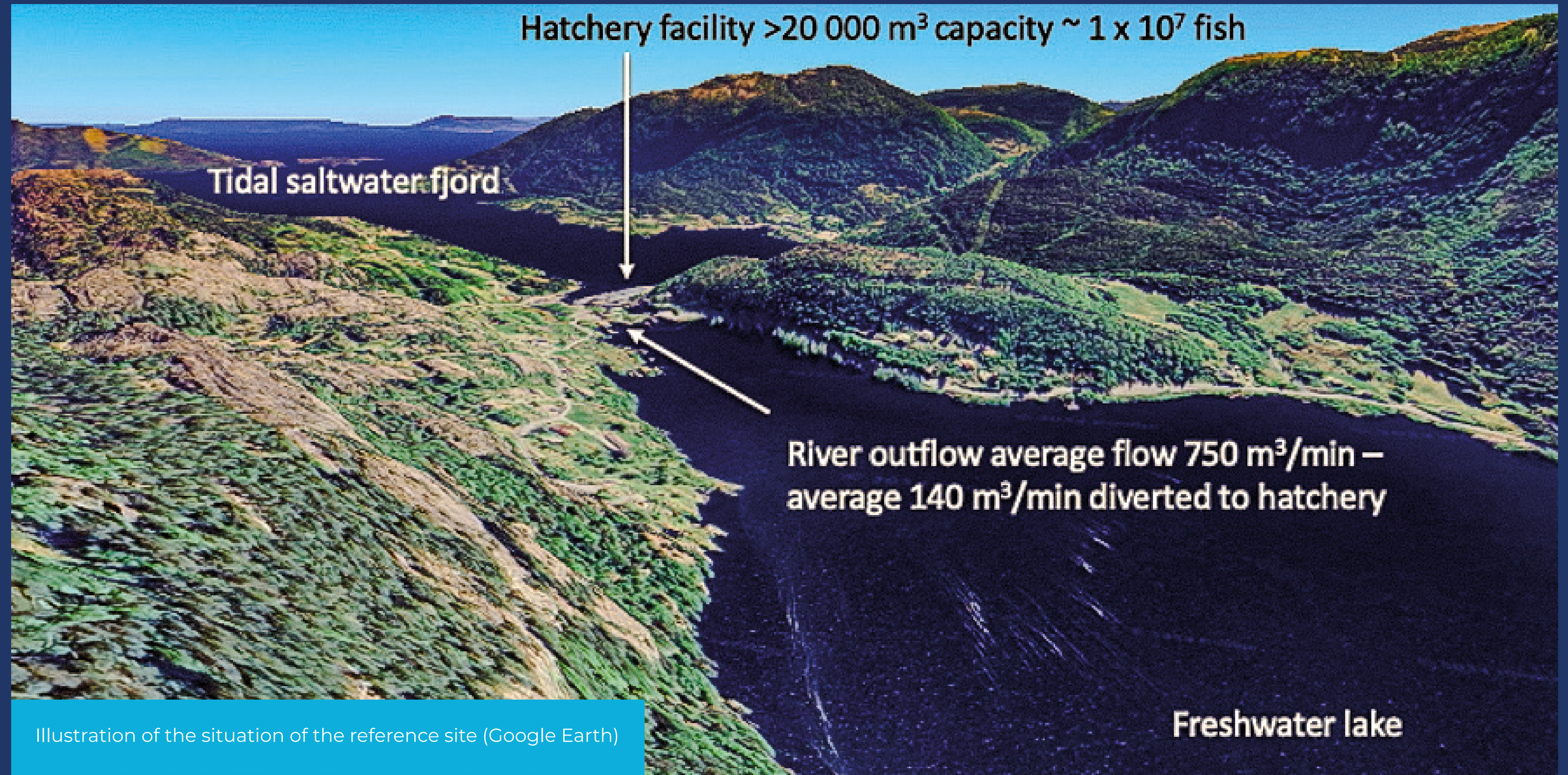
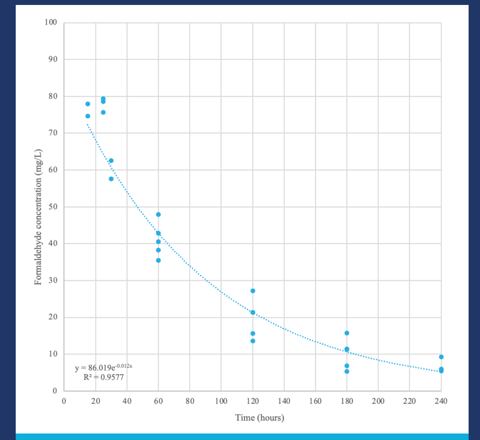
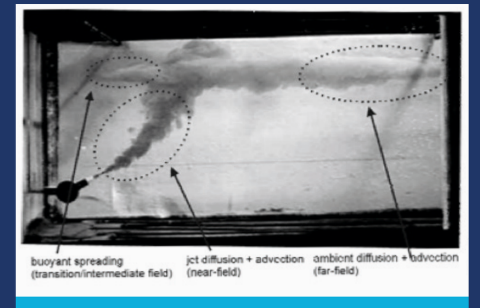


Illustration of the situation of the reference site (Google Earth)



Measured vs. modelled concentrations in treatment tanks



Laboratory investigation of near field mixing

Methods

Reference Facility for Modelling

- Selected as representative as worst-case scenario for discharge volume / biomass
- Large Norwegian flow-through hatchery (>20 000 m^3; ~10^7 smolts)
- River inflow: 750 $m^3 \cdot min^{-1}$ (~140 $m^3 \cdot min^{-1}$ to hatchery)
- Largest tanks: 300 m^3; biomass 100 $kg \cdot m^{-3}$
- In-system dilution: 8–10×
- Outfall: 1.2 m pipe, 35 m depth, 150 m from river mouth

Chemical Parameters

- Treatment concentration: 97.3 $mg \cdot L^{-1}$ formaldehyde
- Tank concentration decline: first-order kinetics, data gathered during trial approved by competent authority
- PNEC: 7.54 $\mu g \cdot L^{-1}$ (acute endpoint, AF = 1 000)
- Biodegradation excluded → conservative

Hydrodynamic Forcing

- Boundary velocities and tidal shear from NorKyst800 (ROMS, 800 m resolution)
- Flow stratification (tidal shear/layered flow) represented
- Salinity-driven density stratification not simulated
- River inflow represented as seawater with correct discharge and momentum
  → Plume buoyancy is conservatively underestimated

Computational Platform

- OpenFOAM, finite-volume Navier–Stokes framework
- Solver: PIMPLEFoam (transient, incompressible, turbulent)
- Turbulence closure: k–ε RANS
- Domain: fjord-like system (~3 km^2; 9.9 × 10^7 m^3)
- Mesh: ~885k cells, refined (<1 m^3) around outfall
- Isothermal model; temperature not coupled to buoyancy

Model Verification

Numerical Verification

A formal mesh-refinement study was not performed. Instead, mesh design followed established best practice for coastal outfall CFD, using <1 m^3 cells in the near-field region where jet momentum, entrainment, and initial dilution occur.

Courant numbers remained stable throughout the simulation with no indication of numerical drift or instability.

Physics Validation (Indirect)

Direct field validation was not feasible. The model relies on the validated mathematical and turbulence models embedded in OpenFOAM, which have been extensively tested for turbulent buoyant jets and stratified plumes in laboratory settings.

NorKyst800 boundary inputs are validated for Norwegian coastal hydrodynamics.

The simulated conditions (jet Reynolds number, buoyancy flux, tidal shear regime) lie well within the published performance envelope of these established models.

Results

Hydrodynamics

- Jet momentum and buoyancy dominate mixing in the first 10 m
- Plume rises rapidly; vertical penetration at surface spreading <3 m
- Tidal flow governs spreading following surfacing

Formaldehyde Dispersion

- PNEC iso-contour depicted in below frames:
  - 1-min, mean flux concentration 223.9 $\mu g \cdot L^{-1}$, iso-contour volume 3 806 m^3
  - Peak at 60-min, 21.16 $\mu g \cdot L^{-1}$, 948 540 m^3
  - 180-min, 8.68 $\mu g \cdot L^{-1}$, 94 725 m^3
  - 215-min, 7.66 $\mu g \cdot L^{-1}$, 563 m^3
  - ~220-min, concentration <PNEC, 0 m^3
- Total dissipation of contour within ~4 hrs

Ecological Relevance

- No chronic exposure; ≤20 treatments per year
- Plume does not contact seabed → no benthic exposure
- Pelagic species exposed briefly at low concentrations
- Mobile fauna likely avoid elevated levels

Discussion

Conservatism of the Scenario

- High biomass and discharge loading
- Low internal dilution
- ~29 kg formaldehyde per treatment
- No degradation (which can be included in a modified model)
- PNEC with AF = 1 000
  → Represents a highly conservative environmental envelope

Large Domain Justification

- Required for realistic tidal propagation
- Prevents artefacts from artificial boundaries
- Near-field plume behaviour preserved by local refinement
  → Large domain improves realism without compromising near-field accuracy

Model Assumptions & Limitations

Flow-Through Hatcheries Only

Not applicable to RAS facilities (different hydrodynamics and effluent pathways, but can be accommodated in a modified model).

Freshwater Constraint

River inflow modelled as seawater due to solver limitations.
→ Conservative, as freshwater would increase plume buoyancy.

Stratification

Flow stratification included.
Salinity-driven density stratification not modelled.
→ Conservatively reduces buoyancy.

Isothermal Model

Temperature not included in density calculation.

Simplified Fjord Geometry; No Degradation

Both assumptions bias predictions toward higher exposure, ensuring a protective result. Simplicity reduces computational resources (~7 days, 100 core AWS).

Regulatory Interpretation

Findings support:

- Compliance with EQS Directive (2008/105/EC) mixing-zone criteria
- Rapid dissipation of formaldehyde
- Limited spatial and temporal extent of PNEC exceedance
- No chronic or cumulative risk under EU and national regulatory frameworks

CFD provides a robust, defensible method for site-specific Environmental Risk Assessment of VMP discharges in Norwegian flow-through hatcheries.

Key References

Albretsen, J. *et al.* (2011). NorKyst-800 model description and validation.
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Weller, H.G. *et al.* (1998). OpenFOAM computational continuum mechanics.