

EGU26 · PICO Presentation



Digital Waters
PhD Pilot



UNIVERSITY
OF OULU



Hydropower in Cold Climates Under Climate Change: A Systematic Review

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A systematic review of 94 peer-reviewed studies and technical reports integrating scientific evidence with expert's perspectives from snow- and glacially influenced hydropower basins

Cold climate Hydropower is under Climate change stress

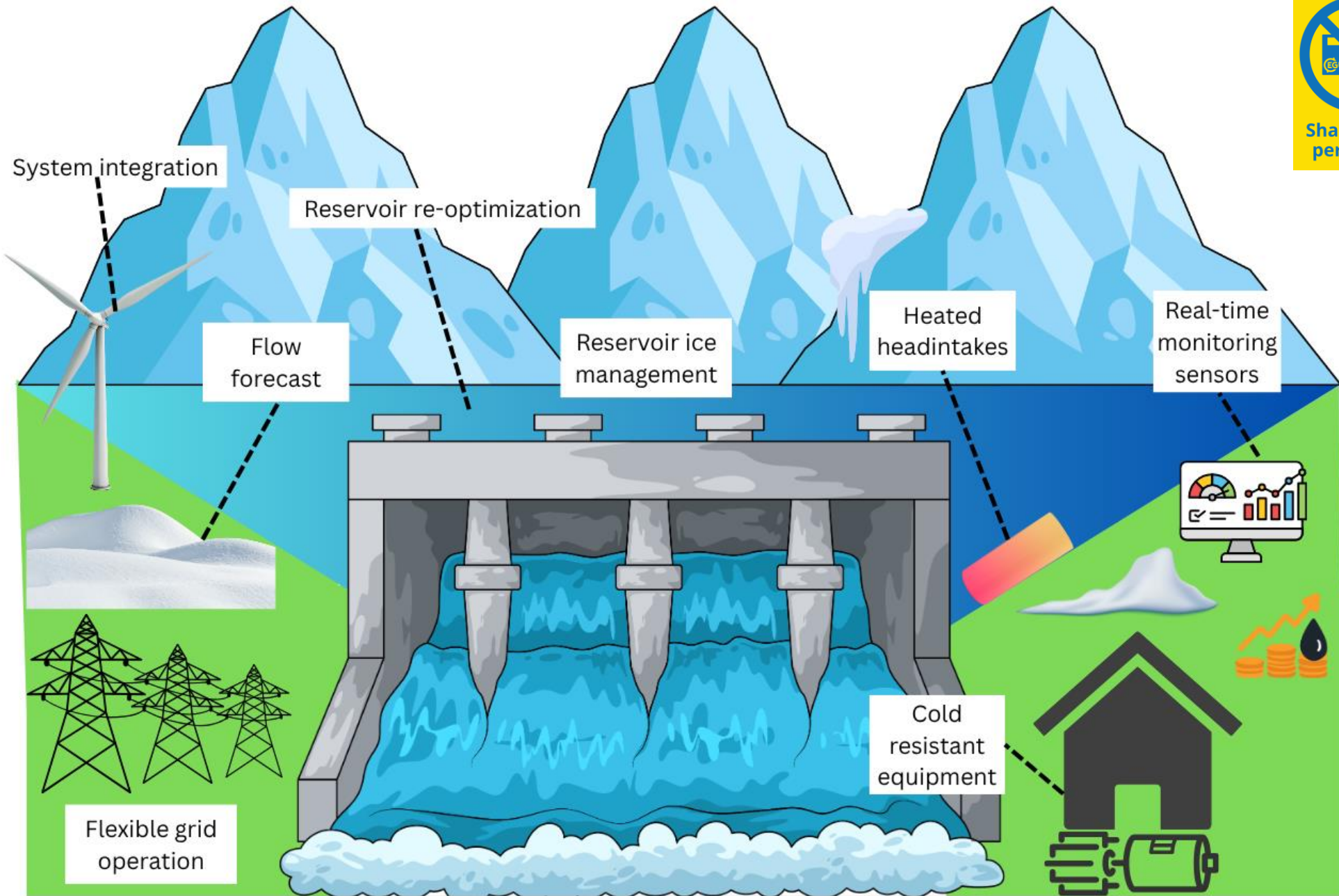


Fragmented Knowledge

Systematic Review, n = 94

Cold climate Hydropower is under Climate change stress

- Hydropower in cold climate regions faces snow and ice challenges
- Flow variability
- Snowmelt shifts
- Ice instability
- Reservoir refill failure
- Data gap limits
- Forecast uncertainty
- Infrastructure stresses
- Increased vulnerability in interconnected systems
- Glacial retreat



**Future
resilience
depends
on
adaptive
and
flexible
hydropower
operation**

Hydropower Adaptation Methods in Cold Climate Regions

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08:59–09:01**

Interactive PICO Session

PICO spot 1b, PICO1b.9

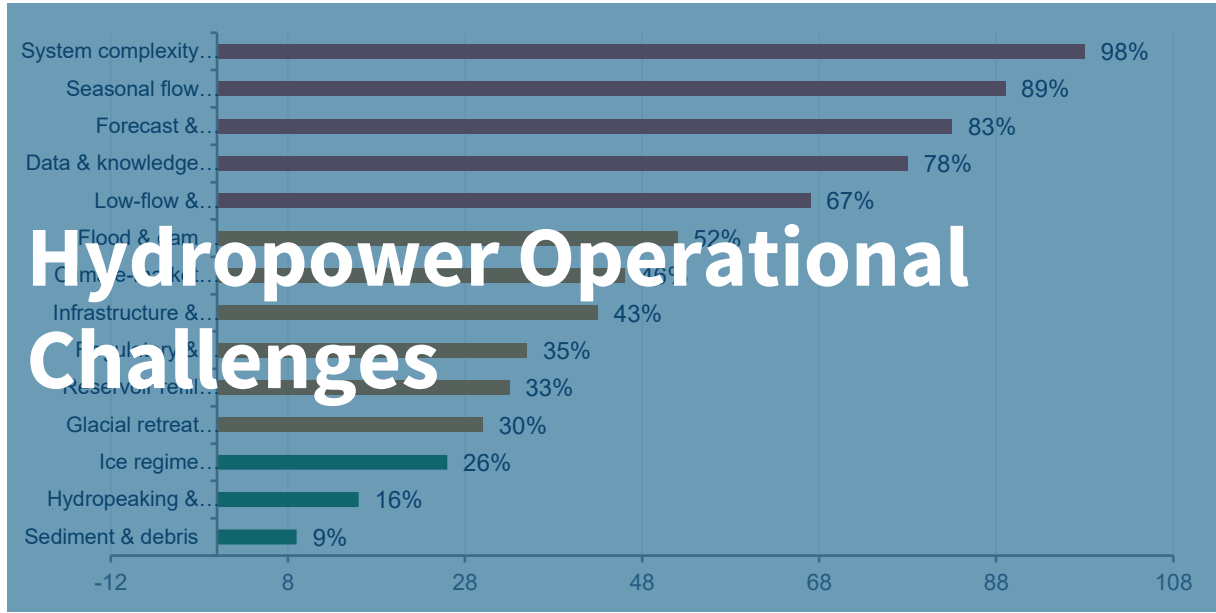
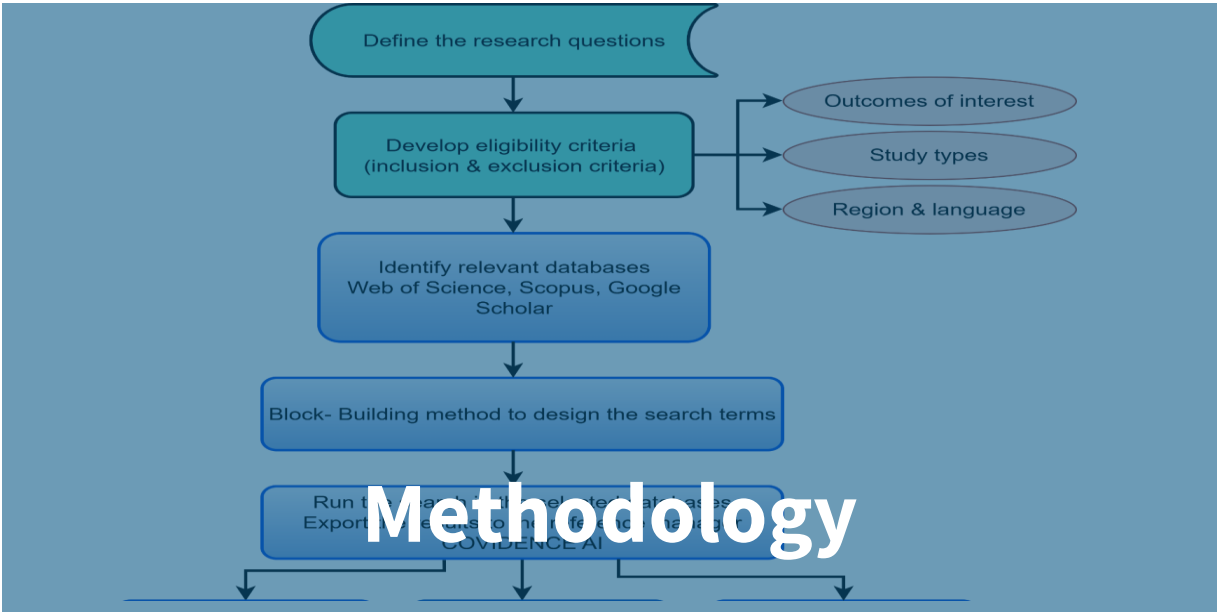


Research Council
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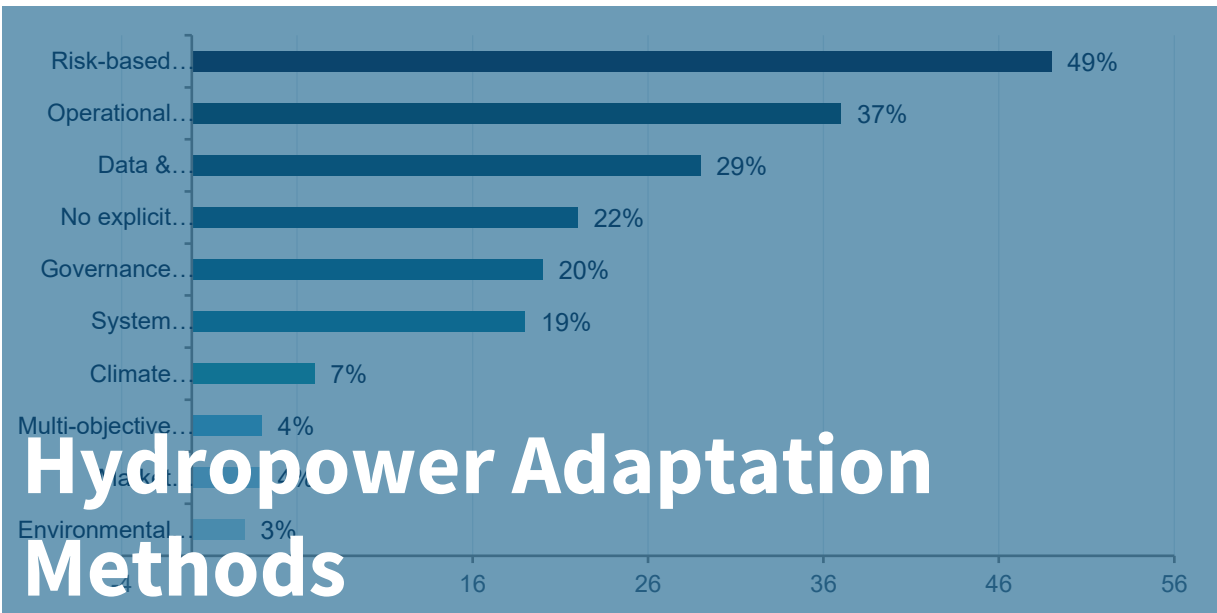


MINISTRY OF
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Navigation



Hydropower Operational Challenges



Conclusions & Implications

- 1 Climate change is already undermining hydropower resilience in cold-climate regions — runoff seasonality, ice regimes, and hydrological variability are all shifting in ways that outpace existing operational practices.
- 2 Seasonal energy-water mismatches are the central operational challenge: earlier snowmelt and higher winter inflows conflict with the need for higher winter and constrain summer generation.
- 3 Ice-related risks (frazil formation, intake clogging, ice jams) remain acute and are poorly integrated into current adaptation frameworks despite high operational impact.
- 4 Adaptation knowledge exists but implementation lags: risk-based planning and operational re-

Outcomes on Hydropower resilience

Research Framework



Motivation

Hydropower facilities in cold-climate, and glacial influenced basins facing future hydrological disruption

Challenges

Climate-driven shifts: earlier snowmelt, rising winter inflows, shorter ice-influenced periods, altered runoff seasonality, and ice process changes

Adaptation

Flexible rule curves, multi-objective optimization, ice control methods, risk-based planning, and improved climate forecasting for cold-climate operations

Outcomes

Hydropower operational resilience is defined as the capacity to absorb, adapt, and recover from disturbances while maintaining essential functions
Climate Change + ***other factors***

System design, institutional constraints, and regulations play an equally important role in Hydropower Resilience



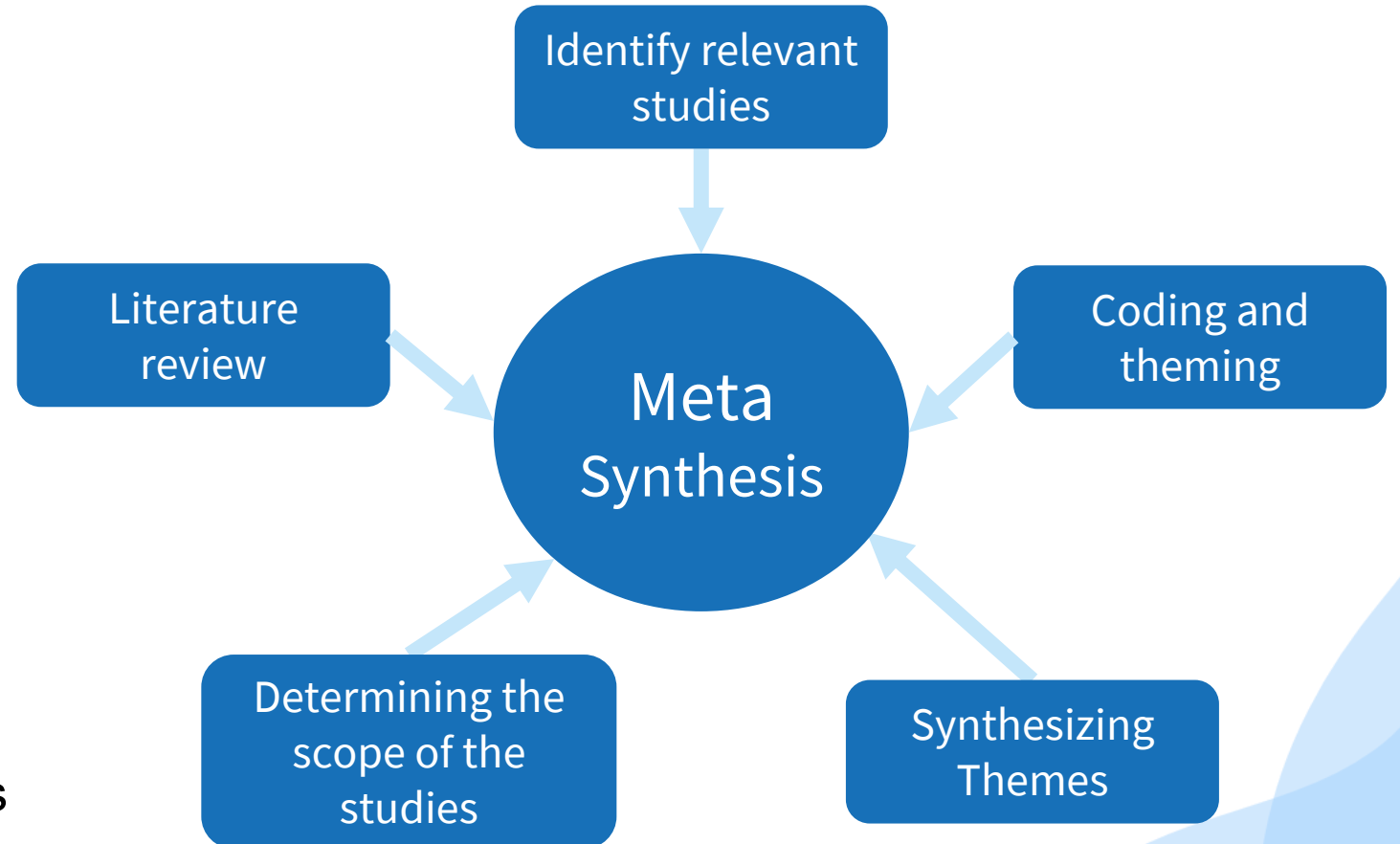
SLR Framework

Inclusion Criteria

- Peer-reviewed or institutional studies on hydropower
- Cold or snow-dominated regions
- Climate change impacts on production, demand, or adaptation
- Published in English

Exclusion Criteria

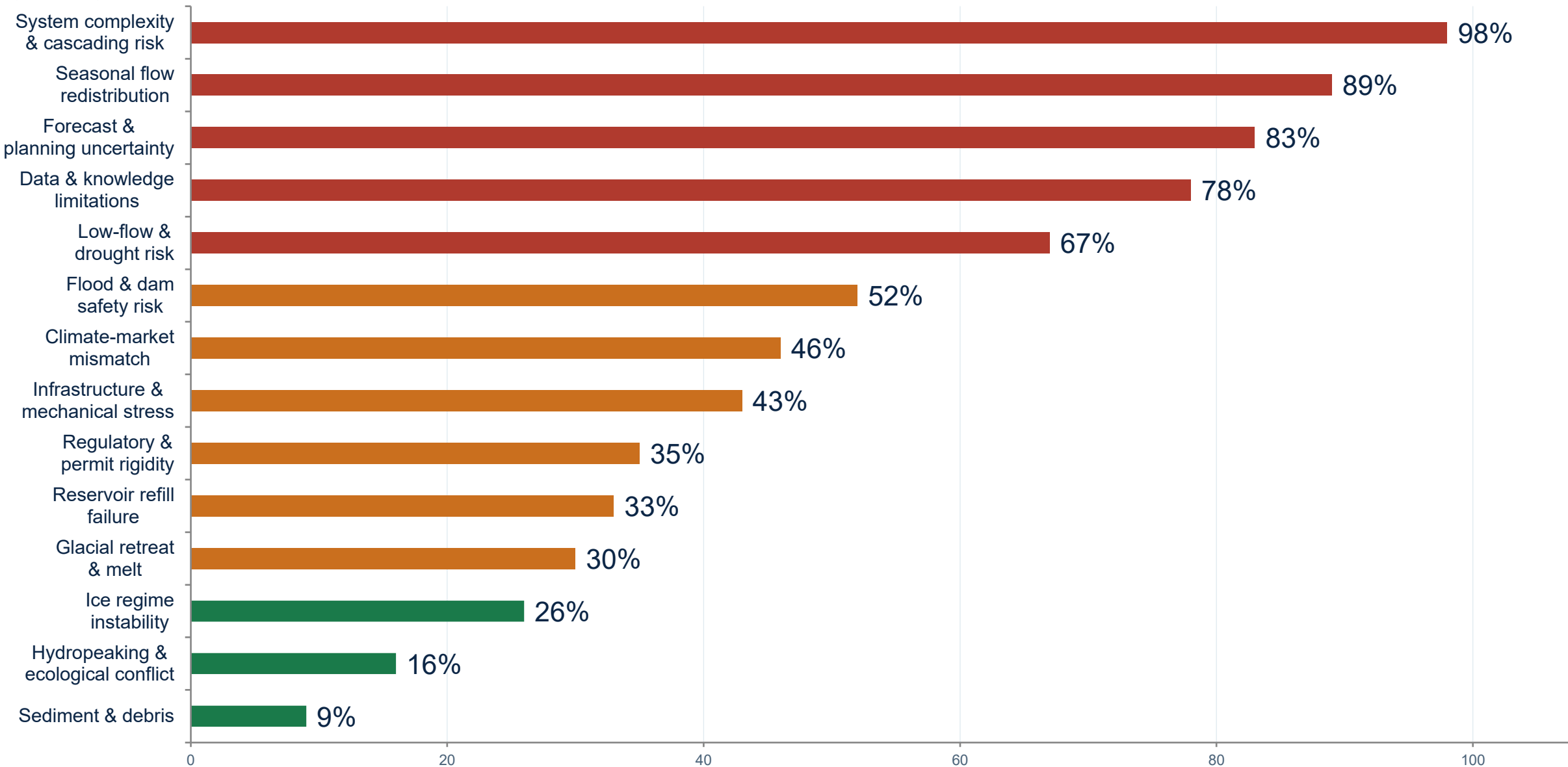
- Tropical, arid, or semi-arid regions
- Groundwater, sedimentation, or ecological focus
- Non-English



Results: Hydropower Operational Challenges



(n = 94)



Key Findings

98%

System complexity
& cascading risk

89%

Seasonal flow
redistribution

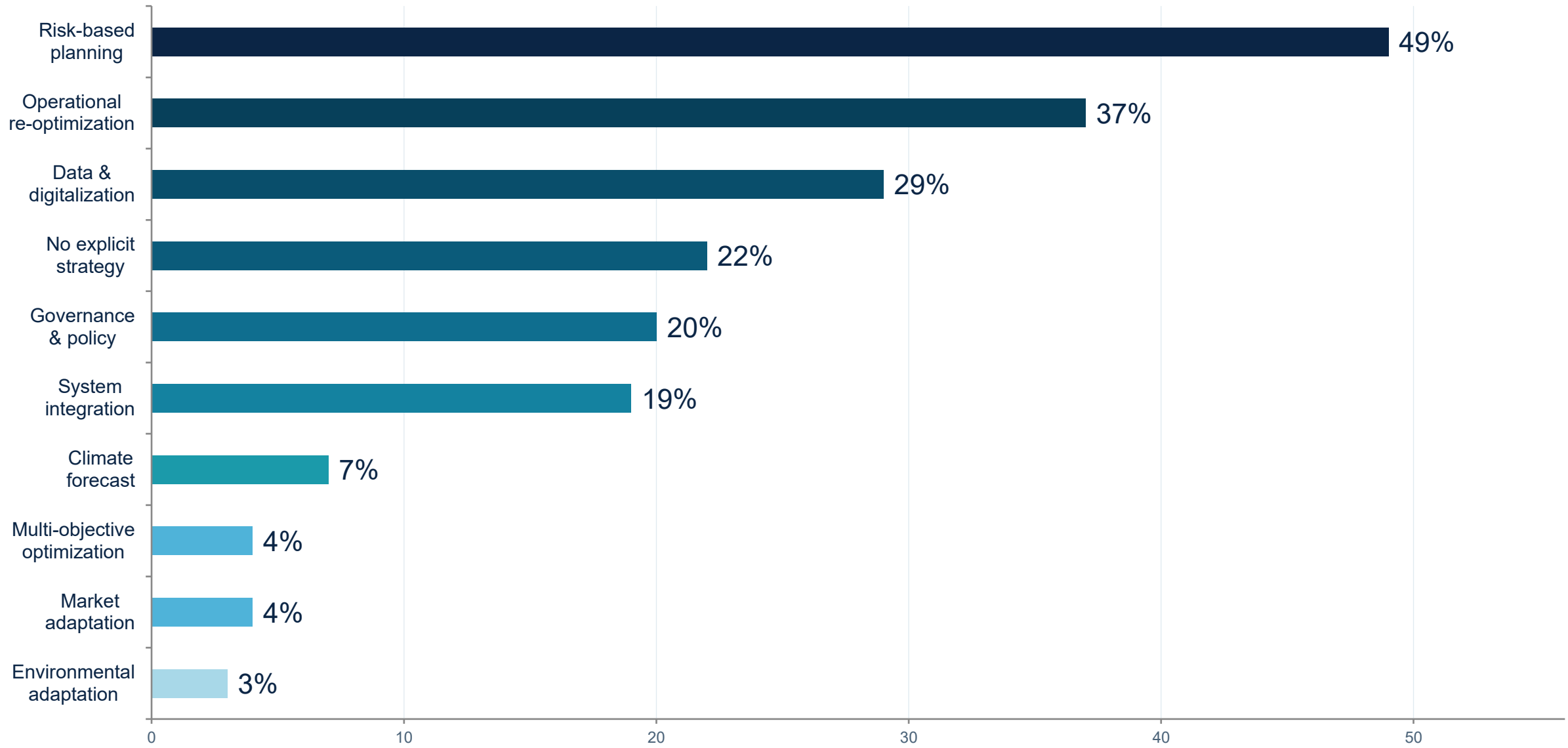
83%

Forecast &
planning uncertainty

- **Cold climate system complexity:** 98% of studies (highest of any challenge), indicating interconnected vulnerabilities across hydropower networks.
- **Hydrological disruption dominates:** Seasonal flow redistribution (89%) and forecast uncertainty (83%) rank as the top hydrological stressors, undermining planning across almost all facilities.
- **Drought and flood pressures co-exist:** Low-flow/drought risk (67%) and flood/dam safety risk (52%) both rank highly, reflecting the dual extremes intensifying under climate change.
- **Data gap undermines adaptation:** 78% of studies cite data and knowledge limitations, meaning the tools needed to respond to challenges are themselves constrained.

Results: Adaptation Strategies Identified

(n = 94)



% of 94 studies

Key Findings

49%

Risk-based planning
(most common strategy)

37%

Operational re-optimization

22%

No explicit adaptation

- **Operational strategies dominate:** 86% of studies address operational or planning adaptation, indicating widespread recognition of climate risk in hydropower management.
- **Digital tools:** 29% of studies include data and digitalization strategies, reflecting a growing role of forecasting tools and decision-support systems.
- **Governance gap remains:** Only 20% address governance and policy, despite institutional barriers being a key challenge in adaptive operations.
- **Environmental considerations:** Environmental adaptation appears in just 3% of studies.

What do we conclude?



Hydrology

Earlier snowmelt & higher winter flows shift runoff seasonality

Summer deficits create energy-water mismatches



Ice Processes

Freeze-thaw instability increases operational risk & uncertainty

Frazil ice causes intake blockages & economic losses



System

Fixed rules & aging assets amplify climate impacts

62% of studies report mixed, not uniformly negative impacts

Hydropower resilience depends as much on internal system adaptation as on responding to external climate change

What Needs to Happen Next?



For whom

Gap

Action needed



Researchers Ice processes poorly represented in models

Develop multi-scenario, high-resolution approaches with explicit ice process modeling



Regulators Licensing frameworks reflect stationary climate

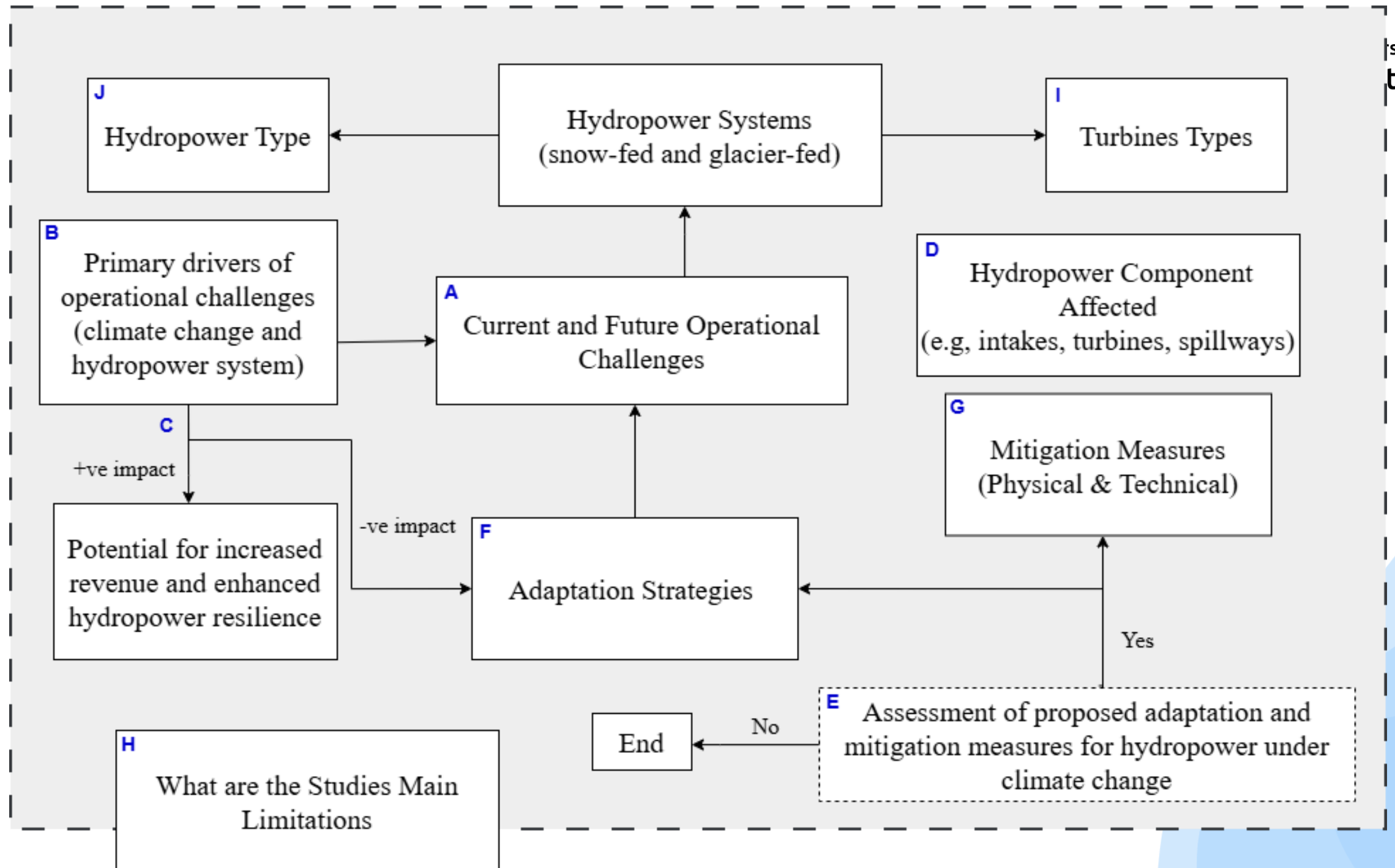
Update permits & environmental flow rules



Operators Winter monitoring data severely lacking

Invest in long-term real-time monitoring of winter conditions

22% of studies proposed no adaptation, proactive climate actions are urgently needed



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