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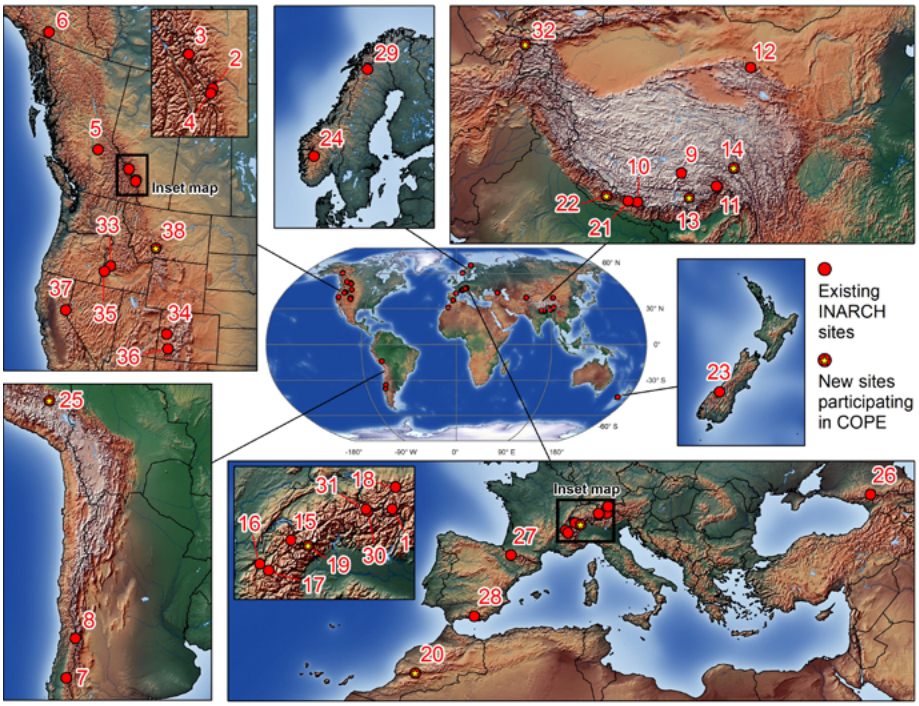
GEWEX is a Core Project of the World Climate Research Programme on Global Energy and Water Exchanges

Updates from the International Network for Alpine Research Catchment Hydrology



Austria: 1. Rofental Open Air Laboratory (OpAL)

Canada: Canadian Rockies Hydrological Observatory: 2. Marmot Creek Research Basin; 3. Peyto Glacier; 4. Fortress Mountain; 5. Quesnel River Research Basin; 6. Wolf Creek Research Basin

Chile: 7. Upper Diguillín River Basin; 8. Upper Maipo River Basin

China: 9. Nam Co Monitoring and Research Station for Multisphere Interactions; 10. Qomolangma Atmospheric and Environmental Observation and Research Station; 11. Southeast Tibet Observation and Research Station for the Alpine Environment; 12. Upper Heihe River Basin; 13. Yala Shampo Cryosphere Hydro-Ecological Station; 14. Changdu Ecological Monitoring Station

France: 15. Arve Catchment; 16. Col de Porte Experimental Site; 17. Col du Lac Blanc Experimental Site

Germany: 18. Zugspitze Basin and Schneefernerhaus Research Station

Italy: 19. Torgnon Ecosystem Station

Morrocco: 20. Rheraya Catchment

Nepal: 21. Langtang Catchment; 22. Hidden Valley

New Zealand: 23. Brewster Glacier

Norway: 24. Finse Alpine Research Centre

Peru: 25. Salcca-Sibinacocha Catchment

Russia: 26. Djankuat Research Basin

Spain: 27. Izas Research Basin; 28. Guadalfeo Monitoring Network

Sweden: 29. Tarfala Research Catchment

Switzerland: 30. Dischma Research Catchment; 31. Weissfluhjoch Snow Study Site

Tajikistan: 32. Kyzylsu Glacier

USA: 33. Dry Creek Experimental Watershed; 34. Grand Mesa Study Site; 35. Reynolds Creek Experimental Watershed; 36. Senator Beck Basin Study Area; 37. Sagehen Creek, Sierra Nevada; 38. Bridger Range

This map of INARCH's instrumented research basins and experimental sites as of 2023 illustrates the network at the center of the cross-cutting activity. These basins and sites serve as testbeds for detailed process studies on mountain hydrology and meteorology, improving our understanding of alpine cold regions hydrology. For more, see Pomeroy et al., page 10.

Inside This Edition

Update on the Activities and Workshops of the International Network for Alpine Research Catchment Hydrology (INARCH) and Its Second Phase as a GEWEX Cross-Cutting Project, 2021–2026

John Pomeroy[1], Ignacio López Moreno[2], James McPhee[3], and Chris DeBeer[1]

[1]Centre for Hydrology and Global Institute for Water Security, University of Saskatchewan, Canada; [2]Institute for Pyrenean Ecology, Spanish National Research Council, Zaragoza, Spain; [3]Department of Civil Engineering, Faculty of Physical and Mathematical Sciences, Universidad de Chile, Santiago, Chile

Overview of INARCH

The International Network for Alpine Research Catchment Hydrology, INARCH (*https://inarch.usask.ca*), is a cross-cutting project of the GEWEX Hydroclimatology Panel (GHP) to better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change, and find consistent measurement strategies. At its core is a network of highly instrumented mountain observatories and experimental research sites, which are testbeds for detailed process studies on mountain hydrology and meteorology, developing and evaluating numerical simulation models, validating remotely sensed data, and observing, understanding, and predicting environmental change. INARCH began in late 2014 with 14 instrumented catchments; there are now 38 research catchments and sites in 18 countries and six continents, with more continuing to join the network (Fig. 1, see cover). By the end of 2022 the network has grown to 57 formal researcher participants from government and academia; however, there have been nearly one hundred other researchers, graduate students, and post-doctoral fellows involved in field research activities, modelling, remote sensing, and participating in our workshops. The network is open to scientists involved in field-based mountain hydrometeorological research or snow, glaciers and water modelling and remote sensing research in mountain headwaters.

INARCH provides an active mechanism for coordinating, sharing, and enhancing cold regions mountain hydrological science. It directly addresses many of the GEWEX science questions and provides a tool for collaboration with other GEWEX Panels and World Climate Research Programme (WCRP) activities. It further contributes to many other high-level international organizations, including the World Meteorological Organization (WMO), the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Intergovernmental Hydrological Programme (IHP), the UN Water Decade, Future Earth, and the United Nations Framework Convention on Climate Change (UNFCCC). INARCH helped organize and co-hosted the WMO High Mountain Summit in 2019 in Geneva, Switzerland (*https://highmountainsummit.wmo.int/en*). This led to a Call for Action entitled "Avoiding the Impending Crisis in Mountain Weather, Climate, Snow, Ice and Water: Pathways to a Sustainable Global Future." Participants agreed on the need for an Integrated High Mountain Observation and Prediction Initiative to improve observations, forecasts, and data exchange in mountain ranges and headwaters around the world. At the 2019 Future Earth meeting in Bengaluru, India, INARCH, through its Future Earth–Water Futures working group, hosted a session and discussions on Global Mountain Water Security and contributed to discussions for a Mountain Water Solutions Laboratory for the Indian Himalaya. More recently at the 27th UNFCC Conference of the Parties (COP) in November 2022 in Egypt, a non-binding resolution on Implementation of the Global Climate Observing System was adopted that specifically addresses filling gaps in observations in mountain and polar regions and of the cryosphere, and follows from the case INARCH has made at several COPs and other forums, including the WMO High Mountain Summit. At the UN General Assembly, INARCH informed the development of the International Year of Glaciers' Preservation-2025, which was adopted by the UN General Assembly in December 2022. The International Year of Glaciers' Preservation will raise awareness of the loss of snow and ice resources and associated risks, give impetus at the global level to act, mobilize financial resources, and improve international cooperation and data sharing. UNESCO-IHP has approved a UNESCO Chair in Mountain Water Sustainability amongst several INARCH members for 2023–2027 that will provide a long-term focal point of research and outreach on mountain waters and how to reach the UN sustainable development goals for high mountain catchments under the stress of development and climate change.

Phase I Advances

A first phase of the network (2015–2020) was completed, and during this time INARCH grew and made significant advances. These include establishment of a suite of well-instrumented research catchments, high-resolution forcing meteorological datasets, and advanced snowdrift-permitting and glacier-resolving hydrological models. These have been used to improve our scientific understanding and evaluate observed changes, data, and models around the world. The models continue to be used to estimate the sensitivity of the high mountain cryosphere and hydrology to climate change. Data sets from around the world were compiled and made available in the journal *Earth System Science Data* in a special issue, "Hydrometeorological data from mountain and alpine research catchments" (*https://essd.copernicus.org/articles/special_issue871.html*). More data sets continue to be added to this special issue.

The global COVID-19 pandemic resulted in a hiatus of network activities, but individual research groups mostly carried on with their work and field-based activities, persevering and developing innovative ways to continue. INARCH held an online workshop in October 2021 to review the status and activities at INARCH's mountain research catchments, advances in modelling, and the use of modelling and observations to find solutions to mountain water sustainability under climate change. Discussions helped refine specific science questions to address as we move into a time when integrated observations, predictions, and services have been adopted for mountains by

WMO and the UNFCC and as our models can better reflect and engage with the research basins to provide answers for regional river basins. During this workshop INARCH developed a collective vision and plans for a second phase of the network (2021–2026), building on achievements during the first phase.

Phase II Science Plans and a Common Observation Period Experiment (COPE)

For Phase II of INARCH, the objectives are to better:

- Measure and understand high mountain atmospheric, hydrological, cryospheric, biological and human-water interaction processes,
- Improve their prediction as coupled systems,
- Diagnose their sensitivities to climate change and propose how they may be managed to promote water sustainability under global change.

The following Science Questions have been proposed to help focus our activities:

1. How different are the observation and measurement approaches amongst INARCH basins and do we expect distinctive differences in our understanding of basin response and hydrological predictability because of the sampling schemes, and data quality and quantity?
2. How do the predictability, uncertainty, and sensitivity of energy and water exchanges vary with changing atmospheric thermodynamics, ecosystem structure, and water management in various high mountain regions of the Earth?
3. What improvements to high mountain energy and water exchange predictability are possible through improved physics in, coupling of, and downscaling of models in complex terrain, and improved and expanded approaches to data collection and assimilation?
4. To what extent do existing model routines have global validity, are transferable, and meaningful in different mountain environments for providing service to society?
5. Can mountain systems be predicted and managed to find solutions to help achieve water sustainability in river basins under climate change?

We aim to eventually contribute to answering: How have mountain atmospheric-cryospheric-hydrological-ecosystem-human systems co-evolved to their current states and how will they respond to climate change over the next century?

As a starting point for Phase II we have begun to provide common and archived observations for basin diagnosis and modelling through a Common Observation Period Experiment (COPE). The focus is on obtaining high-quality measurements to the extent possible, defining this as starting in 2022 to coincide with the start of the snow season in the southern hemisphere, and carrying on until 2024. During this COPE we will ensure all sensors are working, enhance observations at our mountain research basins, fly supplementary drone acquisitions, run high resolution models, and work together for comparison of processes, data sharing, and model testing in challenging environments. By getting these instruments into place and the campaign underway, this would be a start for longer-term observations of higher quality that can be comparable. Tremendous value can accrue from activities such as this and the approach has been used in the past with various GEWEX initiatives. We plan to take a variety of different models and apply them in different basins to see how they work, make sure we have the proper forcing information, try different forcing and apply it at different scales, see what corrections are needed for those forcings, calculate snow and ice dynamics and hydrological dynamics at the surface, and look at these diagnostically with available measurements from ice and snow changes, to soil moisture, streamflow, and turbulent fluxes, as available. This has not been done globally in alpine regions and could be potentially very powerful.

INARCH Workshop, Baños de Panticosa, Spain, October 18–20, 2022

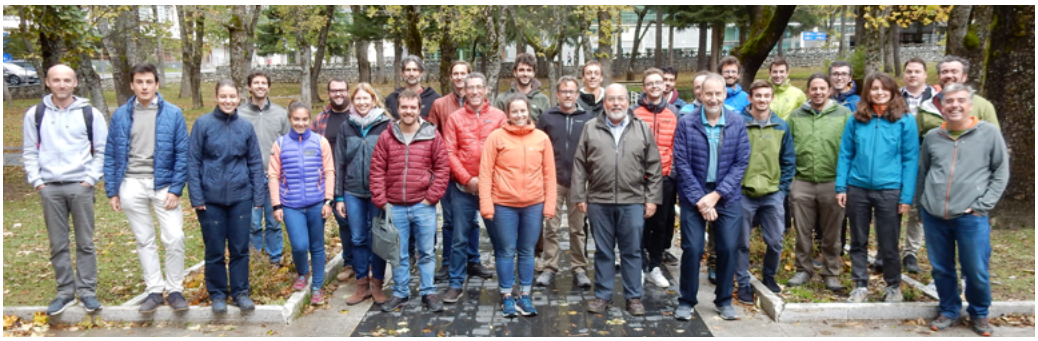
INARCH held its first in-person workshop since before the start of the COVID-19 pandemic, meeting in the Spanish Pyrenees in October. The workshop brought together about 30 scientists from around the world to discuss some of the latest advancements in alpine hydrology, including observations and measurement techniques, prediction, comparability and validity of models, data management, and the ongoing COPE across the network of research basins. All participants presented research updates and new activities, and the presentations can be viewed on the INARCH website.

Summary of Observatories and Measurement Techniques

- Advances in using isotopes to supplement hydrometeorological observations and diagnostic modelling, including model calibration and structural design decisions from isotopic data
- Advances in satellite observations of snow depth, but limited to non-steep and non-forested sites. Density is still a challenge.
- Advances in field techniques to include basin-scale gravimetry, unmanned aerial vehicle LiDAR & IR, tower and terrestrial LiDAR
- Expansion of INARCH instrumented basins to all inhabited continents and new mountain ranges (Pamirs, High Atlas)
- Advances in reanalysis data in the Andes, North America (historical)
- INARCH basins are starting or ready for the COPE observing period

Summary of Predictions, Comparisons, Validity

- Advances in deployment of ecohydrological models to explore co-evolution of snow and vegetation and models addressing vegetation change (shrubification, forest change), revised interception, greening, drought, and management
- Improvements in atmospheric model forcing of precipitation phase and wind fields, high resolution nested models for dynamical downscaling (greater extent)



Participants of the Sixth INARCH Workshop, Baños de Panticosa, Spain, October 20, 2022

- Downscaling of atmospheric models to complex terrain snow models at snow-drift permitting scales (<100 m) applied at continental scales–intercomparison and evaluation against satellite and surface observations are needed to assess model outputs. Standardized comparisons to areal metrics need to be developed
- Improvements in data assimilation techniques for prediction
- Examination of parameter uncertainty, transferability, and machine learning techniques in hydro-cryosphere modelling. Noted that calibration from streamflow of physically based parameters in hydro-cryospheric modelling should focus on routing and subsurface rather than observable surface parameters (equifinality, self-deception)
- Comparisons of impacts of climate change on cryosphere and hydrology in different glaciated and snow dominated basins show different sensitivities to climate change.
- Identification of the distinctive research needs for marginal snowpacks–e.g., ground heat flux and thermal interactions between snowpacks and warm soils

COPE and Data Management

- COPE represents a unique opportunity to implement, focus, and accelerate model comparison and validation, observation comparison, and collaboration to compare process operation and model improvements on INARCH testbed basins.
- GWFNet data catalogue (*https://gwfnet.net/cope*) can help INARCH researchers find each other, papers, models, instrumented sites, data records, and model outcomes.
- Need for INARCH researchers to provide information to the data manager, Stephen O'Hearn, for cataloguing
- Keeping long-term research basins going remains a continual challenge.
- Specific COPE research projects need to be developed–same model for elasticity to change applied at different basins, observed response to extremes and climate differences, comparative eco-hydrology, new model testing?
- Plan for several papers from COPE analyses/comparisons and an overarching COPE data paper

INARCH Statement 2022

We have:

- begun Phase II, started COPE;
- expanded investigators, observations, basins, mountain ranges, and models;
- implemented a data cataloguing system, snowdrift-resolving models continentally;
- explored new measurement techniques, data assimilation, parameter uncertainty, and machine learning;
- started linking to ecosystems and downstream water resources; and
- informed a proposed UN Year of Glacier Preservation and contributed to WMO, UNESCO, WCRP, Future Earth, and the UN Water Decade.

We need to:

- develop detailed science investigations in COPE and ensure that it is used by other groups (WMO, intercomparison projects);
- apply atmospheric/hydrological/other models to INARCH basins for the COPE period; and
- co-develop plans to and share experiences on increasing mountain community/regional science and decision-making capacity.

Next Steps and Future Workshops

INARCH has begun the COPE initiative, which will have tremendous scientific value and contributes directly to GEWEX, WMO, UNESCO, Future Earth, UNFCC, and other global programs. This is expected to produce a valuable set of observations, model simulations and intercomparisons, new process understanding and insights, and better prediction of the changing mountain water cycle in headwater regions around the world. The team is energetic, enthusiastic, and fully engaged. INARCH welcomes new participants who wish to contribute to its goals and objectives, and to participate in the COPE initiative.

At this time INARCH is developing plans to hold the next workshop some time during October, 2023 in Idaho, USA. This would include a field trip and tour of some local experimental snow research sites and exciting presentations and discussions amongst the group over a couple of days. We are looking forward to the opportunity to meet together again in-person. INARCH will also plan for one or a series of online meetings to review and coordinate COPE activities in the coming months. Feel free to contact us or check our website for updates.