

Template for Project Reports for the GEWEX GHP Meeting

Full Panel, Project or Working Group Name (Acronym): International Network for Alpine Research Catchment Hydrology (INARCH)

Reporting Period: November 2018 - October 2019

Starting date: January 2015

End date: January 2020

URL: www.usask.ca/inarch

Chair(s) and term dates: John Pomeroy, University of Saskatchewan, Canada (2015-); co-chair, Matthias Bernhardt, University of Natural Resources and Life Sciences, Vienna (2017-)

1) Regional Hydroclimate Project (RHP) or Cross-Cut (CC) activities over the last year

- Section should not be longer than 1 page
- It should cover the following points:
 - Science highlights
 - Science issues
 - New projects/activities put in place last year
 - Workshops and meetings held
- Please highlight issues which GHP needs to consider or for which advice is sought.

The International Network for Alpine Research Catchment Hydrology (INARCH) is a crosscutting project of the GEWEX Hydroclimatology Panel (GHP) and its objectives are to better understand alpine cold regions hydrological processes, improve their prediction, diagnose their sensitivities to global change and find consistent measurement strategies. INARCH is formulated around addressing five core questions: (1) How do varying mountain measurement standards affect scientific findings around the world? (2) What control does changing atmospheric dynamics have on the predictability, uncertainty and sensitivity of alpine catchment energy and water exchanges? (3) What improvements to alpine energy and water exchange predictability are possible through improved physics, downscaling, data collection and assimilation in models? (4) Do existing mountain model routines have global validity? and (5) How do transient changes in perennial snowpacks, glaciers, ground frost, soil stability and vegetation impact alpine water and energy models?

INARCH has nearly completed its initial 5-year term and has made exceptional progress towards addressing these questions and achieving its goals. Next phases of research coordination and other activities will be determined at the upcoming annual workshop in March 2020 (see section 2 below). Moving forward INARCH will be developing syntheses papers and other products as outputs of the network and contributing to initiatives beyond GEWEX, such as Future Earth, the World Meteorological Organization, the Intergovernmental Panel on Climate Change, UNESCO's International Hydrological Programme, and the UN at large through its International Water Action Decade: Water for Sustainable Development, 2018-2028.

Science issues and highlights

Dr. John Pomeroy (Canada), and Dr. Danny Marks (USA) served as guest editors for an INARCH special issue of [Earth System Science Data](https://www.earth-syst-sci-data.net/), covering **Hydrometeorological data from mountain and alpine research catchments**. The aims of the issue and links to published and in-discussion papers are found at https://www.earth-syst-sci-data.net/special_issue871.html. The issue closed on 30 September 2018, and there have been 21 papers contributed from around the world.

INARCH has been focused on the development of a downscaling methodology toolbox. The Intermediate Complexity Atmospheric Research (ICAR) model has been developed at the US National Center for Atmospheric Research (NCAR), led by Dr. Ethan Gutmann (USA), and its source code is available here: <https://github.com/NCAR/icar>. The ICAR model is a simplified atmospheric model designed primarily for climate downscaling, atmospheric sensitivity tests, and hopefully educational uses. ICAR is a quasi-dynamical downscaling approach that uses simplified wind dynamics to perform high-resolution meteorological simulations 100 to 1000 times faster than a traditional atmospheric model and can therefore be used to better characterize uncertainty across numerical weather prediction models and climate models, and in dynamical downscaling (<https://ral.ucar.edu/projects/icar>). In addition, NCAR has been developing a statistical downscaling method called Generalized Analog Regression Downscaling (GARD), and its source code and description are available here: <https://github.com/NCAR/gard>.

New projects/activities and workshops and meetings

INARCH held its 4th annual workshop on 24-26 October, 2018 in Santiago and Portillo, Chile, organized and hosted by Dr. James McPhee (Chile). 24 scientists from Chile, Argentina, the USA, Canada, Spain, and France participated in the workshop. Participants focused on reviewing activities, progress, and plans towards INARCH's overall objectives and research questions relating to alpine hydrology. A number of topics were reviewed and discussed, including field observations, catchment data, and emerging methods; snow and glacier hydrology, and climate change; model simulation and data assimilation, big data, and remote sensing; and linkages with various organizations, such as Future Earth's Sustainable Water Futures Programme, the World Meteorological Organization, IHP, the Canadian-led Global Water Futures (GWF) Programme, the US-proposed western USA regional hydroclimate project (RHP), and the recently-initiated ANDEX, an RHP for the Andes. Full details, including a summary report in GEWEX News and all presentations, can be found here: http://www.usask.ca/inarch/wkshp4_report.php.

As a contribution to the Future Earth Sustainable Water Futures Programme (SWFP), INARCH has formed a working group on *Climate Impacts on Global Mountain Water Security*, http://water-future.org/working_groups/climate-impacts-on-global-mountain-water-security/. The activities and objectives, and membership, of this working group parallel the broader goals of INARCH, thus providing a mechanism for expanding the influence and exposure of this work through the SWFP. The Grand Challenge that this working group addresses is: how to develop a global scientific approach to better understand, predict and manage alpine water resources in the face of dramatically increasing risks?

A small group of participants attended the Future Earth Water Future Conference “**Towards a Sustainable Water Future**” in Bengaluru, India in September 2019 <https://www.waterfutureconference.org/>. This included Dr. John Pomeroy (Canada), Robert Sandford (Canada), Dr. Ignacio López Moreno (Spain), Dhiraj Pradhananga (Nepal), Dr. Chris DeBeer (Canada), Dr. Corinne Schuster-Wallace (Canada), and Dr. Lawrence Martz (Canada). We provided a session on “Climate Impacts on Global Mountain Water Security”, several talks on knowledge mobilization and sustainable development goals and water and a plenary talk on “Losing our Cool: Water Predictions for the Warming Cold Regions”. Our session was a part of a two-part joint session, also including “Water Solutions for the 21st century in the Indian Himalayan Region (IHR)”, chaired by the Integrated Mountain Initiative (IMI). The IMI, formed in 2010, is a coalition of high-level parliamentarians and representatives from 10 Indian Himalayan states that are wanting to improve their water security through science and collaboration. Following this joint session and as

an outcome of further discussions at the meeting, we are working with scientists from the Indian Institute of Science on modelling Indian river basins to help address the acute water crisis that is evolving in the Indian sub-continent. We will support and guide the IMI as they develop a “**Himalayan Water Futures**” in cooperation with Bhutan and Nepal, modelling it using our experience and advice. Further information on this joint session and on the IMI is here: https://www.waterfutureconference.org/water_solutions

2) Planed RHP or CC activities for next year

- Section should not be longer than 0.5 page
- The following items need to be covered:
 - planed new scientific activities
 - planed workshops or meetings
- Please highlight foreseen risks for the panel/project activities next year and which mitigation strategies are in place.

INARCH is contributing to the **WMO High Mountain Summit** in Geneva, October 2019 with Professor Pomeroy as co-chair of the Summit. The Summit is being co-organized with the World Bank Group (WBG) - Global Facility for Disaster Reduction and Recovery (GFDRR), the Food and Agriculture Organization of the United Nations (FAO), the Mountain Partnership Secretariat, the United Nations Educational, Scientific and Cultural Organization (UNESCO) - International Hydrological Programme (IHP), the Mountain Research Initiative (MRI), Global Water Futures programme (GWF), the International Association of Cryosphere Sciences (IACS), the International Association of Hydrological Sciences (IAHS), the Third Pole Environment program (TPE) of the Chinese Academy of Sciences (CAS), and with the strong support of Switzerland, Austria, Canada, France, Spain, Italy, and other Members. The High Mountain Summit seeks to foster international and regional inter-agency collaboration, across sectors, scales, and actors, by leveraging existing and planned initiatives and projects, for providing integrated climate service delivery functions, along the value chain, addressing the need for reliable information on water and hazard management, precipitated by accelerated changes in high mountain cryosphere and ecosystems, with the objective to inform, and therefore, promote Sustainable Mountain Development.

The Summit will follow shortly after the release of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), which includes a dedicated chapter on high mountain areas, at the 51st Session of the IPCC on the approval of the Summary for Policymakers (accepting the underlying Report), in Monaco, 20-23 September 2019. The Summit will be followed by the Santiago Climate Change Conference, featuring the 25th session of the Conference of the Parties (COP 25) to the UNFCCC and meetings of the UNFCCC subsidiary bodies, from 2-13 December 2019.

The Summit will take into account the needs of WMO Members regarding the monitoring and reporting on targets within the Sendai Framework, Paris Agreement, the 2030 Agenda, and the Sustainable Development Goals. In the broader context, it will contribute to the Framework for Action for Implementing the 2030 Agenda for Mountains (2017) approved by Mountain Partnership members and the International Decade for Action: Water for Sustainable Development (2018-2028).

The Summit will seek to:

- Leverage the influence of relevant stakeholders, rights-holders, public and private sector leaders, and funding agencies for an integrated approach across policy frameworks, for the necessary level of attention and resources for priority action and investments addressing impacts of climate change in high mountains.
- Identify practical steps for strengthening the capacity for the provision of hydrological, meteorological, climate and prediction services, for optimizing and enhancing cryosphere and high mountain observations and access to data, and for advancing the scientific research to bridge the information gaps.
- Identify roadmaps for climate risk and early warning systems for mountain-specific threats, including a focus on regional transboundary scales, e.g., extreme events, glacial lake outburst floods (GLOFs), avalanches, permafrost thawing related risks, Foehn type wind (storms), air pollution, and others.
- Promote closer and interactive links between science and policy at all levels of governance, ensuring science-based input to policy development and long-term adaptation strategies.

For more information, please visit the Summit's website at:

<http://highmountainsummit.wmo.int/>

The 5th annual INARCH workshop is tentatively planned for March 31 - April 1, 2020 in Zaragoza, Spain and at the Hospital de Benasque (<https://www.llanosdelhospital.com/>) in the Spanish Pyrenees. It is being organized and will be hosted by Dr. Ignacio López Moreno, Pyrenean Institute of Ecology, Spanish Research Council, Zaragoza, Spain. The workshop will bring together this network to follow up on activities, progress, and plans towards its overall objective and its research questions relating to alpine hydrology. This will follow on from the WMO High Mountain Summit with a major theme focused on Integrated Mountain Observing and Prediction Systems, merging observations and prediction into coherent systems. Other topics will include forest and vegetation hydrological impacts, remote sensing advances and opportunities, next-generation snow and glacier modelling, and high resolution atmospheric modelling. The workshop will provide an opportunity to build and extend linkages with other international mountain climate and water science initiatives and to plan for the next phases and research priorities post-INARCH.

3) Contributions to the GEWEX Science Questions

For each of the GEWEX grand science questions provide in bullet points the activities carried out or planned in the near future. Please highlight important results for the GEWEX Science questions and provide references to the relevant papers and copies of important figures.

- **GSQ1: Observations and Predictions of Precipitation**
 - INARCH has published invaluable mountain catchment hydrometeorological datasets from around the world through a special issue of Earth System Science Data with 21 articles. It has expanded to 28 catchments with contributions from 45 scientists based around the world.
 - The advent of large area, high resolution atmospheric models at 4 km or less, now permits more confident meteorological drivers for advanced snow and glacier hydrology models in complex mountain terrain. The performance of these high resolution atmospheric models needs to be assessed at point and areal scales and spatial datasets for such assessments and for bias-correction need to be assembled. Global application of these products to mountains is needed. High resolution snow and ice hydrology models, including hillslope hydrology processes need development to take advantage of the more accurate alpine precipitation

- products that will result.
- Downscaling toolbox - see section 1
- GSQ2: Global Water Resource Systems
- GSQ3: Changes in Extremes
- GSQ4: Water and energy cycles and processes
 - INARCH has identified the importance of the changing High Mountain Water Cycle to global initiatives such as GEWEX, ANDEX, GWF, TPE and is contributing to a WMO High Mountain Summit and initiative. INARCH supports the idea of an International Year of Snow and Ice and also a year devoted to Mountain Prediction.
 - There is tremendous potential to assimilate high resolution remote sensing products such as snow depth from airborne LiDAR, albedo, grain size and impurities from hyperspectral sensors and visible snowcovered area from multiple platforms into advanced snow hydrology prediction models and some examples of this are occurring. Efforts are needed to demonstrate how more mountain ranges around the world can be measured by these products and how the outputs can be used together to improve snow prediction models.
 - INARCH has quantified the sensitivity of mountain snow hydrology regimes around the world using cold regions hydrological models of virtual alpine basins, driven by reanalysis data, and has shown that decoupling of the snow and hydrological regime with warming is most severe for temperate winter climates with winter precipitation maxima as typified by Mediterranean alpine environments. The results show the controls of both temperature and vapour pressure in determining the sensitivity of mountain snow hydrology to warming. This approach should be extended to examine the sensitivity of mountain glacier hydrology to global warming.
 - INARCH continues to examine the performance of alpine snow models in simple alpine environments by comparison of model outputs to diagnostic measurements in INARCH catchments. The next step should be to examine model performance in extreme alpine environments that are more typical of alpine landscapes.

See: <http://www.gewex.org/about/science/gewex-science-questions/>

4) Activities contributing to the WCRP Grand Challenges as identified by the JSC

As above only bullet points, references and figures are needed:

- Clouds, circulation and climate sensitivity
- Melting ice and global consequences
 - INARCH has identified dramatic snowpack decline and glacial retreat in the Andes and Patagonia as issues of global concern with some of the highest rates of glacial ablation in the world, due to both sublimation and melt. Global warming has included mountain mega-droughts in South America, causing hydrological shortages downstream. Complications in glacial modelling due to high sublimation rates, debris cover and the occurrence of penitent surfaces require physically based energy balance techniques for glacier hydrology in the Andes. Mining impacts on some of these glaciers are further accelerating ablation through direct disturbance and dust. An increasing number of glaciers are now debris-covered and so techniques to calculate icemelt under debris are needed in hydrological models. International and national mountain hydrology research programmes

should prioritize research in the Andes to address these problems.

- Weather and climate extremes
 - INARCH is focused on conducting cold regions hydrological model sensitivity testing to atmospheric change in various alpine environments and including sensitivity to including the effects of transient changes from glacier mass balance, groundwater changes and vegetation changes. We also aim to demonstrate improvements to model predictability that can be realised from data assimilation, downscaling and model structural improvements.
- Regional Sea-Level Change and coastal impacts
- Water for the food baskets of the world
- Near-term Climate Prediction
- Carbon feedbacks in the climate system

See: <http://www.wcrp-climate.org/grand-challenges>

5) Cooperation with other GHP and WCRP projects (CLIVAR, CliC, SPARC), outside bodies (e.g. iLEAPS) and links to applications

- List cooperation and collaborations with other international projects. Please indicate if they are formal (endorsement, panel membership, ...) or informal. Please highlight if GHP's help is needed to establish or strengthen some of these cooperation.
 - Collaboration with UNESCO IHP and information collaboration with SPICE and Global Cryosphere Watch (CliC).
 - Contribution to developing the WMO High Mountain Summit
 - The Global Water Futures (GWF; www.globalwaterfutures.ca) Program is an expanded follow on initiative from CCRN. INARCH strongly links with the mountain research components of GWF. Distinguished Professor John Pomeroy leads and directs both INARCH and GWF.

6) List of key publications

- Publications related to the RHP or CC activities in the past year.

Burger, Flavia, Alvaro Ayala, David Farias, Thomas E. Shaw, Shelley MacDonell, Ben Brock, James McPhee, and Francesca Pellicciotti. "Interannual variability in glacier contribution to runoff from a high-elevation Andean catchment: understanding the role of debris cover in glacier hydrology." *Hydrological processes* 33, no. 2 (2019): 214-229.

Ly, Z., & Pomeroy, J. W. (2019). Detecting intercepted snow on mountain needleleaf forest canopies using satellite remote sensing. *Remote Sensing of Environment*, 231, 111222.

Stewart, R. E., Szeto, K. K., Bonsal, B. R., Hanesiak, J. M., Kochtubajda, B., Li, Y., Thériault, J. M., DeBeer, C. M., Tam, B. Y., Li, Z., Liu, Z., Bruneau, J. A., Duplessis, P., Marinier, S., and Matte, D.: Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada - Part 1: Projected climate and meteorology, *Hydrol. Earth Syst. Sci.*, 23, 3437-3455, <https://doi.org/10.5194/hess-23-3437-2019>, 2019.