NVE

Hydrometeorology - Research challenges and action plan

Final report from the HYDMET project

Kolbjørn Engeland (Ed.)

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REPORT

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Redaktør: Kolbjørn Engeland

Forfattere: Kolbjørn Engeland, Stein Beldring, Oddbjørn Bruland, Nils-Otto Kitterød, Jørn Kristiansen, Elin Langsholt, William Lahoz, Richard Moore, Thomas Skaugen, Eivind Støylen, Asgeir Sorteberg, Frode Stordal, Lena M. Tallaksen, Chong-Yu Xu

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Sammendrag: The main objective of HYDMET is to develop a national research team (SAK) to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology. The main outcome of the HYDMET project is this report that identifies important research topics and actions to be addressed by a SAK within hydrometeorology in Norway.

Emneord: Hydrometeorology, Hydrology, Meteorology, SAK, ISP Geosciences

Norges vassdrags- og energidirektorat
Middelthunsgate 29
Postboks 5091 Majorstua
0301 OSLO

Telefon: 22 95 95 95
Telefaks: 22 95 90 00
Internett: www.nve.no

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Preface

Hydrometeorology is an area of significant scientific and societal importance, including risk reduction related to floods, droughts and landslides in the present as well as a future climate. Operational services, research and education in hydrometeorology are hosted by several institutions in Norway. An evaluation of research within geosciences was undertaken by an international committee in 2011 and a national report was prepared in 2014 for the Research Council of Norway (RCN). The need to develop a common research language was identified, which can only be achieved via day-to-day joint research and development by relevant institutions both operational (MET Norway and NVE) and university (UiO, UiB and NMBU). The major research topics identified were hydrometeorological forecasting aimed at relieving risk of floods, landslides and avalanches and supporting optimized energy and water resources management under climate change. The HYDMET project was funded in a subsequent call to begin to address the recommendations.

The main objective of HYDMET is to develop a national research team (SAK) to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology.

The main outcome of the HYDMET project is a final report/action plan that identifies important research topics and actions to be addressed by a SAK within hydrometeorology in Norway. The conclusions and recommendations build on conclusions from a national seminar held 9-10 December 2015 in Lillehammer summarized in Engeland et al. (2017), and a workshop 14 December 2016 in Oslo.

Oslo, February 2017

Morten Johnsrud
Director

Stein Beldring
Head of Section

Summary

The HYDMET project was established to address the Research Council of Norway (RCN) Geosciences evaluation (Wilson, et al., 2011; Hov et. al., 2014) funded by the RCN under the program ISP geosciences. The primary objective of HYDMET is to develop a national research team (SAK) to identify the important research topics, methods, and experimental and operational observations for applications in hydrometeorological modelling for improved forecasting and projections of changes in climate and hydrology. The secondary objectives of HYDMET are to:

1) Identify both the potential for improvement of, and research topics for, hydrometeorological forecasting for reducing flood risk and the optimization of renewable energy production.
2) Identify both the potential for improvement of, and research topics for, the optimization of water resource management under climate change conditions.
3) Improve the synergy between the strategic plans of institutions and research groups.
4) Identify topics to be given greater emphasis in education.

Based on a national seminar held 9-10 December 2015 in Lillehammer (summarized in Engeland et al, 2017) and a smaller workshop on 14 December 2016 in Oslo, this report addresses the above objectives. A brief summary is provided below.

Identified potential for the improvement of, and research topics for, hydrometeorological forecasting and climate change projection (sub-objectives 1 and 2):

- ***Hydrometeorological test beds***: New approaches to the design of multi-scale testbeds with observations of all components of the energy and water fluxes between the land surface and atmosphere over different land surface types and climatic conditions are needed. To be successful, test beds require collaboration at a national level and long term funding for instrumentation and maintenance.
- ***Coupling of models:*** Two-way coupling of hydrological and meteorological models and improved model parameterizations are needed. Important processes include (i) precipitation and its spatial and temporal variability, (ii) evapotranspiration and the energy balance in cold environments, (iii) vegetation dynamics and interaction within the hydrometeorological system, (v) soil moisture and runoff, and (v) cryospheric processes
- ***Assimilation:*** Improved techniques need to be developed to make full use of the available observations in hydrometeorological modeling, including snow data, soil moisture, river discharge, lake levels, and land-use/vegetation.
- ***Impact based forecasting***: Forecasts and warnings need to address sensible impacts to increase their usefulness for end users. This requires both post-processing/downscaling/bias-correction of forecast and climate change projections, and a better understanding of the links between climate indices and impacts. There remains a need for targeted analyses and an open dialogue between the scientific community and end users.
- ***Computing infrastructure:*** An improved computing infrastructure for data storage and the sharing of observations and model results and code is needed. This requires an administrative system for managing codes, common coding

standards, quality control, documentation (metadata), and an inter-institution willingness to collaborate and share data, models and knowledge.

Improved synergy between the strategic plans for institutions and research groups (sub objective 3) can be achieved by:

- Establishing a national network for hydrometeorology as a part of NHR
- Encouraging multilateral meetings between NVE, MET, UiO, NTNU and NMBU leaders.
- Arranging regular (annual / biannual) network meetings for discussing co-supervision of students, coordination of project seminars and workshops and project applications.
- At regular meetings between leaders at NVE, MET, UiO, NTNU and NMBU discuss co-supervision of students, coordination of project seminars and workshops and project applications.
- Arranging and participating in conferences, seminars and workshops for students and researchers.
- Establishing a meta-database for experimental data and modelling tools.
- Collaborating in research projects, research infrastructure and a center of excellence application.

Topics to be given greater emphasis in education (sub-objective 4)

- National research school: Collaboration within the current Research School on Changing Climates in the Coupled Earth System (CHESS; see http://www.uib.no/en/rs/chess)
- Co-supervision for masters and PhD projects..
- Use of operational models in teaching based on common model tutorial courses and preset case studies .

The HYDMET project has created the web-site www.hydmet.no that will be used as a nexus for establishing and fostering a hydrometeorological network.

1 Introduction

The HYDMET project was established to address the Research Council of Norway(RCN) Geosciences evaluation (Wilson, et al., 2011; Hov et. al., 2014) funded by the RCN under the program ISP geosciences. The primary objective of HYDMET is to develop a national research team (SAK) with a task to identify the need for important research, methods, and experimental and operational observations for application in hydrometeorological modelling for forecasting and projections of changes in climate and hydrology.

The secondary objectives of HYDMET are to:

1) Identify the potential for the improvement of and research topics for hydrometeorological forecasting for reducing flood risk and the optimization of renewable energy production.

2) Identify the potential for the improvement of and research topics for the optimization of water resource management under climate change conditions.

3) Improve the synergy between the strategic plans for institutions and research groups.

4) Identify topics to be given greater emphasis in education.

The main outcome of the HYDMET project is a final report/action plan that identifies important research topics and actions to be addressed by a SAK within hydrometeorology in Norway.

SAK is an abbreviation for "samarbeid, arbeidsdeling og konsentrasjon" or collaboration, division of responsibility and concentration. The SAK concept is described by Hov et al. (2014): "The intention of SAK is to get public institutions to define common goals that cannot be met adequately by one institution alone, and to meet the new cross-institutional challenges by restructuring own work and shifting existing resource allocation. The SAK concept was devised by the Ministry of Education and Research as a mechanism for the public sector to modernize itself "bottom up" without directives "top down". A plea can be made for additional resources if relocation of current ones is insufficient to meet the common SAK goals.". Hov et al. (2014) emphasize that "moving new knowledge from the results of basic research through to application is another challenge that requires a SAK-approach". Within hydrometeorology, Hov et al. (2014) point to (i) the national global earth system model NorESM by UiB, UNI Research, UiO and MET Norway as a contribution to IPCC and as the core of the national climate services led by MET Norway (with NVE, UniResearch and the Bjerknes Centre for Climate Research), and (ii) national research schools in climate sciences as good examples of SAK at a national level.

A key activity of the HYDMET project was a national seminar with international experts held from 9-10 December 2015 in Lillehammer. The outcome of the seminar is summarized in a separate report (Engeland et al., 2017).

This report presents a synthesis of important research topics based on inputs from the seminar and outlines an action plan for SAK within hydrometeorology. Section 2 addresses sub-objectives 1 and 2 and provides a summary of important research topics in hydrometeorology. In section 3 sub-objective 4, related to education and recruitment in hydrometeorology is discussed. Section 4 re-visits the overarching objective of HYDMET, as well as sub-objective 3 by identifying existing activities related to SAK in hydrometeorology and suggesting a strategy for future co-operation and providing a list of actions for the next five years.

2 Research topics – the complete water cycle

Understanding the water cycle in hydrometeorological systems is important for water resource management and, in particular, for warning, prediction and mitigation of hydrometeorological extremes (i.e. floods, droughts, landslides, avalanches) for lead times from minutes to centuries. Knowledge-based management of water resources, weather and water related natural hazards, and energy production build on two pillars: observations for monitoring and models for forecasting/predicting (in time and space). Concomitantly, there is a significant overlap between models and observations, as observations are used for (i) building models, (ii) testing model hypotheses, and (iii) assimilation into models in order to improve predictions. An optimal use of models and data requires data bases for storing and sharing data and model predictions, repositories for sharing modelling tools, and coordination between institutions and modelers, meteorologists, hydrologists and end users. These main elements and their linkages are illustrated in Figure 1.

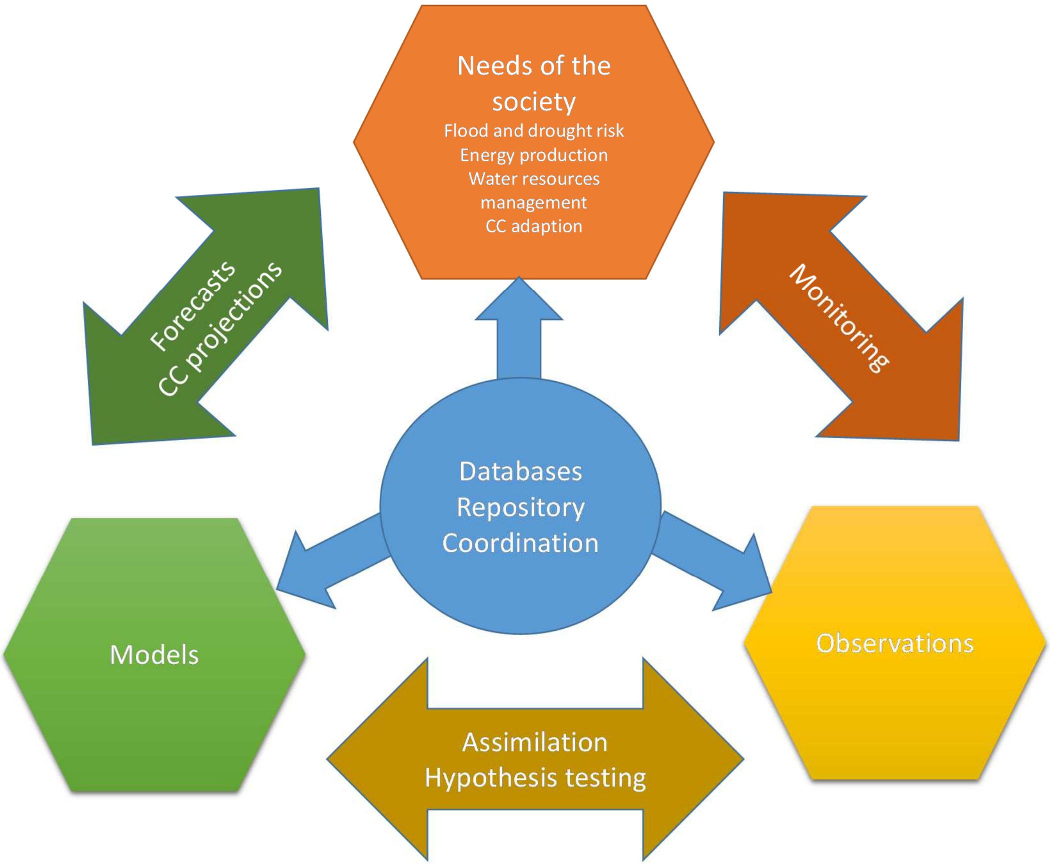

Figure 1: An overview over key research challenges in hydrometeorology and related needs of the society.

In the following subsections each element (as represented in Fig. 1) is addressed by briefly summarizing the state of the art before pointing at key research needs in order to better observe, model, and forecast the water cycle (atmospheric and land surface) as a coupled system. It is believed that an operational water resource and risk reduction management system can integrate the whole observations-models-forecasts-impacts information chain.

The subsections below provide a relatively comprehensive overview of research needs, without giving priorities. To address all the identified research needs, both improved cooperation between the institutions and long term funding is required. This is discussed in section 4.

2.1 Needs of the society

Important hydrometeorological services provided for the society are related to water resource management, reduction of damages caused by natural hazards and climate change adaptation. In Norway, hydropower is an important user of these services. Understanding and predicting hydrometeorological hazards is instrumental in order to reduce the damages caused by such events. In Norway, public forecasting and climate services are provided through a cooperation between MET and NVE. Forecasts aim to predict the weather for the coming days and weeks, whereas the climate services aim to predict the climate in the coming century.

Norway has established forecasting services for major geohazards such as extreme weather (see yr.no), floods, landslides and avalanches (see varsom.no). Each of these services rely heavily on observations and model predictions of extreme hydro-meteorological events. In order to provide reliable forecasts these observations and predictions need to be available at a sufficiently high spatial and temporal resolution, along with uncertainty estimates reflecting the predictability of the event.

Climate services aim to prepare the society for the weather it might experience in a future climate. The core of climate service is to translate the existing wealth of climate data and information into tools and information products that are useful for end users and help decision makers make informed decisions related to climate change adaptation. Useful climate services allow society to build resilience to future climate change and take advantage of opportunities provided by favorable conditions. Important sectors to serve include agriculture, hydropower, municipalities, and public road and railway authorities. A national portal for climate services has been established (klimaservicesenter.no) and the information content is continuously being developed in close dialogue with various user groups.

Both forecasting and climate services will benefit from improvements in modelling an measurement capabilities. These topics are discussed in the following sections. Important issues focusing on improving both forecasting and climate services include:

- Communication to end users in general and, in particular, communicating probabilistic information and uncertainties.
- Predictions at fine time and space resolution, in particular short-term and urban hydrometeorological events.
- Predicting and understanding extreme events, including extreme precipitation, floods, and droughts.
- Impact based forecasting.
- Cost-benefit analysis of forecasting and climate change adaptation. What is the added value for the society?

The ultimate goal is a seamless prediction system for natural hazards across temporal scales, i.e. merging forecasting and climate services.

2.2 Observations

Observations are used to monitor the water cycle, improve model parametrizations, calibrate water cycle models and, concomitantly, constrain model forecasts via data assimilation. It is important to assess the utility and relative value of observational data for varied spatio-temporal scales and platforms (ground-based, to airborne and satellite). Additionally, the availability of appropriate observations allow for the testing of hypotheses related to the dynamics of the water cycle.

Testbeds / experimental field sites

There are several hydrometeorological test-beds in Norway, the most important are Sagelva and Risvollan in Trondheim, Skuterud at Ås, Sæternbekken in Bærum, and Finse. The test beds are used for research and education, including detailed process-based studies for Master and PhD students. A range of meteorological and hydrological data at various spatial and temporal resolutions are available for these sites (see Engeland et al., 2017). Until recently, a missing component in these test beds is observations of evapotranspiration. As a part of LATICE (Land Atmosphere Interactions in Cold Environments) test-bed an eddy-covariance station was installed at Finse in 2016.

A major shortcoming of the observational network is the lack of information on the strength of the incoming atmospheric moisture transport. This reduces the possibility to improve precipitation processes in regional high resolution models as there is no information to accurately partition forecast or climatic errors into those due to a misrepresentation of the large scale moisture transport or those due to local processes such as convection and orographic enhancement. Targeted instrumentation and observational campaigns where this is addressed would enhance the possibility to improve precipitation processes in regional forecast and climate models. A highly successful template is provided by the NOAA Hydrometeorological Testbed (HMT; see hmt.noaa.gov). One key aim of HMT is to “identify new sources of predictive skill and improve predictions of weather, water, and climate through observations, understanding, and modeling of physical processes and phenomena of the coupled Earth system”.

New approaches to multi-scale testbeds in which all components of the energy and water fluxes between the land surface and atmosphere are observed are needed. Important fluxes to observe are incoming (lateral) atmospheric moisture fluxes (atmospheric rivers), detailed observations of atmospheric profiles (to assess stability), precipitation (including radar), land surface energy balance including evapotranspiration, temperature profiles in snow, soil and lakes, snow conditions (important for energy balance and temporal water storage), soil moisture and groundwater levels (important for energy balance through evapotranspiration and catchment dynamics) and river streamflow (to close the water balance). For lakes, time series of vertical temperature profiles, turbidity or light adsorption are important. Testbeds should cover varied land surface types (agricultural, urban, pristine, lakes) and climatic conditions (low-land to alpine). In order to measure and later analyze hydrometeorological processes at their relevant scales, the testbeds need to cover several spatial process dependent scales (e.g below 1 km for soil moisture and 400 km for atmospheric rivers. It is necessary to take into account the existing network of common hydrometeorological variables when designing testbeds with more detailed measurements to ensure that results can be applied to a wider application.

Crowd Sourcing / Citizen data

Crowdsourcing is the practice of engaging a ‘crowd’ or group for a common goal — often innovation, problem solving, or efficiency. It is powered by new technologies, social media and engaging so-called citizen scientists. The potential for using these data is, until now, explored only to a small degree. One example is the NVE-hosted regObs app and web-service (www.regObs.no) where the public might provide information on geo-hazards. Data can be provided and accessed by everyone. Another example is the cooperation with schools in Bergen to collect real-time weather data for educational, research and forecasting purposes (www.bergensveret.no). MET has started to investigate the use of observations from large networks of off-the-shelf weather stations (e.g. Netatmo). Measurements of temperature, humidity, precipitation, and wind from several thousand privately owned stations across Norway are available. Although the quality of the measurements can be lower, the sheer number may provide a different type of information that complements conventional networks.

Thus, new ways to collect, quality control and apply crowd data is needed. The amount of crowd sourcing data from both private and commercial meteorological stations is increasing and has vast potential to improve both analysis of the hydrometeorological system and hydrometeorological forecasts. MET is planning on using these observations in post-processing of weather forecasts in the future. Technical infrastructure must be built to take full advantage of this promising avenue to maximize observational data.

Remotely sensed data

Given the relative lack of in-situ measurements, observations from remote sensing platforms are invaluable for describing the atmospheric state and land surface properties, including changes in time and space (e.g. migration of vegetation and on a shorter time scale, snow cover). The most commonly employed sensors are optical, thermal, laser-altimetry, and, radar. These data are important not only for an instantaneous picture of the Earth system, but also for assimilation into atmospheric and land surface models and for detecting changes over time. ESA's Copernicus program got its first satellite in orbit in 2014 and is the most ambitious Earth observation program to date.

As remotely sensed data seldom measure the variable of interest directly there is a need for research on calibration and validation data products derived from remotely sensed data using high quality in-situ measurements. Thus, optimal usage of new satellite estimates is very much linked to a proper national situ network. A second research need is to find new ways to merge/assimilate remotely sensed data and models. This is addressed in the subsection below.

Monitoring networks

The monitoring networks of MET and NVE provide most of the data for the national databases hosted by the respective institutions. The hydrological database has (as of the end of 2012) 544 streamflow, 180 water temperature, 23 snow, 28 soil moisture, 63 ground water, and 23 sediment transport stations, and the glacier mass balance and/or frontal position at 54 locations. It is estimated (2010) that the national hydrological data base constitutes of the order of 250 000 station years. An analysis of the station network has recently been carried out (Leine et al., 2013) and a further development of the hydrological station network is needed according to the conclusions of this study. Further, the development of the landslide and avalanche forecasting system (operational since 2013) includes a station network analysis that resulted in 52 new meteorological stations in mountainous areas. At present, temperature is measured at about 230 sites and precipitation at about 400 sites. In addition, weather data from other institutions are stored by MET (SVV, LMT). The weather radar network is comprised of 10 radars along the coast, with a recent inland supplement near Lillehammer. Two more inland radars at Hardangervidda and Finnmarksvidda,are planned,to complete the network .

Based on existing evaluations, the efficacy of the network needs to be further evaluated to determine if it is sufficient for the needs of the research communities and various operational purposes. For the research community, these data are important for model development and for assessing climate trends. Continuing observations of long time series is of upmost importance, particularly for statistical usage. It is also necessary to add observations of new variables to the monitoring network. One important missing variable is evapotranspiration.

Operational hydrometeorology requires improved availability of data of higher temporal and spatial resolution, particularly in urban catchments, and data with a better representativity, e.g. for high altitude regions.

There is a potential to better utilize the total information content in the data, e.g. by combining observations from different sensors (e.g. precipitation gauges and radar) or of different types (e.g. streamflow and precipitation) in new ways. Thus, better coordination of the observation network and improved remotely sensed data, like precipitation radar data, is needed.

There is a need for enhanced availability of hydrometeorological data. A streamlined infrastructure for sharing observations and model data is needed, both for researchers and for specific end users. Important issues that must be discussed and clarified are:

- formatting standards
- routines for quality control
- metadata requirements
- other aspects of coordination of hydrometeorological data

Many of the points above are already addressed for several data and model outputs (e.g. SeNorge, meteorological forecasts published on a threads server). The topic is further developed in section 2.6.

2.3 Models

The current practice for operational forecasting and projections is to use a “one way” chain of models, sometimes combined with post-processing (meteorological forecasting -> processing -> hydrological forecasting -> processing). The traditional motivation of land surface modelling has been to provide boundary conditions of momentum, heat and moisture to the atmosphere. As such, these models have been developed to minimise errors in these fluxes. For the hydrological community, the focus of modelling has been at the other end of the terrestrial water cycle, i.e., accurate predictions of streamflow. However, both communities are attempting to solve the same problem, to represent the whole terrestrial water cycle. To increase the interaction between modelling communities, the research community should:

- Develop, share and document models for all branches of the water cycle and facilitate model chains for specific applications.
- Participate in the development of a coupled high-resolution Earth system model for seamless forecasting, including one or more of the following: (i) hydrology-land surface, (ii) land-atmosphere, (iii) ocean-atmosphere, (iv) land-ocean-atmosphere, (v) ensemble prediction, and (vi) operationalize its production chain including tailoring to end-users.

Parameterizations of processes are discussed in subsection 2.3.1, whereas the coupling of models is addressed in subsection 2.3.2. Important issues to consider when developing hydrometeorological models are (Engeland et al. 2017):

- the holy grail: the coupled and seamless system model
- making the most of data, in terms of optimal use of available sources of data, improved quality control systems etc.
- quantifying the uncertainty, taking the different sources of uncertainty into consideration, optimising skill. Ensemble predictions at high spatial resolution is needed in order to increase the predictability on small scale.
- quantifying the performance of different forecasting models, including a discussion of benchmarking and skill
- modelling at fine resolution (in time and space), including urban flooding and drainage
- quantifying hydrological effects of land use changes
- understanding and modeling extreme events
- ranking of variables – which is the most important?
- progressing towards physically linked hydrological models, to prepare for data-assimilation and predictions in ungauged basins and in a changed climate

2.3.1 Processes and parameterizations

2.3.1.1 **Dynamic vegetation**.

Interactions between terrestrial vegetation ecosystems and the climate system is an important research field of high international interest, however, in Norway both research and teaching within this field is fragmented. A particular challenge is that groups working on large-scale climate models to a limited extent collaborate with those studying and observing ecosystems on a small scale.

Thus, there is a need to strengthen the coordination of these research communities and to engage in joint research projects through coordinated field efforts. This is one of the key objectives of, a recently initiated coordinated research effort at the University of Oslo (see Section 4). Further, many land surface models ignore temporal changes in vegetation. It is therefore a need to develop dynamic vegetation models that need to be incorporated in complete earth system models or land surface models. More detailed land use representation is an additional need.

2.3.1.2 **Evapotranspiration**.

Vegetation plays an important role in the climate system in the boreal and arctic zone, and evapotranspiration is an important element in the atmosphere-land surface interaction as it links the energy (latent and sensible heat exchange) and water balance. Evapotranspiration is, however, the "forgotten link" in many models since it is rarely observed. Various methods exist for its estimation, but traditionally (in Norway), rather simple approaches are used that require few input variables.

Thus, there is a need not only for more (direct) measurements of evapotranspiration (e.g. eddy covariance or flux measurements) for validation, but also for promoting state of the art methods and best practice to the community (research and operational users). This relates to both the choice of evapotranspiration model and parameterizations that build on empirical observation (e.g. flux measurements). Recently (September 2016), a LATICE flux station was established at Finse, presently the only in its kind in Norway, and it will be accompanied by a mobile flux station for use at different land cover types. These novel data and the competence that results provide a unique opportunity for advancing the research on evapotranspiration estimates in Norway, and should be taken advantage of.

2.3.1.3 **Precipitation**.

The spatial and temporal inhomogeneity of precipitation is a primary contributor to the variability of the land surface water balance, and accurate forecasting in time and space of extreme precipitation events (ref. atmospheric rivers, section xx) is a key to reliable forecasting of floods, landslides and avalanches. It is a fundamental challenge for atmospheric numerical weather prediction models to properly represent precipitation patterns and the inherent error characteristics of the multiple spatio-temporal scales necessary to represent the hydrologic cycle. Currently, MET Norway employs a high-resolution convective-permitting (i.e. resolves deep convection) limited area model. In addition, a mesoscale ensemble system is now operational to assist in quantifying forecast uncertainty.

There is a need to better understand the interaction between lateral atmospheric moisture fluxes, land surface topography and precipitation enhancement, both for large scale orographically enhanced events and those dominated by deep convection. This understanding can be achieved by combining observational campaigns and models in new an innovative ways (see subsesction on test beds).

2.3.1.4 **Snow**

Snow is an important hydrological parameter in the northern hemisphere and in Norway approximately 30% of the annual precipitation falls as snow. Snow cover influence the energy balance of the land surface, and is a temporal storage for water influencing stream flow. In addition snow itself might collapse and cause avalanches. Snow models in hydrology are typically calibrated empirical relationships between snow variables and the modest model forcing at hand, i.e. snow accumulation and melt vs precipitation and temperature. More physically based snow models, focus on the energy balance and metamorphosis processes, and can provide more detailed information of the current state and evolution of snowpack. However, these models require more forcing parameters and should ideally assimilate observations to constrain the impact of inaccurate forcing data.

There is a need for new physically based snow models with few or none calibrated parameters, that are capable of incorporating new observations (such as snow covered area from satellites and interpolated wind fields), and that might assimilate observations in order to constrain the simulations.

2.3.1.5 **Soil moisture / groundwater / runoff**

Soil moisture provides an important link between climate (land surface) and hydrological models through its role in regulating the energy, respectively, the water balance. Thus, a ‘correct’ simulation of soil moisture would benefit both modelling communities and be a key component in a coupled model system. An essential variable produced by the hydrological model as conditioning/feedback/input to the meteorological model is saturation at the grid scale that is a function of both water fluxes between the land surface and the atmosphere (precipitation and evapotranspiration) and infiltration, and lateral flows that at each point in the catchment is influenced by uphill and downhills saturation conditions and the history of moisture input.

Land surface and meteorological models focus on the soil moisture and the vertical fluxes of water and energy, whereas hydrological models focus on the runoff generation and lateral water fluxes. The linear reservoir model has typically been the basic "building block" for the development of operational hydrological rainfall-runoff models, whereas land surface models commonly utilize physically based points scale equation at grid cells of several square kilometers. Dedicated groundwater models describes the spatial variability of groundwater in 2- or 3 dimensions and captures the observed non-linear and many-valued relations between runoff and groundwater levels, but are challenging to apply due to the need for detailed data.

There is a need for new process parameterizations that can be used at grid- and catchment scales. Physically based hydrological rainfall- runoff models that respects the observed spatial variability of soil moisture/groundwater and are better equipped for multi-objective calibration and data assimilation are needed. A major challenge is that the main information we have on a hydrological system is the signal of the integrated response, i.e. runoff, whereas many of the basic physical equations are valid on a much smaller (point) scale. Decomposing and disaggregating the integrated catchment signal to individual points in the catchment in a consistent way by inverse modelling is a major challenge.

2.3.1.6 ***Lakes and rivers***

Lakes constitute between 5 and 6% of the surface area of mainland Norway. The lakes are (i) important as physical elements in a catchment and are decisive for the hydrological response in catchments, and (ii) a boundary condition (as a local sink/source of energy) in atmospheric circulation models and might impact the local climate. Lakes are included in coupled land-atmosphere circulation models using rather simple model representations.

There is a need for better understanding the processes that drives the lake dynamics. The internal circulation pattern in lakes is sensitive to surface temperature and wind stress. Especially the expected development of capacity production for the European power marked require in-depth know-how of this dynamics. The same is true with respect to global warming. What do we expect of biological feedback in a lake when stratification and circulation pattern is changing due to global warming and/or rapid changes in the water balance?

As many of the large, regulated river systems are prone to damaging spring flood under unfavorable conditions, hydraulic models play a role as a component in the flood forecaster's toolbox and in operation of watercourses and hydropower systems (e.g. deviation of maneuvering schedules. Dynamic flood zone maps that enables forecasting water levels and inundated areas, can be established by coupling water levels from the model to maps. At present approximately 130 river reaches in Norway do have flood inundation maps based on flood estimates and hydraulic modelling.

2.3.1.7 *Urban areas and semi-urban environment*

Urban pluvial (storm water runoff) flooding – flooding in urban areas caused by intense and prolonged rainfall, which exceeds the capacity of the drainage system – is one of the most costly hazards in modern towns and cities. It often happens with short warning and in areas not obviously prone to flooding, making it hard to manage and predict. Urban pluvial flood risk is expected to increase significantly in the future as a result of climate changes and demographic shifts: the former is likely to increase the magnitude and frequency of extreme storm events, the driving force of pluvial flooding, while the latter, depending on the handling of surface water, may increase exposure and hence, risk.

There is a need to improve the ability for now-casting and forecasting extreme precipitation in urban areas by combining radar derived data and forecasts from NWP models. The estimation of design precipitation in cities for current and future climates need to be improved, e.g, understanding the spatial variability of extreme precipitation as well as the spatial co-variance. There is also a need for a new type of model where the effect of changes in the land surface properties (urbanization, green roofs, etc) on design floods is explicitly accounted for.

2.3.2 Coupling of models

The key research challenge for the future will be to design and develop the next generation of earth system models that considers all aspects of the terrestrial water cycle and aim to minimise errors across all components. The main benefit of a coupling is improved representation of the fluxes between the land surface and the atmosphere so that feedbacks and interactions between the land surface and atmosphere are accounted for. A warmer climate has already led to changes in land surface properties, which in turn influence the atmospheric circulation and the hydrological cycle. The observation, understanding and prediction of such processes from local to regional and global scales, represent a major scientific challenge that requires multidisciplinary scientific effort.

The coupling of models is challenging due to the different application scales, different computer codes and different institutions that has developed the different type of models. There are several strategies to follow, from a unified model with one code base to a model based on couplers that links independent models for different sub-systems. For a complete earth system model, computing time and available data resources are a limitation, and there will be a trade-off between resolution, uncertainty and complexity. Coupling of models could also include end user tools, e.g. hydropower optimization tools, consequence oriented tools for engineers in the municipalities that have the infrastructure responsibilities.

2.4 Assimilation of observations into models

Assimilation aims to merge the observational and model information in order to improve predictions. In forecasting, assimilation improves model predictions by adjusting the internal states of the forecasting models before producing predictions for the coming days. For predicting land system variations at seasonal to inter-annual time scales, land data assimilation uses observations to constrain the physical parameterizations and initialization of land surface states and constrain unrealistic simulated storages.

2.4.1 Assimilation of atmospheric data into NWP models

The production of weather forecasts is based on assimilating observations into the numerical weather prediction model. Observations of the atmosphere, land surface and ocean from satellites, aircrafts, SYNOP-ships, weather radars, sondes, atmospheric profilers and SYNOP stations are assimilated into the NWP models. The updating cycle for forecasts is currently 3 hours.

A major challenge for forecasting models are to: (i) assimilate additional type of variables (observations) into the models (e.g. streamflow, snow cover, soil moisture, see section 2.4.2), and (ii) improve the assimilation algorithm and increase the updating cycle.

2.4.2 Assimilation of land surface data

Assimilation of land surface observations is less advanced than assimilation of atmospheric observations. For hydrology, assimilation of snow information is used operationally. Both satellite-based snow covered area (SCA) as well as point observations of snow depth is used in the SeNorge snow model. For hydro power companies it is a standard procedure to measure snow depth and density in the end of the snow accumulation season in order to update (in a manual way) their forecasting models.

Other land surface data are rarely or never used for assimilation in operational models, However, land data assimilation has been and is a very active field of research. Land data assimilation considers both ground based in situ data and satellite data. NILU has developed a land data assimilation system that make use the Ensemble Kalman Filter for assimilating soil moisture data from various satellite platforms into the SURFEX land surface model in an off-line manner. These results indicate the power of the data assimilation method to add value to soil moisture information from satellites and models, in particular over northern regions such as Norway.

For assimilation of streamflow information, different data assimilation techniques, with an emphasis on ensemble Kalman filter and particle filter, are presently being adapted to the flood forecasting model system at NVE, and will probably provide significant improvements in future flood forecasts. When correcting the snow and subsurface states, the reduced error in the runoff simulations may be seen for a number of time-steps, depending on the “memory” (storage capacity) of the catchment.

There is a need to further improve assimilation algorithms for snow data. The new algorithms should manage to combine SCA observations from satellites with snow courses and snow depth measurements at the land surface aiming improvements of both flood forecasts and the snow maps in SeNorge. Assimilation of SCA requires that the models simulates well the spatial distribution of snow caused by both precipitation variability and wind erosion. In the future, efforts should continue to improve the data-assimilation routines for correcting the simulated snow maps on the basis of fresh available snow observations in near real-time.

For other land surface data, there is a need to establish operational assimilation setups and to further refine the assimilation algorithms. In particular, the usefulness of assimilating soil- and ground water information for forecasting has not yet been evaluated. Finally the combined effect of simultaneously assimilating several types of land surface data (streamflow, snow, soil moisture) needs to be investigated.

2.5 Forecasts and climate change projection

Seamless forecasting

The goal of seamless forecasting is to use a common modeling structure to represent processes consistently across a wide variety of space/time scales, from nowcasting to climate change scenarios. Given the inherent uncertainty for all these forecast challenges, albeit from different sources, it is logical to employ a probabilistic (ensemble) approach. To develop such a system, it is integral to discuss what might be termed seamless verification, in that the verification of model forecasts need to be consistent over the varied space/time scales.

From a modeling perspective, it must be established that the model is 'doing the right thing', (i.e. properly representing the fundamental dynamics). From a user perspective, it needs to be established that a forecast helps to make a better decision. It is important to note that the user needs will not be seamless over all space/time scales, and that the needs of a user on a nowcasting time scale will be quite different than that for seasonal and climate timescales.

Downscaling / bias correction / post-processing

Post-processing techniques (a combination of downscaling and bias correction), aim at making forecasts and climate change scenarios more useful, and the main strategy is to adjust the model outputs to improve the agreement with observations. Short range forecasts (1-3 days) are mainly improved by accounting for differences in model grids and resolutions and integrating model forecasts with updated observations. More systematic errors in long range forecasts (seasonal up to 100 years) are corrected by adjusting the statistical properties of the raw output (e.g. mean, standard deviation, number of wet days etc.) using statistical techniques and are generally used to create site-specific forecasts from raw model fields. For northern latitudes, the classification of precipitation phase is of special importance since it introduces both thresholds and long term memory in the hydrological response to precipitation. The need for post-processing is expected to decrease as the complexity and resolution of earth system models increases.

Quantified uncertainty in forecasts is an attribute of great interest for decision makers and the public. Meteorological and hydrological uncertainty is highly connected, and a high degree of interaction is necessary for coping with this aspect.

The need for further research on post-processing is to identify which part of the hydrometeorological modelling chain we should apply post-processing (output from GCMs, RCMs, hydrological models) in order to make reliable and robust forecasts. Secondly, standard post-processing methods destroy the relationships between weather variables as well as their spatial patterns. New spatial-temporal multi-variable post-processing methods are needed (e.g. stochastic weather simulators), and new modelling concepts should be tested.

Impact based forecasts

Even perfect hydrometeorological forecasts are diminished if the content is not targeted to the need of the user. This involves the communication with and identification of 'impact' by the users. Impact is often related to severe weather (heavy precipitation, destructive winds, thunderstorm activity, little precipitation) that can affect life and property. However, beyond short to medium range forecasting, the efficacy of seasonal and climate forecasts are integral to not only human risk, but energy production and water management. As such, it is necessary to not only create the most accurate forecast possible (with an estimation of uncertainty), but also forecast the variable or indices most relevant for a given impact, for instance damages due to flooding. To achieve this it is vital to engage in closer communication with stakeholders to learn their needs for better informed impact based forecasts to aid in decision making and hazard mitigation. Examples of impacts are inundated areas, forest fires, plant growth.

2.6 Databases - repositories - coordination

All activities described above in sections 2.1 - 2.5 require investments in data infrastructure. Modelling activities requires computing power as well as model repositories, whereas observation activities need data storage. To aid interdisciplinary cooperation, it is essential to attain a mutual understanding of the data, methodology and tools that are incorporated into the forecast and hydrometeorological projection framework. To this end, it is suggested that a repository for data and models be created and created in such a way as to enhance information exchange and cooperative activity. A first step towards a common repository is to create a meta-database that provides an over experimental data and existing modelling tools and codes (see section 4).

There is a need to facilitate sharing and exchange of both data and modelling experiments. Data storage has a long-term scope and should be accomplished in a structure able to host large data sets of national interest, with good, map-based visualisation tools. Degree of integration of data from different disciplines and interfaces for data sharing etc. must be considered. Data infrastructure for experimental data and modelling results should be integrated into project applications, e.g applications for hydrometeorological test beds and Centre of Excellence(CoE) (see section 4).

Today's IT-infrastructure would allow for an easy access and distribution of observed and modelled results. MET is already using systems like "thredds" to their model outputs readily available to the public in near real time. Also SeNorge model outputs with daily time resolution for the period 1958-today will be made available for downloading. Other organisations should follow this example. Research institutions should investigate similar solutions to make research results and new or updated models searchable and easily accessible.

Important challenges related to coordination of data storage can be listed as follows:

- System administration: a long-term, national data base with simple automated access to data should be facilitated.
- Standardizing (Benchmarking): common formats
- Quality control: data should be quality controlled, non-subjective and tagged, according to quality/uncertainty. Corrections must be documented
- Documentation: we need metadata at a national level describing which data, including campaign data, are available, where and how to get them.
- The repository should include a common test bench, with reference datasets

- The repository should include both data and model/algorithm tool box with common coding standards

3 Recruitment and education

3.1 Study programs, courses and research-school.

An overview over existing bachelor- and master programs are given in Engeland et al. (2017), and the following summary is provided:

"The overview shows that both UiO and NTNU provide extensive curriculums in hydrology. UiO focuses on process understanding and advanced modelling tools (physical based and stochastic), whereas NTNU focus on hydraulic, hydropower, water supply and drainage systems. At NMBU an introductory courses is given in hydrology, followed by two more advance courses in hydrogeology. Similar, in Bergen only a few courses are given, covering karst hydrology, hydrology/groundwater and glaciology. The overview shows that there is not extensive overlap in hydrology courses, and that coordination on the national level is therefore currently not a major issue, but should be kept in mind in future revisions."

The overview shows that both UiO and UiB provide extensive curriculums in meteorology, whereas At NMBU two courses in meteorology are given, including on in micro-meteorology. Coordination on the national level is currently not a major issue, but should be kept in mind in future revisions."

The study programs at the University of Oslo (UiO) are currently undergoing a major revision, to be implemented fall 2017 (bachelor) and fall 2018 (master). There will be two bachelor programs at the department of Geosciences: i) Geophysics and Climate and ii) Geology and Geography. Hydrology and meteorology (and oceanography) are part of Geophysics and Climate, but some basic hydrology is also included in the Geology and Geography program. The program provides students with a deep capacity for quantitative analysis in the Geosciences and gives practical tools of value in various work environments. Specialisation in meteorology or hydrology is then done as part of the master study (either direction hydrology and glaciology or meteorology and oceanography). The new study programs will imply a closer integration of hydrology and meteorology and build on a strong background in mathematics, physics (mechanics), statistics and informatics (programming). Hopefully, this will imply recruitment of students with competence within hydro-meteorology. In addition, water related master thesis will be supervised for students taking the Geology and Geography bachelor and later specialising in Physical Geography. These study programs are seen as a good basis to develop capacity within the HYDMET topics.

Even though overlap or duplication of study programs and courses on the national level currently is not a major issue, there is still a potential for improved coordination of teaching at the national level by (i) increase the mobility of both student and teachers, (ii) share teaching materials and computer codes for exercises including common model tutorial and iii) common experimental field sites.

For the period 2016-2024 UiB will host the Norwegian Research School on Changing Climates in the coupled Earth System (CHESS) that builds on The Norwegian Research School in Climate Dynamics (ResClim). Participating institutions are University of Bergen, University of Oslo, University of Tromsø, the Universitety Centre in Svalbard, UNI Research, The Norwegian Meteorological institute, Norwegian Institute for Air Research and the Norwegian Polar Institute. CHESS supports courses for PhD students, and issues open calls for new ideas (intensive courses).

3.2 Masters and PhDs – topics and joint supervision

There is already a large degree of co-supervision of master students between UiO, MET and NVE. This is facilitated by that UiO maintains a list of relevant master projects that also include topics and supervisors from MET and NVE. This practice is considered very positive by all partners involved and will continue in the future. Inspired by the HYDMET-project, a one day seminar for master- and PhD students with supervisors form at least two of the three institutions UiO/MET/NVE was held at NVE I june 2016. The seminar will be continued in the following years.

Several PhD students are associated with the LATICE project. The PhD students have supervisors from different disciplines (notably hydrology and meteorology) ensuring integration and knowledge transfer as well as an inspiring and dynamic research environment with many young scientists. For a detailed description of different PhD as well as Postdoc projects see the LATICE website, mn.uio.no/latice.

Master and PhD theses could to a larger degree address operational applications and use the models, software and hardware from the operational forecasting systems at MET and NVE. To achieve this, the access to, and the use of, the operational models must be facilitated, and topics that match operational needs for MET and NVE, and at the same time maintain the research focus at the universities, need to be identified.

Joint research projects are an excellent framework for encouraging joint supervision. In particular a national co-operation on hydrometeorological test beds might be used as a basis for joint field courses, joint supervision and provide necessary infrastructure and data for PhD and master theses.

4 SAK action plan

Section 2 provides a relatively comprehensive overview of research needs, without giving priorities. To solve the research needs, both allocation of internal resources, improved co-operation between institutions, and sufficient funding is needed.

Existing funding that could be used include (i) internal funding and initiatives, (ii) bilateral agreements between MET, NVE and UiO, (iii) coordination of joint meetings in ongoing projects, and (iv) existing networks like the Norwegian Hydrological Council (NHR). Some examples of internal R&D funding are:

- The annual R&D funding at NVE where project applications are submitted each year. Some of these internal projects could be further used to fund R&D projects within the identified HYDMET topics listed in section 2.
- LATICE (Land Atmosphere Interactions in Cold Environments: The role of Atmosphere – Biosphere – Cryosphere – Hydrosphere interactions in a changing climate) is strategic research area identified by the faculty of Mathematics and Natural Sciences at UiO. It provides a framework for collaboration within research and training within the field of hydrometeorology. It has already established itself as a dynamic research group with a high number of early career scientist working together in a highly interdisciplinary environment, including several external partners across Norway (currently 10 organizations). It has secured additional infrastructure resources (approximately 2 million NOK) to establish the LATICE flux site at Finse, which has become a high resolution measurement infrastructure site of national importance. In addition, several additional research projects with external partners are linked to the project through external funding (e.g. from RCN).

Some examples of bilateral agreements include

- Bilateral agreement between NVE and UiO also focus on natural hazards and includes two adjunct positions and PhD students.
- Bilateral agreement between MET and UiO includes two adjunct positions and PhD students.
- Bilateral agreements between NVE and MET on development of operational forecasting services, . Within this framework, common activities are identified.

Additional funding is needed for several of the identified research needs. In particular upgrading and establishing hydrometeorological test beds and research infrastructure and development of coupled hydrometeorological model systems as described above will require funding from several national research projects or a center of excellence. In both cases, extra funding of data storage and computing infrastructure is needed.

The national organization of hydrometeorology can be improved by (i) using existing governance structures, e.g. existing collaboration agreements, (ii) further utilizing meeting places for students and researchers in the form of seminars and conferences, and (iii) improved/expanded collaboration in research projects.

Several of the suggested actions that are mentioned may be easily achieved as they have a small marginal cost in addition to already exiting funding or collaboration. Other actions will require major additional funding. Specific actions that are considered important and that need additional funding are listed in the action plan (Table 3).

4.1 Governance structure for hydrometeorology

The Norwegian Hydrological Council (NHR, see www.hydrologiraadet.no) is a co-operative body open to all Norwegian institutions, organizations, governmental bodies and corporations working in the field of hydrology (based on a broad definition of hydrology). The Council was established in 1995 and has 29 institutional members. Its mandate includes to (i) Organize hydrological meetings, symposia, conferences and courses; (ii) Act as Norwegian International Hydrological Programme (IHP) committee; (iii) Promote co-operation and research co-ordination amongst Norwegian hydrological institutions; (iv) Provide information on international hydrology initiatives and co-ordinate Norwegian participation; (v) Promote hydrological research and education; and (vi) Disseminate relevant hydrological data and knowledge. NHR hosts an international conference on hydrometeorological modelling every second year.

In the wider field of geosciences, parallel networks for cooperation have recently been established within the SAK framework within hydrogeology, "Nasjonalt fagforum grunnvann" (NFG) an agreement on cooperation has been established that focuses on common project applications, exchange of personnel, tools and technical skills, and manifested the cooperation in five working groups. A similar national network on geohazards, mainly focusing on arranging national conferences and seminars, also exists.

In 2016 "Naturfareforum" was established as a co-operation between public institutions. Members are the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Directorate for Civil Protection (DSB), the Norwegian environment agency (MDir), the Norwegian Agriculture Agency, the Norwegian Public Roads Administration (SVV) and the Norwegian railroad authorities (baneNOR, former JBV). The forum focuses mainly on preventive actions to reduce the consequences of natural hazards by exchanging information and identifying challenges that need cross-sectoral solutions.

It is recommended that, as a part of NHR, a network for hydrometeorology is established where important elements are: (i) use the website for facilitating exchange of information, and (ii) arrange an annual (or bi-annual) meeting in combination with national conferences (e.g. the NHR conference) for follow up and modifying the action plan suggested in this report. The HYDMET network will be open for all researchers and practitioners, will have a "bottom-up" profile and rely on the initiatives and engagement form its members. A temporary website is already established (www.hydmet.no) as a first start, but needs to be further developed and possibly transferred to NHR web-site. Collaboration between existing networks should be encouraged when needed.

In addition to this network, a dynamic organization aiming at solving specific research and implementation tasks within a time frame of several months could be used to improve forecasting services. This approach is used within the Nordic MetCoOp cooperation. This governance structure is especially suitable for the cooperation between NVE and MET.

4.2 Networks and Meeting places

Agreements

UiO, MET and NVE have bilateral agreements including annual meetings attended by the institution leaders. The bilateral agreements between UiO and MET and UiO and NVE focus on education (i.e. co-supervision and adjunct university positions) and research collaboration in PhD-projects. The bilateral agreement between MET and NVE focuses on the development of operational services related to forecasting of natural hazards. These bilateral meetings could be extended to three-lateral (NVE, UiO and MET) or multi-lateral meetings (adding NMBU, UiB and NTNU).

Action point:

- *Suggest a trilateral meeting between MET, UiO and NVE and/or multi-lateral meetings (adding NMBU, UiB and NTNU) discussing coordination of ongoing research projects, topics for joint masters and PhD theses, and teaching, as well as profiles for adjunct university positions.*

Conferences:

At a national level, the Norwegian Hydrological Council organizes a biannual conference that focuses on modelling hydrology, climate and land surface processes. This conference has been a meeting-place for hydrometeorology. The next conference will be held in 2017 with the main focus on LATICE relevant topics.

Action point:

- *Continue to use the conference as a meeting place for hydrometeorology by using it for (i) bi-annual meetings in the HYDMET network, and (ii) to a larger extent involve meteorologists in the organization of the conference and encourage more meteorologists and climate scientists to participate.*

Student seminars:

UiO and NVE has since 2014 organized an annual meeting for master and PhD students (with joint supervision from UiO and NVE), where the students present their work and receive feedback. This meeting has proven very popular (~15-20 students participating each year) and is seen also as very useful enterprise for the supervisors in terms of information exchange. Last year (2016) the event also included students with supervisors from MET in combination with either UiO or NVE (or both). The events have been hosted by NVE, but next year MET will host the meeting. Given the success, it is anticipated the seminar will continue in the coming years and other universities may consider to attend.

At a national level, The Norwegian Hydrological Council organizes bi-annual seminar for masters and PhD students. Additionally, the Research School on Changing Climates in the Coupled Earth System (CHESS; see http://www.uib.no/en/rs/chess) provides both training courses and communal meetings for PhD students in Norway. It is an invaluable resource for the dissemination of information and fostering cooperative activity.

Action points:

- *Continue annual master and PhD student seminar in Oslo.*
- *Investigate the possibility for organizing a national seminar for students within hydrometeorology under the NHR or CHESS umbrella.*

4.3 National research collaboration

Co-supervision

The co-supervision of masters and PhD students is an effective way of increasing collaborative efforts between institutions. Successful examples of co-supervision between MET/UiO, NVE/UiO and PhD projects with supervisors from all three institutes are prevalent. There are also examples of successful co-supervision between NVE and

NTNU and NVE and universities abroad. In Norway, co-supervision of PhD students can be extended to NMBU and UiB. In order to facilitate co-supervision, sharing of available infrastructure and competences is important.

Action point:

- *Discuss co-supervision at annual meeting between institutions (see section 4.2).*
- *Discuss co-supervision at HYDMET network meeting.*

Ongoing research projects:

There are several ongoing projects related to hydro-meteorology that are summarized in (Engeland et al., 2017). The list of projects illustrates there would be a benefit from sharing information and results between projects. This could be achieved by organizing joint project seminars or workshops.

One example where collaboration between projects could give valuable new knowledge is the project i) FlomQ with the primary objective to develop a robust flood estimation framework for Norway, ii) ExPrecFlood with the primary objective to quantify the effect of projected climate change on short duration extreme precipitation events and related rapid onset flooding with implications for design value infrastructure, iii) WISLINE, a project to better determine the impacts of wind, ice and snow load on the Norwegian infrastructure, and iv) NAWDEX, a multinational aircraft campaign to examine diabatic modifications along the jet stream and downstream high impact weather and the Norwegian-centric NEAREX which has provided the first in-situ measurements of an atmospheric river in the Atlantic basin.

Action points:

- *Discuss coordination of funded projects at annual meeting between institutions (see section 4.2).*
- *Discuss coordination of funded projects at HYDMET network meeting.*

New project applications.

Researchers within the field of hydrometeorology are very active in applying for research funding, but the competition is fierce, particularly in the open calls from RCN. Thus, resources can be saved by coordinating applications to some degree. This requires trust and good cooperation between the partners involved. Based on the seminar in Lillehammer, the hydrometeorological community has a solid overview of the competence and skills at the different institutions. It is essential to use this network of competences when building consortiums in new project applications.

One of the outcomes from the Lillehammer seminar is the proposed framework for a new project in hydrometeorology (Appendix 1 in Engeland et al, 2017). This proposal should be submitted to a suitable call.

Action points:

- *Discuss coordination of project applications at annual meeting between institutions (se section 4.2).*
- *Discuss coordination of projects applications at HYDMET network meeting.*

Research infrastructure:

Within hydrometeorology, two types of research infrastructure are needed: observational and computing infrastructure. The ongoing research activities include an extensive data collection and use of experimental sites (provided in the summary report from the Lillehammer meeting).

It is very important to combine these data with long time series stored in the national databases at MET and NVE and secure financial support to maintain and improve the data quality from the experimental sites. This includes having personnel that follow up the instrumentation and data collection.

This argues for a concentrated effort. In some cases, specific purposes (high altitude, cold climate, etc.) will call for specific sites, but that should be the exception.

Action points:

- *Establish a metadatabase for experimental hydrometeorological data.*
- *Submit a research infrastructure application on hydrometeorological test beds.*

Centre of Excellence (CoE/SFF):

"The SFF programme gives Norway's best scientists the opportunity to organize their research in centres to reach ambitious scientific goals through collaboration and long-term basic funding" (RCN). The next call will probably be in 2019/2020. MET is a partner in a submitted CoE application (2016) on the atmospheric water cycle with CICERO, MET, NILU and UiO as partners. At UiO, an expected outcome of the LATICE initiative is a CoE application.

Action point: Prepare for and submit a CoE application.

Sharing of and co-operation on modelling tools and codes.

A range of modelling tools and platforms are used, ranging from integrated Earth system models to single-process models. This diversity of modelling tools is reflected in the needs for the society. It is currently necessary to utilize need both approaches, i.e. simple stand alone models that handle sub-systems as well as fully integrated models.

The co-operation should be on all levels, from sharing of codes to participating in a common coding and modelling platform, where the large complex earth system models require co-operation on code.

Action points:

- *Metadatabase for sharing and inform about available modelling tools, codes and platforms.*
- *Arrange national courses on common modelling platforms/codes*

Coordination of university cources and sharing of teaching materials:

Overlap or duplication of study programs and courses on the national level currently is not a major issue, but there is still a potential for improved coordination of teaching at the national level. In order to improve the coordination, a special workshop on education/teaching within hydrology and meteorology could be organized. The workshop could aim to identify: an overview of the specific topics covered, any topic missing, coordination, future plans, increase the mobility of both student and teachers,) shareing teaching materials and computer codes for exercises including common model tutorial, common field cources, .joint supervision beyond current practise etc

Action point:

- *National workshop on teaching in hydrometeorology*

Table 3 Suggestions for action plan. The action plan will need to be approved by NHR and the participating institutions.

	2016	*2017*	*2018*	*2019*	*2020*	*2021*
Establish a HYDMET network within NHR		*X*				
Bi-annual meetings (linked to other conferences or workshops. *Responsible: NHR*		*X*		*X*		*X*
Suggest common meeting UiO / MET / NVE, *Responsible: NHR*		*X*	X	X	X	X
Use the bi-annual conference organized by NHR as a meeting place for researchers, *Responsible: NHR*		*X*		*X*		*X*
Arrange annual student seminars in Oslo, *Responsible: UiO*	*X*	*X*	*X*	*X*	*X*	*X*
Arrange annual student seminars National level, NHR/The universities		*X*	*X*	*X*	*X*	*X*
Disicuss co-suprvision, coordination of seminars and workshops and coordination of project applications at annual meetings between institutions and at HYDMET-meetings. , *NHR, All*		*X*	*X*	*X*	*X*	*X*
Establish a metadatabase for experimental hydro-meteorlogical data and modelling tools/codes *Responsile: UiO and NTNU*		*X*	X	X	X	X
Prepare and submit CoE application, *Responsible: UiO (LATICE)*			*X*	*X*	*X*	
Prepare and submit a research infrastructure application,		*X*	*X*			

Responsible: UiO /NTNU/UiB/NMBU						
National courses on common modelling tools – when necessary			***X***		***X***	
National workshop on teaching on hydrometeorology ***Responsible: NHR and universities***			***X***			
Coupling of models – improvement of process parameterizations. If CoE application is successful				***X***	***X***	***X***
Establish/upgrade hydrometeorological test beds –Universities – If infrastructure application is successful				***X***	***X***	***X***
Promote hydrometeorological topics in future calls		*X*	*X*	*X*	*X*	

5 Conclusions

The degree of SAK within hydrometeorology at a national level is already relatively high. In this report and the parallel summary report from a HYDMET seminar (Engeland et al, 2017), existing co-operation on development of services, research and education has been identified. There is, however, still a potential to enhance SAK in order to improve forecasts, climate projections that again requires an improved understanding of the hydrometeorological systems. This improved knowledge will be the foundation for meeting the needs of the society by providing effective systems for forecasting and climate services, and improve the future water resources management.

Increased co-operation need to build on mutual understanding of the role of and the research topics covered by each institution. The main role of MET and NVE is to host research that results in improved services and products, whereas the universities should have a more independent role and also perform more fundamental research. These different roles might be challenged when research funding is strongly linked to innovation and services, and it is important that also in the future, supervision of PhD candidates should have a strong foundation at the universities. Concerning research topics, there is partly overlap in the topics covered at the different institutions, which is not necessarily a negative thing, as complementary knowledge is a prerequisite for collaboration within a given field. The topics covered by NVE and MET are to a large degree given by their award letter, whereas the Universities have more freedom and the research topics in focus are often decided by the profile of recruited scientific staff and funding available (ref. program calls at RCN).

We believe the following text, taken from the World Meteorological Organization report regarding Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO-No. 1150) does an excellent job explaining the motivation for a Norwegian SAK in hydrometeorology based on an identified knowledge gap between forecasts and warnings of hydrometeorological events and an understanding of their potential impacts:

"If the knowledge gap is to be closed, then an all-encompassing approach to observing, modelling and predicting severe hydrometeorological events, and the consequent cascade of hazards through to impacts, needs to be developed. Tackling this problem will require a multidisciplinary and highly integrated and focused endeavour. This is essential to ensure access to the best possible science, and the optimum services, to manage multi-hazard events today, and to provide the best possible evidence base on which to make the costly decisions on infrastructure needed to protect the population in the future as climate changes."

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Norwegian
Water Resources and
Energy Directorate

Norwegian Water Resources
and Energy Directorate

Middelthunsgate 29
Postboks 5091 Majorstuen
0301 Oslo

Telephone: 09575
Internet: www.nve.no