

Scientific evaluation of programme area 2

Water Resources (2015-2022) at the
Geological Survey of Denmark and Greenland (GEUS)

Sabine Attinger, Joseph Ayotte, Roland Barthel,
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Introduction

The evaluation process

The panel was asked to undertake an evaluation of research and dissemination activities to identify strengths, gaps as well as needs for amendments and improvements in relation to GEUS' strategy and mission within the GEUS Program Area 'Water Resources'. The evaluation concerned the period 2015-2022 and covered the following overall themes and research disciplines:

- Hydrological and hydrogeological modelling
- Groundwater quality
- Groundwater resources

The evaluation of the research and the research outreach activities was to be based on:

- Publications, reports, and other relevant material produced over the period 2015-2022
- Presentations by GEUS researchers
- Interviews with GEUS' researchers and management
- Visits to laboratories and work facilities at GEUS.

To improve GEUS' ability to fulfil its main mission within the program area seen in the perspective of the GEUS' statutes and general mission, the goal of the evaluation was to:

- Identify areas of high-quality research
- Identify areas where the research and facilities of GEUS could be strengthened
- Provide comments and suggestions as to strategic changes, amendments, and improvements to GEUS' activities within the program area.

The evaluation took place at GEUS' premises in Copenhagen in the period 18–21 May 2023, and the members of the evaluation panel were:

- Sabine Attinger, Helmholtz-Centre for Environmental Research - UFZ Leipzig, Germany
- Joseph Ayotte, USGS, Pembroke, New Hampshire, USA
- Roland Barthel, University of Gothenburg, Sweden
- Marijke Huysmans, Vrije Universiteit Brussel, Belgium
- Stephan Kraemer, University of Vienna, Austria

The context for research at GEUS

Role and tasks of GEUS are described in the *The Geological Survey of Denmark and Greenland Act*¹. According to this document, GEUS is an independent and self-governing research institution under the Ministry of the Climate, Energy and Utilities, responsible for the scientific exploration of geological conditions in Denmark and Greenland and adjacent shelf areas. GEUS task is to conduct research to the highest international level into matters of importance for the exploitation and protection of Denmark and Greenland's geological natural values. GEUS must also carry out mapping, monitoring, data collection, data management and communication about these matters. GEUS also has the task to provide geological consultancy to public authorities on matters relating to nature, the environment, energy and mineral resources and takes part in carrying out activities for authorities in these areas. GEUS is also a national geological data centre, and in this capacity GEUS makes data and knowledge available to authorities, educational institutions, enterprises, individuals, etc. Furthermore, GEUS is asked to contribute to undergraduate, graduate and PhD programs at the universities, etc.

¹ Act no. 536 of 6 June 2007

GEUS has formulated a strategy for the period 2020–2023 (a strategy document for the coming four years is currently under development). In the strategy for 2020–2023, the main goals for the Water theme are to:

- increase the interdisciplinary process understanding of the water and transport cycle² to support the increasing focus on sustainable water resource management,
- further develop the National Water Resource Model targeting new management needs, whereby quality and quantity of groundwater and surface water are managed in an integrated way,
- contribute to the development of the scientific basis for targeted and differentiated regulation and efforts aimed at reducing nutrient losses from agriculture,
- further information about the occurrence of identifying xenobiotic substances in the Danish groundwater and increase the understanding of the geological, hydrogeological, microbiological and chemical processes that determine the occurrence of these substances.

This context described above formed a guideline for the panel’s evaluation. The combination of the various roles and tasks (research organization, data management, communication and consultancy) in combination with a focus on Denmark, form an important background for the organization’s research strategy and scope.

² The panel suggests replacing “transport cycle” with a more appropriate term

Detailed evaluation of activities

Hydrological and hydrogeological modelling

Activities

Presentations on research within the theme of “Hydrological and hydrogeological modelling” focused on the Danish National Water Resource model, hydrogeological modelling, modelling of nitrate transport, integration of satellite images into hydrological modelling and hydrological modelling and climate change. Main activities within this theme are:

- National hydrological model based on MIKE-SHE established for whole Denmark on two spatial resolutions (100m / 500m) - called the DK-model
- Development of various parametrization and calibration methods
- Further development and improvement of the geological model and groundwater model which is the heart of the DK-model
- Development of tools and modules that run in offline coupling with the DK-model:
 - nitrate module with the national redox map
 - transport module based a random particle approach
 - uncertainty estimation (e.g., impact of uncertainty of geological structure model)
 - mHM to test spatially-pattern oriented model calibration
- Future: real-time modelling for flood forecasting (MIKE-SHE versus HYPE) together with DMI
- Field experiments: soil moisture observations using stationary cosmic-ray sensing together with gamma-ray sensing for interception, groundwater-surface interactions based on temperature measurements, monitoring of peatland hydrology.

Observations

The main assets of GEUS are its unique groundwater dataset on groundwater levels and groundwater quality, the hydrostratigraphic model and the Danish National Water Resource model. The heart of the DK-model is the groundwater model based on the geological model developed and further being improved at GEUS.

Within the hydrological and hydrogeological modelling theme, GEUS manages to combine their advisory work with high-level research. The developed models serve society but are also the base of high-level publications in top journals in the field (e.g., JoH, HP, HESS, WRR, etc.). The model is also the basis for strong collaboration between GEUS researchers from different disciplines and groups.

A strong team of about 10 modellers / researchers is working on the model developments. Model development is supported by a 50% position but there is no dedicated “model keeper” with an IT background to work on stewarding coded modules, code development, repository, maintenance, metadata, model description, etc.

The choice to use MIKE SHE³ has advantages and disadvantages. MIKE SHE is not always the ideal choice for ensemble modelling, uncertainty analysis, probabilistic approaches, integration of remote sensing, real-time modelling, etc. GEUS is also not the code owner and there are risks associated with using a commercial versus an open-source software. At the moment, there is also no structural access to a high-performance cluster or supercomputer.

Recent developments focus on uncertainty assessment, probabilistic approaches, real-time modelling, and data-driven approaches and should be continued in the future. Conceptual

³ <https://www.mikepoweredbydhi.com/products/mike-she>

model uncertainty and uncertainty on groundwater recharge may still be underestimated. Topics on hydrological extremes (flooding and drought) are started and offer more potential for research in the context of climate adaptation. The models offer underexploited potential for interdisciplinary collaboration, e.g., ecohydrological modelling and the links between hydrology and biodiversity. The strong modelling expertise within GEUS also has the potential for more international collaboration than currently exploited.

Scientific quality

The research output and the presentations of ongoing work on hydrological and hydrogeological modelling demonstrate a very high scientific quality and the drive to keep up with current scientific development. The quality of the scientific work in this area is evidenced by high-level publications in top journals in the field (e.g., JoH, HP, HESS, WRR, etc.). The model is also the basis for strong collaboration between GEUS researchers from different disciplines and groups.

Recommendations

As the groundwater model is the main asset, we recommend continuing to rely on the national groundwater model as a backbone and to link different model parts to the groundwater model. The model also offers opportunities for further exploitation, research, and collaboration. The model could be exploited more as consultants in Denmark are trained in MIKE SHE, e.g., by selling cut-outs to run scenarios for climate adaptation by municipalities. The model could also be used as a base for interdisciplinary collaboration such as ecohydrological modelling and the link between hydrology and biodiversity. The potential of applying methods and hydrological and hydrogeological modelling approaches on other countries could be exploited more. GEUS could push the other geological surveys more, e.g., by developing a geological model for Europe thereby playing a bigger part in *Destination Earth*⁴.

We also see an opportunity to do research in the field of participatory modelling, co-creation, and communication of model results, preferably together with social scientists. That means not only performing outreach activities, but rather engaging in research in how outreach and participation could and should be performed. GEUS may be in a unique position to carry out research in this field because of the applied focus of some of its tasks and the role in society that is prescribed by law. Some 10-15 years ago, GEUS seemed to be more active in this field.⁵ We recommend continuing and strengthen the research lines on:

- hydrological extremes such as floods and droughts, especially in the context of climate adaptation and the risk of maladaptation
- probabilistic approach and uncertainty analysis, also including conceptual model uncertainty, uncertainty on groundwater recharge and prediction uncertainty
- data-driven approaches and hybrid modelling combining hydrological models and data-driven models, and on using machine learning models and other models to inform and extend the DK-model.

As the choice for MIKE SHE has advantages and disadvantages, we recommend evaluations of the DK-model or a model-intercomparison study on large scale modelling software and to develop a vision on how different models can be used for different purposes in the future.

⁴ <https://digital-strategy.ec.europa.eu/en/policies/destination-earth>

⁵ See e.g., Henriksen, H.J. et al., 2009. Harmonised principles for public participation in quality assurance of integrated water resources modelling. *Water Resour. Manage.*, 23(12): 2539-2554.

To exploit all the opportunities that the unique model expertise of GEUS offers, we also recommend improving model infrastructure by having a dedicated model keeper and data keeper, and by arranging access to high performance computing.

Groundwater quality

Activities

A number of presentations gave an overview of the research at GEUS within the field of “Groundwater Quality”. A strength of GEUS are activities that are cross-cutting over themes, so some of the presentations may be associated with other themes as well. Presentations focused on nitrate reduction in groundwater, geogenic compounds in groundwater, transport in fractures, fate of organic pollutants with a focus on pesticides and biocides, treatment of polluted groundwater, groundwater quality and health, greenhouse gas emission and groundwater geochemistry, high resolution mass spectrometry, emerging contaminants, managed aquifer recharge, circular economy for arsenic, and the ‘pure groundwater campaign’.

The laboratory infrastructure relevant for the groundwater quality area was visited, including the inorganic environmental chemistry laboratory, the organic chemistry laboratory including the new HRMS facility and the molecular microbial ecology laboratory.

Important activities within the theme of groundwater quality have been:

- Warning system for pesticide leaching (PLAP)
- Nitrogen retention mapping
- Development of circular water technologies
- Understanding of fate of contaminants and nutrients in soil and water
- HRMS facility: testing (water samples from PLAP fields), method developments, QA/QC, development of joint applications with EPA, project development, development of applications
- Triazole fungicides resistance in fungi
- Emerging pollutants, PFAS
- Contribution to exposure assessment in epidemiological studies through characterization and prediction of geogenic and anthropogenic contaminants in drinking water (nitrate, pesticides, trace metals).

Observations

Scientific work in the groundwater quality theme is conducted by 15 scientists (primary association) of which 11 are senior researchers. It appears that scientists in the theme are unified in their vision to solve water quality challenges in Denmark and have an excellent collaborative environment. Besides, a bottom-up approach allows them a high degree of scientific freedom and creative space in order to take full advantage of their scientific capacities. This demonstrates excellent scientific management practices at GEUS.

The laboratory infrastructure devoted to groundwater quality is very good in the areas of inorganic analytics, organic analytics and molecular microbiology, and laboratory spaces for experimental work are available. These facilities are complemented by other analytical facilities of GEUS, and by infrastructure in collaborating Danish institutions. Modern spectroscopic techniques that are not available locally (e.g., synchrotron radiation spectroscopy at international user facilities) are also actively used.

GEUS has a clear vision of developing its laboratory infrastructure to tackle the problem of emerging organic contaminants. In this context, the development of a HRMS facility for non-targeted analysis of organic contaminants as a tool in environmental analytics has recently become a strong focus of laboratory infrastructure investments. It was stated that the goal of

this effort is not to undertake monitoring tasks but rather to play a leading role in method development and for investigating fundamental processes that may play a role in solving applied problems.

In general, the goal of the groundwater quality theme appears to be process oriented. Very interesting work was presented that was geared to gain a molecular level understanding and thermodynamic and/or kinetic quantitation of key environmental processes that are essential for the solution of pressing environmental problems and that will inform decision making processes with potentially costly consequences. The research personnel in this area appears to be highly qualified to make progress on that level.

Researchers in the groundwater quality theme face the challenges of integrating a mechanistic and quantitative understanding of key chemical and biological processes into models on different scales. This problem is not specific to GEUS, as it generally remains an unsolved problem in the field. However, given the excellent intellectual capacities in modelling on various scales, it appears that GEUS is in an excellent position to help reduce the existing gaps, e.g., by the application of reactive transport modelling.

It was noted that despite the existence of laboratory infrastructure for molecular biology and past successes in the field, the number of scientists working in environmental microbiology has significantly decreased over time. For example, GEUS lost a scientist in April 2023 and the retirement of a professor in that field is imminent. Research in microbiology is clearly getting sub-critical and focused decisions in this field are needed.

Scientific quality

The research output and the presentations of ongoing work demonstrate a very high scientific quality and the drive to keep up with current scientific developments as far as they may be relevant for future maintenance or improvement of the groundwater quality in Denmark. The contributions in the groundwater quality theme are strongly process oriented, but their collaborative approach takes advantage of the exceptional data collection and availability at GEUS and its modelling capabilities in order to solve groundwater quality problems. The quality of the scientific work in this area is evidenced by a good publication activity in high-impact journals.

Recommendations

Given the current sub-critical personnel situation in the research field of microbiology, we recommend starting a structured approach to reconsider the future of that field in the groundwater quality theme. Indeed, the current personnel situation may provide an opportunity to fundamentally re-align this area with the research goals of GEUS in the future. Part of this effort should be a consideration on how this field could be leveraged for the benefit of other research areas within the theme such as inorganic contaminants, organic contaminants, and groundwater quality protection. We recommend involving key GEUS researchers in the discussion that may benefit from collaborations with a strong microbiology section. Also, it would be critical to get external advice from top-level international experts and research managers in the field. Based on these discussions, it should be decided if GEUS aims to develop this field in-house (our recommendation). Alternatively, a key partner outside GEUS should be identified that may provide needed collaborative research capacities. In the former case, we recommend making key hires of young high-potentials or excellent mid-career scientists capable of creating a consistent research group that may generate synergies with other research areas and that again strengthens the capacities of the GEUS groundwater quality theme.

We recommend continuing the development of process-oriented, molecular level, mechanistic and quantitative research in the area of inorganic contaminant geochemistry. The impact of decisions on the future of the microbiology field should be considered in this context. Also, we recommend using the considerable modelling know-how of GEUS to strengthen the development/implementation of reactive transport models in order to quantify the effect of molecular processes on larger scales in time and space.

Regarding the recent developments in organic analytics at groundwater quality, we recommend to partner with other (international) organizations interested in suspect screening for non-targeted compounds, not only for method development, but in response to a need to identify emerging contaminants (pesticides, PFAS, hormones, pharmaceuticals etc.).

Groundwater resources

Activities

Past activities on Groundwater Resources and Health), Quantitative Management, Groundwater Quality Protection, Groundwater – Surface Water Interactions, and on International Groundwater Activities were presented.

The area of groundwater and health appears to be a relatively new area of focus for GEUS and represents a significant contribution to the world of interdisciplinary studies. The work is completed with researchers from GEUS and from Health Agencies within and outside Denmark as well as researchers from other research institutions. This represents a move toward modern collaborative opportunities where partners bring unique expertise to problem solving, such as environmental exposure and human health.

Groundwater resources quantitative management is taking a novel approach to assessing sustainability by examining long-term trends in water levels and use, model-based indicators of water use, and quantitative assessment starting with gap analysis and a decision-based risk assessment. This facilitates understanding of resource needs, such as ecological flows and identifies vital drinking water and resource areas. Optimization of resources is a goal of this analysis and attempts to account for climate change impacts.

As might be expected, the groundwater monitoring program has a focus on contaminants from point and non-point sources, supported by long-term data collection efforts. This is accomplished, in part, by providing direct input to the Danish EPA for monitoring priorities and monitoring protocols. The program also is responsible for annual reporting of data and for scientific interpretation of those data. As a supplement to the national monitoring program, GEUS also conducts groundwater level monitoring in real time, which provides needed research-grade information for current levels, trends, and climate change conditions.

There is a clear interest in groundwater – surface water interactions, owing in part to the high use of groundwater for water supply and its close connection to surface waters in Denmark. Studies have been conducted on the local to regional scales and are multi-faceted in nature and are applied to exchange with coastal waters (submarine discharge, saltwater intrusion) as well as to groundwater – lake hydrology and seasonally flooded riparian zones. This serves to provide a framework for research on biogeochemical processes, such as denitrification in riparian zones, for example.

GEUS is solidly in the international arena, conducting and participating in studies in Europe, Asia, and Africa, primarily. There is a clear emphasis on technology transfer and on applying research methods – particularly on topics of climate change, data management over various scales (especially in data-poor areas of the world), and in drinking water quality. There is a focus on a pan-European groundwater recharge map, presumably in support of a groundwater

model for the same region. Managed aquifer recharge is a smaller topic of interest in Denmark but is still important to GEUS and its work in South Africa, India, and China.

Other activities, as indicated in the most recent work plan for GEUS, include: Data extractions for monitoring, assistance to EPA, research on buried glacial valleys, groundwater mapping, groundwater condition assessment, expanded monitoring systems for stable isotopes of water, fate and transport of contaminants, national nitrate model hydro-stratigraphy, testing a new High Resolution Mass Spectrometer (HRMS) with VAP samples, discussions with EPA on the use and application of the HRMS output, publishing biocide research, targeted and non-targeted methods development, and emerging contaminants identification.

Observations

Groundwater resources is a large and encompassing topical area for the GEUS. By nature, it interfaces with modelling and geochemistry topical areas and is inextricably linked to those activities. It includes areas of rich research as well as more operational activities, such as groundwater and water quality monitoring. Annual reports provide an outlet for identifying current conditions, trends, and new research opportunities. This is in part due to the combining parts of a larger set of topical areas, discussed in the previous review of research that included groundwater monitoring, mapping, the hydrologic cycle, water quality, water and environmental technology, and water resources management.

From the presentations, it follows that GEUS depends on EPA for national monitoring to understand groundwater quantity and quality through study of those data. Because the focus of this review is on research, there was little effort devoted to the monitoring itself, protocols, and associated quality control measures. It is assumed that those elements are reviewed elsewhere. Nevertheless, a large database of water resources information, the Jupiter database, houses information collected by the GEUS and agencies and entities outside of GEUS, which is both a benefit and a potential liability in terms of data quality and integrity. Some additional observations from the review are described below.

GEUS has a database of high-quality national data on water that can be coupled with many other kinds of data (such as national human health data) providing unique opportunities to test hypotheses and to help other external partners test and verify hypotheses where such data sets are more limited.

The national nitrate hydro-stratigraphy model update using stochastic methods may improve understanding over the deterministic model (DK-model) and can be evaluated for uncertainty. Interest by GEUS (and now EPA) in understanding potential threats from emerging contaminants to groundwater resources: this led to a strategic purchase of a high-resolution mass spectrometer for non-targeted analysis of emerging contaminant compounds.

Water-level monitoring at GEUS consists of a limited number of sites managed directly by GEUS with real-time data collection and transmission to the Jupiter database.

National water quality monitoring is continually evaluating its monitoring plan and adding value to the quality of the overall data set and the ability to make novel discoveries with those data.

Scientific quality

Scientific quality of research at GEUS appears to be very high with demonstrable knowledge of state-of-the-art methods for data collection and scientific analysis. This enables sophisticated interpretation of data as well as meaningful and relevant conclusions that can help a wide array of customers / stakeholders. Scientific evaluation of monitoring data benefits from having a high-functioning, collaborative environment across organizational boundaries. There appears to be a strong output of journal papers within high-impact journals. Efforts to engage

the scientific community to improve science at GEUS is apparent (attendance at conferences, meetings, workgroups). Understanding of water resources problems in Denmark is contextualized by interest and understanding of the global water resources environment, which is limited to specific areas of the globe. Real-time water-level data across Denmark are state-of-the-art and integration of IoT and high- quality low-cost sensors provide context for the vast amount of water level data in Jupiter.

Recommendations

Because of the focus on high-quality and state-of-the-art research, there still may be many opportunities to gain relevancy and more quickly by increasing collaborative opportunities outside of GEUS. Thus, it may be possible to make more of an effort to engage a greater number of collaborators in other parts of the world as well as within Denmark, through conference participation (presenting and chairing sessions). This also may make possible the opportunity to use research from other areas to help put Denmark-specific research into a more international context.

If not already done, represent a generalized model of redox hierarchy to inform contaminant occurrence and transport; Machine Learning (ML) models can help. For example, use of ML or other models of existing chemistry data to inform finer-scale redox status. This may also provide additional opportunities to represent physical and geochemical processes with surrogate variables so that they can be represented in stochastic models, interpreted in the context of the processes they represent, and ultimately up scaled to the DK-model.

Additional work in redox boundary mapping could lead to consideration or discussion of the development of redox boundary-based policy for location of groundwater abstraction for drinking water—for example, locating water supply wells in anoxic zones of aquifers where nitrate contamination is an issue.

Consider an outreach coordinator position specifically for the Water Resources Program and possibly other programs. This is a way to support scientists and share some of the burden of dissemination (research translation). Many organizations from other governmental agencies to academia make good use of such positions. Although the department heads in the Water Resources Program at GEUS handle this task internally currently, there is great power in having this task operationalized through a specific hired position.

In Water Resources, it was not clear whether there is a formal process or program to incorporate water level-data from others into the web-based water-level monitoring network grundvandsstanden.dk. If not, this could be accomplished by developing policy for measurement that includes elements such as certification of measurement devices, quality control of data, integrity testing of wells that is at the same level as that done at GEUS. Such a program can greatly enhance the quality of data for all and improve data technical defensibility. In this way, and if not already being done, the Jupiter-based real-time water-level data could potentially be augmented with “furnished data”; furnished data are data collected by others but that meet all the standards for data collection, quality assurance, and real-time delivery to the data base.

Although not entirely clear, it appears that there has been a de-emphasis on the collection of bacteriological data as part of the monitoring done by the EPA and recommended by the GEUS. If true, consider the re-introducing of more bacteriological testing of wells in Denmark to test for changes over time and to assess potential unanticipated effects related to climate change.

Determine whether co-locating GEUS staff in EPA or other (Health?) offices to help facilitate better data collection to benefit both agencies is useful. Perhaps this is not an issue as there appears to be excellent collaboration amongst a variety of agencies, yet nuance in operation

and culture often can be a barrier to achieving national goals, and one way to improve interaction is to have staff from GEUS physically locate within the offices of sister agencies. This can foster improved understanding, while at the same time signalling a deeper interest in common or shared mission-related goals.

GEUS is in a unique position to work (more) on topics like drought, saltwater intrusion, and climate change in general. Again, consider how changes in climate (and recharge to groundwater) can affect redox boundaries and therefore the accuracy (and transient nature) of the redox boundary mapping. This could impact and improve the ability of researchers to more accurately represent the fate and transport of contaminants from sources in the urban and agricultural environment.

GEUS Water Resources Program

In this section, the panel comments on overarching topics and conditions that are common to all three themes and may impact performance and future strategies. The information presented here is based on the various documents made available to the panel in an information package before the site visit, the presentations about GEUS' tasks, structure and organisation, previous evaluations, background of the evaluation, a Water Resources Program overview, international projects, bibliometrics, and outreach.

In addition to the scheduled events, the panel asked for individual meetings to discuss questions that had come up during the first days of the site visit. Meetings were held with the managing director to discuss GEUS vision, strategy and future plans and with one department head, to discuss economy and allocation of resources. A meeting with the three department heads focused on strengths, weaknesses and plans for the individual departments and some clarifications of open questions.

The panel also performed interviews with 13 GEUS employees, where the selection of interviewees aimed at covering all staff categories active in research (PhD student to professor), as well as all themes and research topics. These interviews were regarded as very valuable to clarify questions that had remained unanswered thus far and to understand the structure and organization of GEUS.

Lastly, the panel was very grateful for the opportunity to have informal meetings and conversations during lunches, dinners, coffee breaks and the walking excursion.

Organization and structure of the Water Resources Program area

Observations:

At GEUS, water research is primarily conducted across three distinct departments. The three research themes considered by this evaluation do not strictly align with the departmental structure and the division into these departments is not mirrored in the research activities. The panel views this as an advantage. This structural arrangement fosters an environment of flexibility and openness, encouraging cross-theme and cross-departmental collaboration. Researchers seem to be free to explore and interact across different themes and departments and they make use of this opportunity. This results in low internal competition and diminishes the impact of any economic or organizational barriers that might typically exist between departments. In essence, this approach to research organization at GEUS promotes a dynamic and collaborative atmosphere, enhancing the quality and breadth of the research output.

Recommendations:

The panel felt that the connections and overlaps with other research areas, namely geophysics and climate could be presented (and used) more efficiently. For example, the previous evaluation pointed out that *"GEUS is a world leader in using airborne EM surveys and in integrating the resulting geophysical data into geological maps"*. Another example would be

greenhouse gas emissions in relation to the nitrogen model. These overlapping areas should be highlighted more to demonstrate and use the potential for interdisciplinary research outputs.

The role and tasks of the “SURFACE” department located in Aarhus is still a bit unclear, which may be a result of its newly performed reorganization (merging two previous departments). Overall, an organigram explaining the organization’s structure much clearer could be helpful for outside viewers. The Aarhus department may require special attention in this respect.

Staff

Staff numbers and a meaningful distribution to staff categories and research activities is an essential prerequisite for a research organization to be efficient and successful. The proportion of senior, leading research staff, mid- and early career technical and administration staff is decisive for strategic development, acquisition of external funding and not the least performing and publishing the research.

Observations:

The GEUS Water Resources Program has a diverse range of employment categories with two distinct career paths with researchers and advisors. While the distinction is not always clear from looking at tasks and scientific activities, the panel feels that the two paths create clear expectations and roles and are thus an advantage.

A concern is the lower female representation in higher positions, with none out of the two professorships held by women and only about 38% of senior researchers being female. In particular, the hydrology department had no female senior researcher or professor in the period from 2015-2022. These gender aspects had not been adequately addressed by leadership, apart from in personal communication, which suggests a pressing need for a more formal, systemic approach. The panel was told that GEUS has a Gender Quality Policy as well as working group. Gender Equality is an issue that has been mentioned in several staff interviews and informal communications.

The share of international staff members is, with 14 out of 46 in total in the expected range, however, considerably lower in the leading positions. We could not identify any international professors, and six out of 22 senior researchers are internationals. The national scope and the necessity to perform tasks that require communication in Danish provide a reasonable justification, but an increase of the international staff, also in leading positions may be a key to increasing international collaboration and leadership. The international staff felt mostly well integrated in the organization, even if language and cultural barriers were mentioned.

In the recent past, there has been a reduction in research staff numbers which may or may not be explained by a reduction of incomes, reorganization, or changes in internal distribution of resources. The panel only had access to data on incomes from 2020 to 2022, showing a decreasing trend in total annual turnover, but otherwise a quite stable distribution of incomes on different funding sources.

The number of PhD students employed in the program area has decreased over the past years, while the number of postdocs had been increasing for some time. Many more PhD students are employed at Danish Universities and co-supervised by GEUS researchers. Some researchers at GEUS regard the lack of possibilities to hire and be main supervisor as a disadvantage, while others consider being co-supervisor of a PhD student at a university as an equally good opportunity. There is no outspoken strategy for PhD students but a general wish to have more. Overall, PhD students and postdocs are underrepresented in relation to senior researchers. While co-supervising PhD students at universities may be a better approach than employing them at GEUS, hiring more postdocs could be beneficial for fostering international collaboration. GEUS should be a very attractive place for postdocs. The hiring of PhD students

or short-term postdocs may also help to alleviate a problem that was mentioned on several occasions. It appears that short-term hiring of researchers for defined projects is difficult, leading to phases during which permanent staff is overallocated and staff to work on acquired projects is missing. As also stated in the next section (on economy), accepting projects that lead to an over allocation of specialized staff should be avoided if there is no possibility for short-term hires.

Professors at GEUS could play an important role in integrating PhDs and university postdocs in the research efforts of GEUS, particularly if they have the right to teach and supervise PhD students at a partner-university. Also, they could provide a link for GEUS postdocs to get involved in teaching at the university. That would give these postdocs the opportunity to build a teaching portfolio and improve their career chances in the academic field.

Recommendations:

Firstly, we recommend a concerted effort to increase the number of female senior research staff. This could be achieved through specific recruitment drives, mentoring programs, and gender-inclusive policies. Secondly, a clear strategy for PhD students should be developed. PhD students provide flexibility and are optimal for certain types of work, not to mention that they represent a more cost-effective resource. It is evident that young scientists are well supported by GEUS. We recommend continuing these efforts by identifying 'high potentials' among the young and mid-career researchers and senior researchers, and make sure that they get exposure to the international field by supporting their presence at international events (e.g., conferences, workshops, panels) and by fostering scientific exchange by supporting research visits at international research institutions with similar goals and structures (e.g., EAWAG, Switzerland). Finally, we recommend to further train such high-potentials in research management. To strengthen the efforts of GEUS to link 'Professors' with partner universities, we recommend negotiating with partner universities in order to give GEUS professors full professor status. This should involve the right (but not necessarily the obligation) to independently advise graduate students and to teach. Moreover, it is recommended to simplify the process for hiring extra short-term researchers, to improve international recruiting, and to improve the environment for international employees.

Overall, it may be beneficial to put more efforts into analysing staff numbers and composition: distribution to be able to make more effective use of resources and to make the organization / program more successful, sustainable and resilient. It seemed that the leadership was not always fully aware of some of the developments the panel observed and that consequences had not been analysed.

Economy, allocation of resources

Observations:

GEUS financial resources consist of two major parts, basic funding from the government and external sources. Ignoring interannual fluctuations each part contributes with roughly 50%. The largest share of external funding with around 30% stems from other public institutions (e.g., the Danish EPA). EU and national funding organizations contribute with around 20%, private funders and companies stand for 3-4%.

Basic funding is predominantly allocated to selected staff categories such as leadership and administration. It is also directed towards premises, other essential services, and selected research activities. Such selected research activities include a number of internal grants, that researchers can ask for to develop ideas, write publications, and initiate collaboration and proposals. A considerable fraction of the basic funding is also used for co-funding of externally funded research projects, which do not cover overheads or only a smaller fraction of these.

Research staff is largely supported by a mix of internal and external funding. External funding is obtained from a variety of sources. Partly in competition through grant proposals to national and international (here foremost EU) funding organisations, partly commercial activities, services paid for by private companies, and finally the largest share, from other public institutions (e.g., EPA or the Agricultural agencies).

The dependency of research staff salaries on external funding creates a situation of apparent lack of job security. Employments of researchers and research staff apart from PhD students and postdocs are usually permanent (i.e., not time limited) but need to be ended when no further external funding is obtained. This situation, however, is not perceived as problematic, instable or insecure by neither leadership nor employees. Success rates in grants received in competition are high and the funding coming from other public institutions such as EPA is described as reliable and stable.

More often it is described as an issue that too many projects are acquired, leading to a situation where staff is overallocated. Lack of staff may limit performance, rather than financial constraints. This situation has led to double-booked researchers and a shortage of short-term hires to work on new projects, indicating an operational bottleneck that could impact research productivity and innovation.

GEUS, as described in the introduction, has the task of doing research on the highest international level, but also must provide services (monitoring, data management, consulting). The latter activities are sometimes described as “mandatory” and perceived as an obstacle to performing (and publishing) research. This, however, is not consistent throughout the organization. The panel also heard statements “there are no mandatory tasks”. Overall, it was not always clear what mandatory tasks are. A large part of these seems to be tasks commissioned (and paid for) by other public agencies and thus be part of the external funding required to pay salaries. We also understood that “mandatory” tasks more often are performed by advisors than by researchers. The hydrological modelling themes seems to be less engaged in mandatory tasks than the other two themes.

Recommendations

Based on these findings, we recommend a more strategic approach to project selection and staffing. Specifically, when staff time is a limiting factor, it is recommended to concentrate on projects that align closely with the organization's strategy and vision. We have noticed a few instances where this approach could have been beneficial. One of the presented projects focused on water treatment, which may be regarded as being outside the scope. On the other hand, convincing arguments were produced to motivate this specific project.

Additionally, it would be advantageous to establish mechanisms that facilitate the hiring of short-term staff. This would ease the workload of current researchers, enable the organization to take on new projects, and contribute to a more flexible and responsive research environment.

Being a large national research organization with outstanding access to data and models, GEUS could operate even more in the international arena and assume a leading role, e.g., in nationwide hydrological modelling in Europe. In the context, there is more potential for international collaboration and EU funding than currently exploited.

The panel feels that having these mandatory tasks contributes to creating what we call an asset, rather than an obstacle to performing research. Data and tools are created, and networks and funding opportunities are created. Also, mandatory tasks very often seem to include a research component. What is important is that GEUS staff gets the opportunity to publish even such research that may not be mandatory.

In the presentation of research activities, it would have been desirable if the distinction between free research and mandatory tasks would have been more consistent and clearer, although we acknowledge that sometimes they are quite interrelated.

Publication output

Observations:

The work produced under the Water Resources Program is consistently published in reputable journals within the field. The overall publication output per researcher aligns with what is typically expected from a top-tier research organization, as evidenced by the number of papers and the development of the h-index value.

The panel was presented a list of publications listed in the Web of Science (WoS) as well as a bibliographic evaluation including journal impact factors, citations, and development of individual h-values over time. In addition, the panel performed some own analysis using the Scopus database. Aside international journal publications, GEUS is also active in publishing in an own journal/series and publishes many reports (in Danish). The panel has only looked at the international publications.

The average impact factor of the journals, GEUS water researchers publish in, is around six, which is excellent in the water field. There has been a strong increase in impact factors since the last evaluation, yet this shows rather a general trend in the development of journal impact factors than a change in the publication strategy.

Most of the publications from GEUS, including those from the Water Resources Program, are co-authored with researchers from Denmark, that is from Danish universities or other Danish public organizations. This is followed by co-author affiliations from Sweden and Norway, followed by Germany and the Netherlands. However, it's worth noting that less than 10% of the collaborations are with overseas partners. This information is based on the result of an ad hoc analysis of GEUS publication output in Scopus.

A "publication fund" (100 hours to work on a publication) was frequently mentioned as being helpful to publish project results under otherwise time limited conditions. This is an effective strategy that should be continued and extended. It was also mentioned that it is difficult to find the budget for Open-source publications. The panel regards it as crucial to make open-source publishing possible for all publications.

In summary it can be concluded that the publication output, according to all available indicators, is excellent and has increased and improved since the last evaluation period, in particular when considering that the number of active researchers (i.e., publishing) staff has slightly decreased. Normalized with full time equivalents ("academic years"), a quite strong increase in total number of publications can be observed. At the same time the number of first authored paper per research / year has remained relatively stable of the past 15 years. This indicates that GEUS authors follow a general trend where overall more papers with more co-authors are published while the individual output as main author remains the same. It is difficult to interpret this as a positive or negative development.

Recommendations:

While we don't advocate for an excessive focus on bibliometric data, we believe a more detailed analysis could be beneficial for GEUS. For instance, understanding co-author affiliations could shed light on potential areas for expanded collaboration. A closer look at highly cited papers could highlight the most impactful research themes. Analysing who cites GEUS research and which aspects of the work are cited, could provide insights into the broader impact of the research and where to focus future research efforts. Lastly, tracking citation trends over time, both immediate and long-term, could reveal the sustainability and continued

relevance of the work done at GEUS. These recommendations, if implemented, could be used to enhance the strategic approach to research at GEUS.

The "publication fund" provides a great opportunity to get results published. It is very likely that extending this fund would further increase publication output.

Funds for open access publishing are crucial.

Collaboration

Observations:

GEUS researchers have an excellent national network, both to other research organizations, other public agencies, and private companies, and make very good use of it. The international network is also very good, but it is obvious that more focus is on national collaboration.

Recommendations:

The panel sees significant potential for further international collaboration and securing more EU funding than what is currently being exploited. Internal collaboration exists within the organization, and it would be beneficial to make these collaborative efforts more visible to promote further synergy. In some fields, in particular national hydrological modelling, GEUS has a unique position and should not only seek international collaboration but strive to assume a leading and coordinating role among European countries.

Moreover, the collaboration with universities, particularly concerning PhD students, adds a dynamic academic facet to GEUS's operations. However, it was noted that partnerships with the 'Nature and Climate' program area could be further amplified, offering broader interdisciplinary insights and possibilities.

GEUS has robust collaborative relationships with various universities, which lays a foundation for further academic and research cooperation. To further enhance its research and impact, it would be beneficial for GEUS to strengthen international and interdisciplinary collaboration.

The panel sees both a large potential for and a current lack of collaboration with social scientists. The collaboration between natural and social scientists offers robust problem-solving approaches. Natural scientists provide understanding of the physical world, while social scientists offer insights into human behaviour and societal structures. This combination yields sustainable, equitable solutions that integrate scientific accuracy with societal considerations, addressing real-world challenges effectively.

Outreach

Observations

A significant amount of work is being done in this area. However, it's uncertain whether these efforts are being conducted in a strategic manner which becomes particularly important when dealing with sensitive or conflict-prone topics that require careful communication.

Recommendations:

Based on these observations, we strongly recommend the further development of a clear and robust outreach strategy specific to the Water Resources Program. This strategy should define the organization's outreach objectives, target audiences, key messages, and the channels for conveying these messages. Having such a strategy would ensure that all outreach activities align with and contribute towards the organization's overall goals.

In addition, it may be beneficial to appoint an outreach coordinator. This role could manage and monitor the outreach activities for the water disciplines, ensuring they are effectively implemented and that the organization's messages are consistently and accurately conveyed. Additionally, this would provide an opportunity for enhanced coordination with the GEUS Press and Communication Department.

Finally, continued effort should be made to improve the visibility of water science at GEUS. This could be achieved through various means, such as enhancing the organization's online presence, actively engaging with the media, participating in public events, and building relationships with other organizations and key stakeholders in the field. These steps, combined with a strategic approach, would significantly amplify the outreach impact of water science at GEUS.

Work environment

Observations:

The panels impressions in this field have been largely positive. It appears that the majority of GEUS employees are highly satisfied with their workplace, confirming the organization's good culture and values. GEUS seems to have established a reputation as a desirable place to work. Further strengthening this positive perception is the relative absence of stress and conflicts reported among staff. The high degree of flexibility and autonomy provided at all levels within the organization contributes obviously to a good work environment.

A good work environment is a substantial asset for any organization. It not only boosts employee satisfaction and productivity but also aids in talent attraction and retention. Given this, the positive work environment at GEUS is a significant strength.

Recommendations:

Nevertheless, while the overall work environment is positive, we've noted some gender-related issues that require attention. It's crucial for GEUS to address these matters to ensure a truly inclusive, equitable, and harmonious workplace for all employees. This would only serve to further enhance GEUS's reputation as a top-tier employer and research institution.

Concluding remarks

The previous evaluation panel concluded their report with an overall evaluation section containing observations, statements on scientific quality, and recommendations. In the present evaluation report, the panel has decided to take a different approach. We feel that the contents of the previous sections do not need to be summarized and repeated. Instead, we conclude with summarizing our overall impression of the work being done its scientific quality: The Geological Survey of Denmark and Greenland (GEUS) has a variety of roles and responsibilities. It aims to be leading in international research while simultaneously being active on a national level in monitoring, data management, consulting, outreach, and communication with the general public. By default, the geographical scope of GEUS primarily encompasses Denmark and Greenland. While research in other parts of the world does occur, it is considerably less frequent than the research conducted in Denmark. The specific tasks and roles assigned to GEUS, and the limited geographical scopes are setting unique boundary conditions for GEUS' research, distinguishing it from other research organizations that have more freedom to decide on their research focus and location. At the same time, the focus on research within Denmark also creates unique opportunities. Through this focus, the availability of data and models in the country has become exceptional, and the established network and collaborations with other Danish agencies, municipalities, and universities provide excellent opportunities for in-depth and comprehensive research. In summary, the GEUS Water Resources Program manages the different roles and tasks exceptionally well and makes excellent use of its opportunities. GEUS is recognized as one of the leading geological surveys in Europe. Within its Water Resources Program, GEUS performs internationally recognized research at the highest level. GEUS is well positioned to leverage capabilities with other survey organizations and to provide direction and leadership across Europe.

Programme for the Research Evaluation

GEUS' Programme area 2 – Water

18 – 21 April 2023



April 2023

Tuesday, 18 April

9:00 *Welcome, coffee/tea.*

The panel members introduce themselves.

9:15 Introduction to GEUS and the Research Evaluation, General introduction to GEUS by Managing Director *Flemming Larsen*

9:45 Uptake of recommendations from the previous evaluation by Managing Director *Flemming Larsen*

10:00 Introduction to and discussion on the role of the evaluation panel members, on the mission programme, the outcome of the mission, and the time frame for the evaluation etc.

10:20 Introduction to programme area 2 – Water, by Heads of Departments *Claus Kjøller, Heidi C Barlebo* and *Torben Bach*

10:50 Questions

11:00 Coffee break

Presentation of main research areas

11:15 Introduction to 'Hydrological and hydrogeological modelling'

11:20 The Danish National Water Resource model by Professor *Simon Stisen*

11:35 Hydrogeological modelling by Senior Researcher *Anne-Sophie Høyer*

11:50 Modelling of nitrate transport by Senior Researcher *Anker Højberg*

12:05 Integration of satellite data into hydrological modelling by Senior Researcher *Julian Koch*

12:20 Climate change and hydrological modelling by Senior Researchers *Ida Seidenfaden* and *Torben Sonnenborg*

12:35 Questions and discussion

13:00 Lunch

14:00 Introduction to 'Groundwater quality'

14:05 N-reduction in groundwater by Senior Researcher *Hyojin Kim*

14:20 Geogenic compounds in groundwater by Senior Researcher *Jolanta Kazmierczak*

14:35 Transport of microorganisms in fractured clayey tills by Professor *Jens Aamand*

14:50 Fate of pollutants in topsoil and subsurface soil by Senior Researcher *Anders Johnsen*

15:05 Treatment of polluted groundwater by Senior Researcher *Christian Albers*

15:20 Questions and discussion

15:45 Coffee break

16:00 Introduction to 'Groundwater resources'

16:05 Groundwater resources and health by Senior Researcher *Birgitte Hansen*

- 16:20 Groundwater resources quantitative management by Senior Advisor *Hans Jørgen Henriksen*
- 16:35 Groundwater quality protection by Chief Consultant *Lærke Thorling*
- 16:50 Groundwater - surface water interactions by Senior Researcher *Bertel Nilsson*
- 17:05 International groundwater resources activities by Senior Researcher *Ida Seidenfaden* and Professor *Simon Stisen*
- 17:20 Questions and discussion
- 17:30 Review of the day, plans for the evaluation
- 17:40 *Leaving GEUS for dinner (18:00; Panel, Directors, Head of Dept.)*

Wednesday, 19 April

- 9:00 Recollecting Day 1
- 9:15 Strategy and visions for the future introduced by Heads of Dept. *Claus Kjøller, Heidi C Barlebo and Torben Bach, followed by short presentations:*

5 min presentation of present/future activities; break for coffee around 10:00

- Urban hydrology and nature-based solutions by Senior Researcher *Jacob Kidmose*
- Greenhouse gas emissions and hydrology by postdoc *Tanja Denager* & Senior Researcher *Julian Koch*
- Greenhouse gas emissions and groundwater geochemistry by Senior Researchers *Hyojin Kim & Birgitte Hansen*
- Reactive transport modelling by Postdoc *Chris Henri*
- Probabilistic data integration by Researcher *Rasmus Bødker Madsen*
- Land-sea interactions by Senior Researcher *Peter Sandersen*
- Hydrologic real time modelling and forecasting by Researcher *Raphael Schneider*
- Visibility and accessibility of research output by Hydrologist *Maria Ondracek* and Specialist consultant *Lars Trolborg*
- Introducing new water quality analytical methods by Senior Researcher *Nora Badawi*
- Emerging contaminants by Senior Researcher *Ulla Bollmann*
- MAR – Managed Aquifer Recharge by Senior Researcher *Christian Albers*
- Circular economy and water quality by Senior Researcher *Case van Genuchten*
- PURE GROUNDWATER FOR THE FUTURE - A GEUS campaign by Professors *Jens Aamand* and *Simon Stisen*, and Senior Researchers *Birgitte Hansen* *Christian Albers*, *Klaus Hinsby* and *Rasmus Jacobsen*.

Discussion and questions

11:15 Coffee break

- 11:30 Bibliometric analyses, by Professor *Simon Stisen*
- 12:00 Outreach, by Head of Department *Claus Kjøller*

12:30 Lunch at GEUS with the staff members from the sessions today

- 13:30 Evaluation panel reflects on the day and decides which staff members to interview Thursday.
- 14:00 Laboratory visit.

15:00 Coffee break

- 15:30 Discussion including reflections on the day.
- 16:00 The panel starts working.
- 17:30 End of day 2.

No pre-arrangements for the evening

Thursday, April 20

9:00 Preparation of draft report and interviews with staff members selected by the evaluation panel.

12:00 *Lunch at GEUS*

13:00 Preparation of draft report, preparation of debriefing conclusions.

17:00 needed by panel.

18:00 *Leaving GEUS for dinner (18:30; Panel, Head of Dept., Professors)*

Friday, April 21

9:00 Preparation of final draft report.

12:00 *Lunch at GEUS.*

13:00 Debriefing, presentation of main conclusion, incl. a draft report (a date for the final report is agreed).

14:00 End of research evaluation mission.

**EVALUATION OF GEUS' RESEARCH AND
RESEARCH OUTREACH ACTIVITIES IN**

Water Resources

(GEUS' PROGRAMME AREA 2)

1. Terms of Reference - The Evaluation Panel

According to the Executive Order from the Danish Ministry of Climate and Energy of January 20, 2009 on Evaluation of Research conducted by the Geological Survey of Denmark and Greenland (GEUS), the GEUS Board has decided that the next research evaluation will cover the Water Programme Area.

Objectives

The panel is asked to undertake an evaluation of research and dissemination activities to identify strengths, gaps as well as needs for amendments and improvements in relation to GEUS' strategy and mission within the GEUS Programme Area 'Water Resources'. The evaluation concerns the period 2015-2022 and covers the following overall themes and research disciplines:

- Groundwater resources
- Hydrological and hydrogeological modelling
- Groundwater quality

The evaluation must be based on a thorough examination of selected GEUS publications and reports in addition to a visit to the premises of GEUS in Copenhagen.

Tasks

The task of the panel is to evaluate the research and the research outreach activities based on:

- Publications, reports and other relevant material produced over the period 2015-2022
- Presentations by GEUS researchers
- Interviews with GEUS' researchers and management
- Visits to laboratories and work facilities at GEUS.

In order to improve GEUS' ability to fulfil its main mission within the programme area seen in the perspective of the GEUS' statutes and general mission, the evaluation need to:

- Identify areas of high-quality research
- Identify areas where the research and facilities of GEUS could be strengthened
- Provide comments and suggestions as to strategic changes, amendments, and improvements to GEUS' activities within the programme area.

Output

The evaluation panel must report their observations and conclusions to the management at a debriefing meeting followed by delivery of a written draft evaluation report before departure.

Based on possible clarifying comments, in order to prevent misunderstandings, the evaluation panel must deliver the final draft report in due time to be presented to the GEUS Board.

Time schedule

The evaluation panel visits GEUS for the evaluation (four days), including preparation of the final draft report. The evaluation will take place 18–21 April 2023, and the final report must be delivered to GEUS no later than 1 June 2023.

The findings in the final report will be presented to the GEUS Board in September 2023.

Upon accept by the board, the final report will be presented to the Minister of Climate, Energy and Utilities, and then published.

Based on the findings, an implementation plan will be developed by the programme area staff and presented to the GEUS Board in December 2023. The Board decisions are expected to be implemented from the beginning of 2024.

2. Confidentiality

The experts must not disclose information gained in their capacity of being a member of the evaluation panel to any third party.

3. Expenses and compensation

GEUS will reimburse all reasonable expenses related to the visits of the experts to the institution. Additionally, GEUS will compensate each expert for his time paying a lump sum of DKK 20,000.

Copenhagen, September 2022

Flemming Larsen
Managing Director