DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2015/27

Scientific evaluation of programme area 2 Water resources (2007-2014) at the Geological Survey of Denmark and Greenland (GEUS)

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1. THE EVALUATION PROCESS

1.1 Introduction

The evaluation panel consisting of

Prof. Janet Hering, Eawag, ETH Zurich, EPFL, Switzerland (***Chair***)

Prof. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota, USA

Prof. Frans van Geer, TNO, Utrecht University, The Netherlands

Prof. Willy Verstraete, University of Ghent, LabMET, Belgium

Dr. Clifford Voss, US Geological Survey, USA

was given the following task:

The panel shall undertake an evaluation of research and dissemination activities to identify strengths, gaps and needs for amendments and improvements in relation to GEUS' strategy and mission within the GEUS Programme Area 'Water Resources'. The evaluation concerns the period 2007-2014.

The panel is asked to make its evaluation on the basis of:

- Publications, reports and other relevant material produced over the period 2007-2014, both years included,
- Presentations given by GEUS scientists, and
- Interviews with GEUS' management staff and scientists, and visits to laboratories and work facilities at GEUS.

Specifically, the panel is asked to:

- Identify areas of high quality research,
- Identify areas where the research of GEUS should be strengthened in order to meet GEUS strategy, and
- Provide comments and suggestions as to strategic changes, amendments, and improvements to GEUS' work within the programme area, in order to improve GEUS' ability to fulfil its main mission within this programme area seen in the perspective of the survey's statutes and general mission.

1.2 The context for research at GEUS

GEUS is a research institution which has the mandate 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*" and "*must also carry out mapping, monitoring, data collection, data management and communication about these matters*." [1] In addition GEUS "*is a national geological data centre, and … makes data and knowledge available to authorities, educational institutions, enterprises, individuals, etc.*" These mandated national responsibilities constitute a set of core, ongoing activities

[1] Act no. 536 of 6 June 2007

(herein referred to as ***mandated tasks***) that provide not only the context for GEUS's research but also a unique platform for research activities.

GEUS is also mandated to conduct research at the highest international level and to contribute to undergraduate, graduate and PhD programmes in areas in which GEUS has special expertise. There are four key synergies within GEUS that can benefit its research activities:

- Research projects can build on observational data collected through mapping and monitoring activities, which are made accessible through GEUS's databases,
- Models developed and supported by GEUS (in particular, the National Water Resources (DK) Model) can stimulate and facilitate interdisciplinary, collaborative research,
- Research gaps identified through advisory and/or consultancy projects can stimulate new lines of research, and
- GEUS provides a capacity for long-term engagement (e.g., at field sites and/or in engagement with stakeholders) that can support individual research projects.

Thus researchers at GEUS have the opportunity not only to position themselves uniquely in the research landscape (i.e., vis-à-vis research at Universities) but also to attract collaborative project partners both nationally and internationally.

At the same time, it must be recognized that there are also some tensions between GEUS's research activities and GEUS's fulfilment of its responsibilities for its mandated tasks. These tensions derive from two principal bases:

(1) Senior researchers at GEUS are under increasing pressure to acquire external funding. Success in funding acquisition is often closely linked to research productivity, which puts pressure on researchers to increase their output of scientific publications.
(2) Completion of mandated tasks demands substantial time and effort but generally does not lead (directly) to scientific output. Thus emphasis on scientific output creates a disincentive to invest time and effort in mandated tasks.

These observations provide the context for the panel's evaluation and recommendations.

2. DETAILED EVALUATION OF ACTIVITIES

2.1 Groundwater Monitoring

Activities

Activities in this area were presented by Laerke Thorling and Walter Brüsch. A clear distinction was drawn between monitoring of pollution associated with point sources (for which the Regions are responsible) and GEUS's responsibilities relating to diffuse sources. GEUS serves as the specialist data centre for groundwater and wells, providing expert advice on monitoring, preparing annual status reports and providing guidance and technical instructions. GEUS also manages the Danish Pesticide Leaching Assessment Program (PLAP) in which pesticide leaching is monitored at five test fields. The Waterworks are responsible for sampling and data collection for abstraction wells used for drinking water supply and for tracking abstracted volumes. The EPA and Nature Agency are responsible for monitoring groundwater quality based on samples from dedicated monitoring well (GRUMO programme). The Nature Agency also collects data on groundwater levels. Data from abstraction and monitoring wells are submitted to the Jupiter database, which is maintained by GEUS. The panel also visited the Geological Well Sample Laboratory; operations were described by Henrik Granat, who also provided a brief introduction to the Jupiter database.

The panel noted that the boundaries between the research topic Groundwater Monitoring and the other research topics are not very distinct. The examples presented for the topic Groundwater Monitoring overlapped substantially with other research topics, particularly Water Quality and Hydrological Cycle. Also the points presented for future research would have been equally appropriate for Groundwater Mapping, Hydrological Cycle or Water Quality.

For clarity, the panel defines Groundwater Monitoring as all activities directly related to the observation of the dynamic behavior of groundwater levels and groundwater quality. This includes design of monitoring strategies, collecting data, data quality control, data storage and reporting. Thus the interpretation and the analysis of the data is assigned to other research topics.

Many parties are involved in groundwater monitoring, on the national as well as the local level. GEUS is not an 'owner' of monitoring networks nor of a groundwater monitoring program. The monitoring activities are carried out in the framework of the mandated responsibilities of the Geological Survey of Denmark, as well as within the framework of specific monitoring programs. It is useful to draw a distinction between four different roles:

(1) GEUS develops strategies and writes guidelines for monitoring programs. GEUS advises the 'owner' of a monitoring program on monitoring network design, observation frequency and data handling, in particular at the national level for example for the EPA. GEUS provides sound scientific knowledge, but the decisions about the actual monitoring strategy are taken by the 'owners' of the monitoring program.

(2) The observed groundwater level and concentration data are stored and maintained in the data base Jupiter. Some of these data are collected and analyzed by GEUS itself, but a substantial part of the data is submitted by third parties.

(3) GEUS writes annual reports on the data. Data analysis like the interpretation of chemical status and trend analysis is done in combination with other research topics.

(4) For some programs, GEUS performs field work and lab analysis, including water sampling and drilling, and data quality control.

Groundwater data from the Jupiter database are used in many further studies and analysis, including groundwater modeling and studies on water quality processes. The groundwater data are used by GEUS researchers as well as by external stakeholders.

Observations

The research topic Groundwater Monitoring has primarily an operational character and does not constitute scientific research as such. It is, nonetheless, a very important source of information for other research topics, such as the Hydrological Cycle and Water Quality. Although Jupiter is an open database, it certainly is an advantage for other research topics that GEUS maintains and manages Jupiter. For example, the annual reports can provide new ideas and insights for other research topics.

In the previous review, the corresponding research topic was Groundwater Quality Monitoring. Although the broader title Groundwater Monitoring includes water levels, there is strong emphasis on quality issues. This might be due to the fact that the presentations were about research using the data rather than research related to monitoring as an activity.

Typically the monitoring programs have a limited duration, after which they are re-evaluated. On one hand, it's good to evaluate and up-date the monitoring programs regularly. This provides an opportunity to reconfirm the added value of the monitoring program. On the other hand, continuity for long-term monitoring is not guaranteed. In practice, however, changes to the monitoring programs have been limited.

Guidelines and annual reports are all written in Danish. Only very few publications are in English. Therefore innovations regarding monitoring strategies have only a limited exposure in the international scientific community.

In some monitoring programs, dating of the water samples is an integral part of the monitoring; this is not common in many other countries. Dating groundwater is of great help in analyzing the effects of groundwater management, for example in the assessment of trend reversal.

The field work and lab analysis are not done entirely by GEUS. Many other parties collect and up-load data to Jupiter. Quality control is the responsibility of the parties that collect the samples and do the laboratory analyses. For some years, GEUS has not had any role in the quality control of the data from third parties, apart from making comments in the annual reports. As a consequence, the quality of data included in the database can vary and it is difficult to maintain a transparent quality standard.

Scientific Quality

The work performed within the topic Groundwater Monitoring is of high quality, but it is also largely operational. For this reason, it is difficult to assess in terms of scientific quality. Nevertheless, in the field of monitoring strategies and studies of new monitoring equipment, the work is certainly of high quality in comparison to international efforts, in particular regarding advanced monitoring of nutrients.

Recommendations

Publication. An important recommendation in the previous review report was to publish more research papers on groundwater monitoring. This recommendation is still valid. As a spin-off of the monitoring programs, peer-reviewed papers can be written on monitoring strategies.

Data-model integration. The most research-oriented aspect of groundwater monitoring is the design of monitoring strategies. The high profile of GEUS in groundwater modeling supports the use of models to guide monitoring strategies. Thus, not only can monitoring results be used in modelling, but models can also be used to improve monitoring strategies.

Data quality control. GEUS should play an active role in data quality control. Although GEUS is not responsible for the data of third parties, the value of the information in the database increases if there are labels or flags indicating the quality of the data that are visible to users of the database. The knowledge to do quality control is in house.

2.2 Groundwater Mapping

Activities

Activities in the Groundwater Mapping area were summarized by Flemming Jørgensen and Birgitte Hansen. The panel later viewed the Geophysical Borehole Logging Equipment, which was introduced by Klaus Hinsby. Members of the panel saw that groundwater mapping outlines the spatial context of groundwater resources, complementing the temporal approach of monitoring. Monitoring and mapping thus facilitate groundwater flow modeling. In addition, for example, mapping is required for analysis of groundwater-surface water interaction, groundwater vulnerability assessment, as well as a basis for epidemiological approaches.

The work involves intricate and advanced field research in glacial, sedimentary, and structural geology, supported by geophysical survey design, data processing, inversion, and inference both of lithology and properties, along with drillhole compilation and geostatistical methods. With the support of landform analysis and advanced stratigraphic methods, these approaches combine to support cognitive and stochastic, layer and voxel 3D geology, in which the succession of strata including their thickness and properties are specified, with for example indications of the presence of preferential flow pathways.

GEUS indicates that their activity supports the Ministry of Environment by developing and implementing standards and methods for national groundwater mapping. In relation to both geological and geophysical methods, GEUS and the Ministry of Environment are involved in a collaboration with Aarhus University to optimize the use of SkyTEM helicopter-borne EM

and other methods, and management of the resulting GERDA database, which contains large quantities of geophysical data from the groundwater mapping activities.

It was apparent to members of the panel that the 3D groundwater mapping can now be extended and combined with other activity (such as more comprehensive physical hydrogeological and hydrogeochemical surveys) to build a consistent nationwide 3D geology. This will provide a comprehensive foundation for fields ranging from water to energy, minerals, engineering, and basic research, including a next-generation national water resources model.

Observations

This review is taking place on the eve of the bicentennial celebration of the first geological map – the William Smith geological map of England and Wales that was published on August 1, 1815. It was noted that much is unchanged in the field of geological mapping over 200 years - the discipline continues to be a carefully-planned activity that is focused on user needs while accommodating unanticipated applications, based on thorough data compilation and acquisition, committed to the highest achievable level of detail, and assembled as regularly updated, jurisdiction-wide seamless compilations at multiple levels of resolution.

As we enter the third century of geological mapping, however, much exciting change is occurring worldwide, as the field completes the transition from the library to the database, and on to the GIS and the web. The current dramatic acceleration of data acquisition, technological progress, and scientific insights is taking place concurrent with escalating societal demands related to water, energy, minerals, hazards, climate change, environment, waste, and engineering, as well as fundamental research priorities.

Therefore, in contrast to aspects of the field that are unchanged over two centuries, dramatic changes in other aspects of the activity are thus occurring as we enter its third century. All mapping must now be seamless, queryable, coordinated, and zoomable, while at the same time subject to peer-review. This means that while the most detailed mapping will continue where needed, we now have an urgent need for a consistent and jurisdiction-wide compilation of detailed mapping to support applications and to manage content.

In this context, due to the demands of users and the opportunities of technology, we need to reconcile our mapping from onshore to offshore with topographic and bathymetric data; coordinate with soil mapping; map on a material properties basis; categorize using broadly accepted terminology; map in 3D; coordinate with increasingly 3D versions of regional, continental, and global-scale maps; link our mapping to a compilation of scanned and searchable publications, as well as consistent and comprehensive geological, geophysical, geochronological, and geochemical databases; and ensure that mapping is readily accessible through robust and ideally open-source software.

The people of Denmark have recognized the urgency with which they must secure their drinking water, and thus their future, by protecting their water from contamination, and from threats such as climate change. Pilot activity to date has served to clarify what can now be done to ensure that needed research on processes, development of technology, and

implementation of new management mechanisms will take place with the support of essential knowledge that can now be provided by a consistent national 3D geology that will combine with ongoing meticulous monitoring to permit construction of the next-generation national hydrological model that is needed to clarify what the people of Denmark must to do to secure their future.

Scientific Quality

The Danish groundwater mapping program is very well known throughout the world. As a result of a high number of very well cited papers in influential journals, and through regular important presentations at conferences, people in many other countries have begun to model their activities after those of Denmark. This in particular is the case in the field of airborne EM surveys, in which the Danish methods are seen as the model for best practices worldwide.

Recommendations

The panel members urge GEUS to commit to establish a consistent nationwide 3D geology, designed for full incorporation into a next-generation national water resource model. This should be a layer model to the extent achievable, with voxel infill to account for heterogeneity, along with indications of uncertainty. This will permit further dramatic improvement in groundwater vulnerability assessment and resource protection protocols, thus permitting essential progress toward human health and water supply resilience protocols.

2.3 Hydrological Cycle

Activities

Activities in this area were presented by Jens Christian Refsgaard and Simon Stisen. As Denmark's water supply is nearly wholly groundwater-based, a large part of the hydrological-cycle work, both practical and research, by GEUS can be ultimately interpreted as evolving towards development of a national hydrogeologic model that will serve as a repository for most hydrogeologic and hydrologic information collected by GEUS and other actors and as the best-available representation of groundwater levels and transport pathways in Denmark's subsurface.

The current hydrogeologic model (DK model) consists of two parts:

(1) a three-dimensional (3D) hydrogeologic model representation of Denmark
(2) a physics-based numerical simulator of groundwater flow that is based on the 3D hydrogeologic model, and on hydrologic conditions measured at the ground surface (e.g. streamflow, recharge) and in boreholes (hydraulic head levels).

The hydrogeologic model combines and represents all important aspects of the hydrologic cycle in Denmark and should be considered as a primary scientific and practical product of GEUS efforts, following significant efforts in data collection and mapping (hydrologic, geologic and geophysical) and in hydrogeologic database development (e.g. Jupiter). The DK model ties together much of GEUS' parallel data-collection and research efforts of the past ~15 years.

This activity focuses mainly on subsurface water flow (hydrology), but hydrochemistry and isotope chemistry are used to improve the flow representations in the model, and the model is used in research and practical applications to better understand and manage subsurface chemistry and water quality in Denmark.

Observations

The DK model may be considered as a high-level public database, similar to Jupiter in spirit and public accessibility. Jupiter data is regularly enhanced by contributions from water authorities that are included by GEUS; the public can freely access Jupiter for hydrogeologic data on individual boreholes. However, whereas Jupiter's highest function allows users to construct simple geologic cross sections, the DK model is a more-sophisticated database that includes a 3D nationwide representation of all borehole and borehole geophysical data and in some areas geophysical data from the Groundwater Mapping and it allows groundwater flow to be simulated through this 3D structure.

The public and private interests can freely use the DK model to analyze relevant problems, and, as part of this process, each user may enter additional hydrogeologic information and may modify their copy of the national model as needed to improve its applicability to the problem at hand. These user modifications can later be reviewed for quality assurance and accepted by GEUS to become part of the official DK model. It is noted that such upkeep and maintenance requires significant effort by GEUS personnel who are dedicated to managing this database. To date, the developments leading to development of the DK model have been carried out as effectively as possible only on temporary central funding and on temporary competitive funding.

The DK model is structured in an effective manner consisting of several regional sub-models. It includes a high level of detail of the geologic geometry in Denmark as provided by borehole lithology and geophysical (resistivity) soundings. However, the parameterization is kept relatively simple, with only several free groundwater hydraulic parameters that need to be estimated (by GEUS, as part of development of the official DK model) for each regional sub-model. This hydrogeologic modeling approach contrasts with that employed in the national groundwater model of The Netherlands, which also has highly-detailed geometry for geology, but which employs large numbers (thousands) of groundwater hydraulic parameters to achieve model fit with measured hydraulic data. Neither of these modeling approaches is yet standard or generally accepted; thus, GEUS' approach needs to be assessed with respect to true effectiveness (i.e., high value in representing aquifer response in terms of economic benefits of model use vs. cost of intensive data collection and maintenance of a highly-detailed and evolving model) in representing system behavior.

Scientific Quality

Given the large quantity of collected hydrogeologic data, the DK model has unusually high level of detail in hydrogeologic structure. There are few other such-detailed examples in the world at the national scale. As a result, the GEUS effort could become a potential world

leader as an example of effective hydrogeologic data collection and mapping, hydrologic monitoring, 3D database construction, and groundwater simulation modeling.

An impressive history of significant high-quality international-level research results and publications of GEUS scientists has been produced during the current review period and in previous years for the purposes of developing the subsurface model representations to be used (deterministic, statistical, spatial level of detail, numerical-spatial) and the hydrologic drivers of groundwater flow (e.g. streamflow, recharge, remote- and satellite-sensing data input). Many of these results are used in the DK model.

The DK model is a high-quality scientific product that provides direct support to GEUS efforts in all other water-related research and national water security areas. It is used by GEUS, by Danish universities and by other institutes, private companies and the public. It can be used to predict and manage groundwater withdrawals where water-level drop is a constraint on water supply or ecology. It can be used to protect groundwater well water supplies by predicting capture zones that require regulatory protection at the ground surface. It can be used to optimize hydrologic and geochemical monitoring networks. It can be used to predict travel paths of contaminants in the groundwater system for studies of water quality and chemical processes between contaminant sources and water wells or streams. It can be used as a basis for site-specific research (e.g. regarding hydrology, geochemistry, and water supply management and remediation technology).

Recommendations

(1) Establish the associated 3D geologic model of Denmark and using the completed 3D geologic model, refine the hydrogeologic representation used in the DK model, capturing more geologic and hydrogeologic detail where achievable and where beneficial.

(2) Consider and advertise the DK model system as Denmark's hydrogeologic database of the future. This 'active database' would be analogous to the spirit and intent of Jupiter, but will have fully 3D geology and groundwater physics simulation. This effort should be fully supported as a basic function and public database of GEUS. Regular central (not competitive) funding for DK maintenance and for research on assessment of and improvement of geologic and physics models contained in DK should be provided and guaranteed.

(3) At present, the value of the high data density and highly-detailed groundwater model needs to be reliably demonstrated on practical projects in Denmark. This is a key scientific question regarding much of the water-cycle work and approaches developed. It is recommended that site-specific efforts, as well as generic research studies by GEUS on appropriate levels of detail in geologic and groundwater models for various purposes, should be carried out with the intent of developing guidelines for characterizing and modeling groundwater systems in geologic fabrics similar to those found in Denmark. Due to the opportunity provided by the data density and high resolution of the geology that exists (uniquely) in Denmark, such guidelines would be beneficial to groundwater studies throughout the world.

2.4 Water Quality

Activities

Activities in this area were presented by Christian Nyrop Albers and Dieke Postma. This was followed by guided visits to the following laboratories: the Inorganic Chemical Laboratory (guided by Vibeke Ernsten), the Environmental Chemistry Laboratory (Nora Badawi), the Stable Water Isotope Laboratory (Rasmus Jakobsen) and the Molecular Microbial Ecology Laboratory (Jens Aamand).

Water quality aspects were prominent in several of the projects presented under other research topics; in these projects, water quality was addressed mainly in terms of the chemical composition of groundwater. In contrast, the research in the area of Water Quality (*per se*) focuses on the identification and characterization of the biogeochemical processes that determine the chemical composition of groundwater. Stated goals of the research in water quality are to explain and predict trends in groundwater composition.

Observations

Core expertise in this area relates to process-oriented field studies. These are supported by analytical facilities for inorganic chemical analysis, organic chemical analysis and stable isotope measurements; additional analytical capacities (e.g., ICP-MS) are available through other GEUS locations/departments. In addition, GEUS has the capacity to conduct complementary laboratory experiments. In addition, geochemical and reactive transport modeling is performed to complement experimental work; modeling capacity within the water quality area and/or Geochemistry Department is supplemented by collaboration with colleagues in other Departments having greater expertise in hydrogeological modeling.

As examples, two projects were presented in some detail. One project addressed the natural occurrence and formation of chloroform in groundwater in a forested area and the other was a field study examining the concentrations and spatial distribution of arsenic in groundwater in the Red River Basin (Vietnam).

Scientific Quality

The two highlighted projects are of excellent quality. The chloroform project is more mature and has generated a series of publications, including a review article published in the journal *Chemosphere* in 2015. The current arsenic project in Vietnam began in 2014 through an ERC Advanced Grant awarded to Dieke Postma. This builds on Postma's previous work, which has been published in leading journals such as *Nature Geoscience* and *Geochimica et Cosmochimica Acta*. Postma's ERC project will also incorporate 3D geologic mapping based on geophysical surveys being conducted in Vietnam and benefits greatly from GEUS's expertise in geologic mapping and hydrogeologic modeling.

Overall, the researchers in the Water Quality area are scientifically very productive; their contributions account for about 30% of the total scientific output in the Water Resources programme over the period 2007-2014. Papers in this area are cited at an average rate of 11 citations per paper.

Recommendations

The presentation on Water Quality included a list of proposed future research directions, specifically to:

- Continue the investigations of biogeochemical processes to include the vadose zone,
- Address effects of tile-drain run-off on surface water quality,
- Continue to highlight inorganic geogenic constituents of groundwater with bearing on human health, and
- Include investigations of geochemical conditions in the deep subsurface

The panel supports these proposed directions but notes that the last topic may lie outside the Water Resources programme.

The panel especially endorses future research that would leverage GEUS's core strength in geologic mapping and hydrogeologic modeling. We also note that the chloroform project was initially motivated by a problem arising in practice (i.e., the occurrence of chloroform in groundwater in an uncontaminated, forested area). We would encourage researchers in the Water Quality area to continue to draw inspiration from stakeholder concerns and from work done on GEUS's mandated tasks.

The panel notes that two senior (and highly productive) researchers in the Water Quality area are approaching retirement. It would be hoped that these senior researchers would use their national and international networks to support and advance their junior colleagues and make every effort to ensure continuity in the intellectual leadership at GEUS in this important area.

2.4 Water and Environmental Technology

Activities

Activities in this area were presented by Jens Aamand and Annette Rosenbom, who described projects on bioaugmentation of sandfilters in waterworks with pesticide-degrading bacteria and a laboratory and 3D-modelling study to assess the potential for biodegradation of solutes in agricultural soils. Jens Aamand also led the panel on a tour of the Molecular Microbial Ecology Laboratory.

The activities presented under the research topic Water and Environmental Technology focus mainly on bioremediation in the context of soils, groundwater and filters at drinking waterworks. In these environments, considerable problems are caused by pesticides and other organic pollutants (volatile chlorinated organic, hormones, pharmaceuticals, etc.). These compounds, although generally present in low concentrations, are of specific concern in relation to environmental quality and human health.

Moreover, removal of such compounds from the environmental matrixes examined by GEUS must be addressed on time scales of years to decades. To deal with such recalcitrant pollutants, specific attention has been given to aspects of microbial metabolism and microbial ecology. In particular, GEUS has been innovative in emphasizing the concept of bioaugmentation. Using complementary and elegant microbiological methods, the micro-organisms responsible for the breakdown of the target organics have been isolated and

identified. This allows the microorganisms to be grown up and added to the polluted matrixes in order to promote the removal processes. In this context, attention has been given to aspects of spatial heterogeneity and kinetics of removal. Approaches such as cryofracturing to gain access to the pollutants are quite innovative. The aspect of groundwater dating in relation to the presence of pesticides and their metabolites is also most interesting. Moreover, the work has been extended to the level of pilot plant installations in the case of drinking water production. This work is well documented and focused. GEUS has established expertise in this area at the highest international level.

A diverse set of other topics were mentioned that are also relevant to technological approaches to deal with contamination of the soil and groundwater environment. This includes the potential remediation of nitrate in the soil environment (i.e., by chemical reduction processes based on ferrous iron or abstracting water to decrease concentration levels). The polluting potential of manure can be decreased by processes that lower levels of hormones, pharmaceuticals and pathogenic or antibiotic-resistant bacteria. In addition, there is a growing interest in addressing the urban water cycle. Examples include stormwater management and the rehabilitation of degraded water bodies in the urban environment. These environmental technologies have been developed at GEUS to a good status, and they certainly merit further development.

Observations

The panel would emphasize the importance of considering environmental technologies in the context of active implementation of technical approaches either to contain environmental contamination or to improve the environmental status at specific sites. For GEUS in particular, it would be most appropriate to focus on environmental technologies that relate to a geological /hydrological setting in which the problem must be dealt with over an extended period of time. In such cases, available environmental technologies would not be sufficient and innovative, alternative approaches would be needed.

With its high level expertise in the domain of pesticide monitoring, GEUS has a unique opportunity to develop the potential of technological remediation by extending its capacities along these lines. This should, however, be accompanied by the development of a strategy for this type of environmental remediation. It is important to consider this in context. GEUS has reported significant occurrences of residual pesticides and their metabolites in Danish agro-ecosystems; some 16 pesticides and/or their degradation products are reported to be leached in concentrations above 0.1 μg /L. Since such occurrences may be revealed by systematic and advanced monitoring, it would be advisable to compare the GEUS data with other datasets from analogous settings. In view of the large number of xenobiotic compounds reported by GEUS, consultation with specialists in ecotoxicology would be advisable to interpret these values carefully with respect to their overall long-term significance for ecosystem functioning and environmental health. Although such observations can be indicative that pesticide are applied at levels or in a manner that is not consistent with the approved code of practice, this is not relevant to the conditions of Danish agriculture. Thus, even when good practices are followed, the pesticides are not degraded to the extent expected under the

governing rules and regulations (i.e., REACH) . If this is indeed the case, feedback to the national and international regulatory authorities would be warranted .

With respect to bioremediation /augmentation technologies, it is important to examine carefully the metabolic constraints on the lower limits that can be attained by means of the envisioned bio-technologies. Indeed, there may be critical levels of bio-availability below which it is not realistically possible to achieve microbial remediation. By exploring these limits at an early stage, the technical potential (with regard to effect levels, time, costs, etc.) of the intended approaches can be delineated and adequate strategies can be defined.

Scientific quality

The record of ISI publications on the topic of Water and Environmental Technology makes it clear that the quality of the work in this domain is certainly above average. The number of papers, the number of citations and the level of impact all reflect high standards. The statistics on h-index versus academic age leaves no doubt that the scientists involved in this area are performing very well; approximately 30% demonstrate outstanding performance.

However, the domain of environmental technology has a second axis of quality; this axis deals with the implementation of novel technologies in practice. The example of bioaugmentation at the pilot-plant scale to improve drinking water is a nice (though not yet entirely successful) step in this direction. An orientation toward implementation warrants more attention for the researchers engaged in the Water and Environmental Technology area. At present, R&D is still emerging; in the near future, sufficient attention must be given to practice so that the technology is transferred to potential users, ranging from farmers to commercial organizations in the Cleantech domain.

Recommendations

One general recommendation is that the researchers engaged in the topic of Water and Environmental Technology would benefit from a detailed discussion of the aims and scope of the group to reach some consensus on the overall approach. By mining the many valuable datasets derived from the survey activities at GEUS, the group would have a unique opportunity to scout for novel routes to generate 'solutions' for problems that match the capabilities at GEUS. This would require an intensive interaction between scientists and engineers and could facilitate the development of technologies that fit within the mission of GEUS and that would also generate interest from stakeholders facing environmental challenges or from industries dealing with the commercialization of environmental technologies . Development in the Water and Technology area could be instrumental in increasing GEUS's income from commercial contracts.

Specific recommendations. In the domain of pesticides and related recalcitrant pollutants , the long-term, highly valuable expertise must be maintained. Collaboration within GEUS on the role of preferential transport in leaching and on the effects of the patchy distribution of pollutant-degrading microbes should be continued. Tools to manage pollutant-degrading microbial communities and to design effective microbiomes and methods to cope with the patchiness of microbes in soil and groundwater need to be further addressed. For this,

molecular methods are essential. The current loss of staff with this expertise needs to be dealt with. The necessary data must continue to be generated (either by expanding in-house capabilities in molecular methods or by outsourcing) so as to be available for the proper interpretation and implementation of bioremediation /bioaugmentation approaches.

Danish agriculture is constantly faced with the impacts of fertilizer application. Technologies that use the soil/sediment system as a reactor to decrease residual nitrogen are certainly worth considering and should be investigated in more detail by GEUS. The concept of using ferrous iron deposits or of injecting other electron donors in specific aquifer sites to remove nitrate offers the potential to provide long-term services to agriculture as well as the users of surface- and groundwater. It is also interesting to note that GEUS's strategic topic in geothermal energy and heat storage could be combined with operating deep soils and sediments as 'reactor systems' to achieve certain ecological services.

Although GEUS is, at present, strongly focused on agriculture, it also holds data that are relevant to water quantity and quality in the urban water cycle. Contamination derived from uses of solvents, hydrocarbons and other chemicals by industry often pose problems that are not amenable to short-term solutions. GEUS scientists and engineers would have the competence to explore the alternatives of containment and natural attenuation as a way to manage these problems and to provide a service to society.

Finally, the areas of climate mitigation and adaptation to climate change offer many opportunities for creative, geo-related environmental technologies. Management of water levels can have major effects on both temperature and the rate of carbon dioxide production by ecosystems. In this context, closing the urban water cycle by re-introducing treated, reclaimed water is important for both the mitigation of climate change and sustainability and also fits within GEUS's interests in green cities. It would be advisable to explore the extent to which these technological ways of managing water could profit from GEUS's capacity to survey, monitor and manage massive amounts of geological-hydrological data as well as from and GEUS's reputation as a long-term, reliable partner for the assessment of environmental quality and sustainability.

2.5 Water resources management

Activities

Activities in the Water Resources Management area were summarized by Hans Jørgen Henriksen and Klaus Hinsby. They indicated that their efforts under the Water Resources programme area are designed to develop the knowledge that is now needed to guide optimal management of Danish water resource utilization, building on needed monitoring, mapping, modeling, research on processes, and development of technology. Activities included in the programme were shown to have been designed to bring the science to the interface with users through integration of hydrogeology, engineering, epidemiology, economics, social science, and ecology.

A focus is on new approaches for integrated and adaptive management of water resources, with an emphasis on ensuring that land use activity will not unacceptably degrade water quality, while confirming that abstraction for domestic, agricultural, and industrial use is at a distribution and a rate that is compatible with sustainable use as well as maintenance of landscape features and aquatic biodiversity – in relation to both groundwater levels as well as quality, including saltwater intrusion.

A major activity is to engage with activity meant to further develop a consensus in society regarding priorities and objectives, while considering the benefits and sacrifices associated with choices.

This activity will be carried out to large degree within the context of EU directives dealing with topics such as water, groundwater, and river basin management, while being adequately linked to climate change policy development.

An active presence on the international scene will bring benefits to the people of Denmark through broadening of thinking, acquisition of ideas, and facilitation of commercial opportunities.

There seems to be excellent potential for further development of stakeholder involvement, participatory scenario development, and approaches such as the work that GEUS has done on Bayesian belief networks as a tool for participatory integrated assessment and adaptive groundwater management.

Concurrently, it was contended and the panel members agree that there is a need for further development of alert systems that influence human activity in relation to pending drought or flood.

It also is clear that there is a need for further climate change scenario and response development.

Observations

As with other topics in the Water Resources programme, coordinated multi-agency projects that contribute to a well-planned broader strategy toward water security nationwide will be required.

Scientific Quality

The panel is impressed by the quality of work being done, as indicated by the level of influence being achieved by publications, and by the GEUS role in engagement with and influence on dialogue on water resource planning that seems to be taking place throughout society.

Recommendations

The panel endorses the direction of GEUS water resource investigations that are focused on human health and prosperity, as well as biodiversity maintenance. While much progress has been made on reducing unnecessary pumping, and reduction of contamination, much remains to be done to optimize usage, protect quality, and maintain aquatic ecosystems.

The focus surely will remain on minimizing the human impact on groundwater, due to pumping and contamination. In addition, the panel agrees that further insight into protection of aquatic ecosystems is needed.

Concurrently, further preparedness for sustained drought is needed, as it is needed everywhere, while there are ongoing issues such as salt water intrusion that need to be better understood and managed.

Crucial to the success of this activity will be achievement of the next generation of capabilities in national hydrological cycle and water use scenario modeling, as well as national syntheses of the controls on, status of, and scenarios for contaminants with emphasis on nitrate and pesticide – all of these essential modeling activities will require continuation and intensification of a broad array of needed monitoring, mapping, modeling, and research on methods, processes, and technology.

3. OVERALL EVALUATION

3.1 Observations

The presentations made to the scientific evaluation committee as well as laboratory tours, discussions with individuals and groups of GEUS staff and the documents prepared for the committee form the basis for this evaluation. On this basis, the evaluation committee is convinced that GEUS has established a collaborative and productive working environment. This is appreciated by research staff members at all levels, especially by the Ph.D. students.

GEUS combines internationally-competitive research (with scientific output in peer-reviewed (ISI) journals) with a responsibility to fulfill mandated tasks (i.e., a set of core, ongoing activities that should fulfill national responsibilities). The performance of GEUS's mandated tasks constitutes an important national service, which is conducted at a very high level.

The evaluation committee sees a great potential for increasing the synergies between GEUS's activities in research and its performance of mandated tasks (see also section 3.3). It must be recognized, however, that some members of the GEUS research staff express the perception that research with scientific output is more highly valued than contributions to fulfilling GEUS's national mandates.

The GEUS research staff is strongly motivated to increase their scientific output. Some concern was expressed that conditions are not optimal for this. In particular, the shortage of time need for writing and the pressure to attract external funding were mentioned. There also seems to be a perception that Departments in which a colleague holds a professorial appointment has better opportunities to attract external funding than other Departments.

The link to neighboring Universities, particularly through Geocenter Denmark and the co-location of GEUS and University offices, is extremely important for the GEUS researchers. This promotes contact with students (at all levels) and also benefits the University partners by providing thesis supervision at the Masters and Ph.D. levels. The Geocenter Denmark consortium appears to be a very successful instrument to promote collaboration and leverage capabilities.

The evaluation committee notes that the previous external review included an explicit focus and discussion of expanded work in low- and middle-income countries (LMICs). Such work is now well integrated into the GEUS research portfolio. Research in LMICs can be valuable to gain access to interesting field sites for research and can also serve national interests by expanding international cooperation and potentially creating export opportunities. At the same time, it must be recognized that research in LMICs often requires a substantial commitment to capacity building, which can be quite time intensive. Furthermore, funding for research in LMICs (which usually comes from development and donor agencies or foundations) is often not sufficient to cover the full costs of the projects.

3.2 Scientific quality

GEUS has a strong portfolio of research projects in the Water Resources area, with excellent international visibility. Over the period 2007-2014, researchers in the Water Resources area published 350 scientific papers in ISI journals with an average citation rate of 11.6 citations per paper. GEUS researchers are internationally active (i.e., in publishing, in participating in scientific conferences, in collaborating on projects, etc.). One senior researcher at GEUS (Dieke Postma) was awarded a very prestigious ERC Advanced Grant.

A principal strength of GEUS is its capacity to use the National Water Resources (DK) hydrogeological model as a tool to integrate across the research topics (groundwater monitoring, groundwater mapping, hydrologic cycle, water quality, water and environmental technology and water resources management) and in concert with monitoring and 3D geologic mapping. Integration of geology, hydrogeology and biogeochemistry at this level of detail and sophistication is a unique competitive advantage for GEUS. Such integration is especially advantageous for biogeochemists and ecologists. It offers an important and uncommon level of sophistication in the research on arsenic occurrence in groundwater in Vietnam (which will incorporate 3D geologic mapping based on geophysical surveys) and in the assessment of ecological flows and nutrient inputs to surface waters in Denmark (which relies on the DK model). GEUS is also employing innovative tools (e.g., Bayesian belief networks) for stakeholder engagement.

GEUS is a world leader in using airborne EM surveys and in integrating the resulting geophysical data into geological maps.

In the recently-established area of water and environmental technology, GEUS has demonstrated its capacity to perform top-level work in bioaugmentation that is corroborated by molecular analysis. The capacity to combine microbial technology and in-depth analyses based on molecular methods should be maintained.

3.3 Recommendations

It is nearly a cliché to say that the success of a research institution rests on the quality of its staff, but it is vitally important that the working conditions for the research staff allow them to realize their strong engagement with GEUS's mission and mandate.

The evaluation committee sees a need for the development of instruments to acknowledge and appreciate work related to mandated tasks (survey, consultancy, advisory, etc.). It is important to be wary of the unintended consequences of overemphasizing scientific output; this can create disincentives for open access publication and also for publications for practitioners (i.e., articles in trade journals, which are an important means of outreach to professionals). Mechanisms should be sought that would promote leveraging of advisory and research activities (e.g., specified research time allocation for staff with large advisory responsibilities).

It is important that careful attention is paid to the professional development for GEUS research staff. Expectations and opportunities for advancement should be articulated clearly

and consistently across the entire institution, avoiding unnecessary inconsistencies among the Departments. This is particularly relevant for advancement from postdoc to researcher and researcher to senior researcher. Senior researchers should be supported in building their visibility through networks and in achieving recognition, for examples as adjunct (research) professors.

It would be advisable to align professorial planning with research opportunities (e.g., in solution-oriented innovation).

A particularly pressing issue is the careful monitoring and re-evaluation of the current business model for external funding, which appears to be reaching the limits of sustainability. This will require the development of principles for prioritizing research in all contexts, but especially for research in LMICs.

Areas to be strengthened to meet GEUS strategy

In section 3.2, the importance of the DK model and the 3D geologic mapping for interdisciplinary, collaborative research at GEUS has been highlighted. It is also important that this modelling and mapping capacity provides GEUS researchers with a competitive advantage in the acquisition of external funding. This unique positioning should be made more visible not only externally but also internally (so that the benefits of this capacity are more widely exploited within GEUS).

In order to realize this potential, however, the modelling activities, in particular, need to be made more sustainable. Activities that require long-term engagement, upkeep and improvement cannot be run solely on a project basis. The evaluation committee recommends that a sustainable business model for these activities be developed and implemented.

The committee furthermore recommends that GEUS make a commitment to establish a consistent nationwide 3D geology model. This would position GEUS to develop the next-generation DK model, which would permit further dramatic improvement in groundwater vulnerability assessment and resource protection protocols.

The evaluation committee also sees an competitive advantage for GEUS researchers that derives from their access to "insider information" about questions and problems that arise in the context of water management. It was indeed this kind of information that provided the initial impetus for the research on natural formation pathways for chloroform in forest soils. Making these avenues of information more visible within GEUS would tend to increase the leveraging between research activities and the performance of mandated tasks.

Possible areas to be considered for future expansion

It would be of interest to consider broadening the scope of GEUS's research beyond its current pressing priorities, such as the impact of agriculture on groundwater. Although problems remain to be solved in this area, some focus could be shifted to, for example, urban hydrogeology (including aspects of both water quality and quantity). This would also provide a link to the energy program through the use of shallow groundwater for thermal storage. The

potential of urban hydrogeology as a productive area of expanded future research and technological development should be assessed.

Other comments

GEUS is recognized as one of the leading geological surveys in Europe. Thus, GEUS would be well positioned to leverage capabilities with other survey organizations and to provide direction and leadership across Europe.

ANNEX 1. TERMS OF REFERENCE

EVALUATION OF GEUS' RESEARCH AND RESEARCH OUTREACH ACTIVITIES IN

Water Resources

(PROGRAMME AREA 2)

Background

GEUS

GEUS is an independent and self-governing research institution under the Ministry of Climate, Energy, and Buildings and is the national geological data centre. It is assented by the Geological Survey of Denmark and Greenland Act. GEUS is app. 50 % financed through the annual Finance and Appropriation Act and must provide income from other sources. It may take on tasks from public authorities or private individuals in Denmark and abroad against full or partial payment. Besides the Ministry of Climate, Energy and Buildings GEUS contributes especially to the Ministry of Environment, the Ministry of High Education and Science, and the Greenland Self-Government. It also provides advice to and carries out activities for public authorities.

GEUS is managed by a board and the managing director assisted by two deputy directors, and has nine research departments and five main work areas (programme areas). GEUS' main tasks are governed by the role as a national geological survey for Denmark and Greenland but GEUS finds it important also to join international cooperation and contribute to international tasks and projects in line with Danish political priorities to maintain and develop GEUS' importance to the Danish society. GEUS' main research priority areas are described in 'GEUS Strategy 2012' and translated into actions in GEUS' 'Performance Contract 2012-2015' (in Danish), which again provides a framework for the annual work programmes.

Programme areas and departments

GEUS' research is mainly carried out in four of the five programme areas and each of these is evaluated every eight years by an international evaluation panel. Programme areas are purely administrative units used in connection with the 'Performance Contract 2012-2015' and in the yearly 'Annual work programme' (all in Danish). GEUS' strategic objectives are defined across programme areas.

The programme areas comprise a number of research projects based in the departments often involving staff across several departments in a matrix structure. Thus, the programme areas are not a part of the GEUS organisational structure and, except for the coordination by the deputy directors, they have no separate management.

In the departments, management is carried out by the heads of department to whom GEUS' professors refer.

1. Terms of Reference - The Evaluation Panel

According to the Danish Statutory Order from the Ministry of Climate and Energy of October 7, 2008 on Research Evaluation at the Geological Survey of Denmark and Greenland (GEUS), the GEUS Board has decided that the next research evaluation shall cover the Water Resources Programme Area.

Objectives

The panel shall undertake an evaluation of research and dissemination activities to identify strengths, gaps and needs for amendments and improvements in relation to GEUS' strategy and mission within the GEUS Programme Area 'Water Resources'. The evaluation concerns the period 2007-2014, constituted by the following main themes:

Groundwater monitoring
Groundwater mapping
Hydrological cycle
Water quality
Water and Environmental technology
Water resource management

and will be based on a thorough examination of selected publications and reports produced by the survey in addition to a visit to GEUS in Copenhagen. Capacity building is included in the six themes.

Tasks

On the basis of

- Publications, reports and other relevant material produced over the period 2007-2014, both years included
- Presentations given by GEUS scientists
- Interviews with GEUS' management staff and scientists, and visits to laboratories and work facilities at GEUS

the task of the panel is to evaluate the research and the research outreach activities of GEUS in order to

- Identify areas of high quality research
- Identify areas where the research of GEUS should be strengthened in order to meet GEUS strategy
- Provide comments and suggestions as to strategic changes, amendments, and improvements to GEUS' work within the programme area, in order to improve GEUS' ability to fulfil its main mission within this programme area seen in the perspective of the survey's statutes and general mission

Output

The evaluation panel shall report their observations and conclusions 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 shall deliver the final draft report in due time to be presented to the GEUS Board.

Time schedule

The evaluation panel pays a visit to GEUS for evaluation (3-4 days), including preparation of the final draft report in May 2015.

The presentation of the findings in the final report will be presented to the GEUS Board in June 2015.

Upon accept by the board the final report will be published.

Based on the findings an implementation plan will be developed by the programme area staff and presented to the GEUS Board in autumn 2015.

The Board decisions are planned to be implemented from late 2015.

2. Confidentiality

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

3. Expenses and compensation

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

Copenhagen, December 2014

Bjørn Kaare Jensen

Deputy Director

ANNEX 2. DEBRIEFING PRESENTATION

DEBRIEFING: EVALUATION OF THE GEUS PROGRAMME "WATER RESOURCES"

Presented by the evaluation committee:

- Prof. Janet Hering, Eawag, ETH Zurich, EPFL, Switzerland (***Chair***)
- Prof. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota, USA
- Prof. Frans van Geer, TNO, Utrecht University, The Netherlands
- Prof. Willy Verstraete, University of Ghent, LabMET, Belgium
- Dr. Clifford Voss, US Geological Survey, USA

Presented on 28 May 2015
Corrected version 29 May 2015

CHARGE TO THE EVALUATION COMMITTEE

The panel shall undertake an evaluation of **research and dissemination activities** to **identify strengths, gaps and needs** for amendments and improvements in relation to GEUS's strategy and mission within the Programme Area "Water Resources". The evaluation concerns the period **2007-2014**.

Specifically, the panel is asked to:

- Identify **areas of high quality research**,
- Identify **areas where the research of GEUS should be strengthened** in order to meet GEUS strategy, and
- Provide comments and suggestions as to **strategic changes, amendments, and improvements** to GEUS' work within the programme area, in order to improve GEUS' ability to fulfil its main mission within this programme area seen in the perspective of the survey's statutes and general mission.

CONTEXT FOR RESEARCH AT GEUS (1/3)

GEUS is a research institution with mandated tasks (i.e., a set of core, ongoing activities that should fulfill national responsibilities)

- To provide geological consultancy and advisory services for authorities
- To carry out "mapping, monitoring, data collection, data management and communication"
- To be "a national geological data centre [that] makes data and knowledge available to authorities, educational institutions, enterprises, individuals"

CONTEXT FOR RESEARCH AT GEUS (2/3)

GEUS is also mandated to conduct research at the highest international level and to contribute to undergraduate, graduate and PhD programmes in areas in which GEUS has special expertise. There are four key synergies that can benefit GEUS's research activities:

- Research projects can **build on observational data** collected through **mapping and monitoring activities**, which are made accessible through **GEUS's databases**,
- Models developed and supported by GEUS (in particular, the **National Water Resources (DK) Model**) can stimulate and facilitate interdisciplinary, collaborative research,
- **Research gaps identified through advisory and/or consultancy projects** can stimulate new lines of research, and
- GEUS provides a **capacity for long-term engagement** (e.g., at field sites and/or in engagement with stakeholders) that can support individual research projects.

CONTEXT FOR RESEARCH AT GEUS (3/3)

There are also some tensions between GEUS's research activities and GEUS's fulfilment of its responsibilities for its mandated tasks. These tensions derive from two principal bases:

1. Senior researchers at GEUS are under **severe pressure to acquire external funding**. Success in funding acquisition is often closely linked to research productivity, which puts **pressure on researchers to increase their output of scientific publications**.
2. Completion of mandated tasks demands substantial time and effort but generally does not lead (directly) to scientific output. Thus **emphasis on scientific output creates a disincentive to invest time and effort in mandated tasks**.

DETAILED EVALUATION: GROUNDWATER MONITORING (1/2)

Activities

- Monitoring strategies / producing guide lines
- Field work; lab analysis (limited)
- Annual reports; analysis with other research topics

Observations

- Mostly operational work; supporting other research topics (hydrologic cycle, water quality)
- Few changes in monitoring programs over the years, but no guarantee for long term continuity
- Almost all written output in Danish (reports; guide lines)
- Data base largely dependent on many other parties for quality control of the data

DETAILED EVALUATION: GROUNDWATER MONITORING (2/2)

Scientific Quality

- Data base; monitoring is high standard, but not really scientific research

Recommendations

- Research papers on monitoring strategies
- Use data-model integration (data assimilation) to improve monitoring strategies
- Active role data quality control (quality labels? ; substantial part of annual reports?)

DETAILED EVALUATION: GROUNDWATER MAPPING (1/2)

Activities

- groundwater mapping outlines the spatial context of groundwater resources
- the mapping is required for modeling, analysis of groundwater-surface water interaction, groundwater vulnerability assessment, & epidemiological approaches
- involves geology, geophysics, drillhole compilation & geostatistics
- landform analysis and stratigraphic methods guide 3D geology
- GEUS role supports the Ministry of Environment
- collaboration with Aarhus University and SkyTEM on airborne geophysics

Observations

- Geological mapping is completing the transition from the library to the database
- The need for mapping will escalate as management intensifies
- Geological mapping is becoming seamless, queryable, coordinated, and zoomable
- The urgency of water quality and capacity issues seems to still be high

DETAILED EVALUATION: GROUNDWATER MAPPING (2/2)

Scientific Quality

- The GEUS groundwater mapping program is very well known throughout the world
- A high number of very well cited papers in influential journals
- Other countries have begun to model their activities after those of Denmark
- In particular, Danish airborne EM methods are global best practices

Recommendations

- Commitment to a more comprehensive and consistent nationwide 3D geology can support broadened vulnerability assessment and modeling, while stimulating progress in all related fields

DETAILED EVALUATION: HYDROLOGIC CYCLE (1/4)

Activities

GEUS Focus: Development of the DK Model

The Model

- Serves as a repository for most hydrogeologic and hydrologic information (collected by GEUS and other actors)
- Primary scientific and practical product of related GEUS efforts
- Model combines/represents all important aspects of the hydrologic cycle
- Developed following many years of
  - data collection (hydrologic, geologic and geophysical)
  - hydrogeologic database development (e.g. Jupiter)
  - research on effective modeling techniques for Denmark
- The DK model ties together all of these parallel efforts.

DK model consists of two parts:

- 3D hydrogeologic model representation of Denmark
- Physics-based numerical simulator of groundwater flow based on:
  - 3D hydrogeologic model,
  - hydrologic conditions measured at
    - ground surface (e.g. streamflow)
    - in boreholes (hydraulic head levels)

DETAILED EVALUATION: HYDROLOGIC CYCLE (2/4)

Observations

DK model has effective structure

- Several regional sub-models
- High level of geometric detail for geologic structure
- Simple parameterization of groundwater hydraulic parameters
- state-of-the-art hydrologic drivers (streams and recharge)
  - derived from ancillary research analyses.

DETAILED EVALUATION: HYDROLOGIC CYCLE (3/4)

Scientific Quality

DK model has unusually high level of detail in geologic structure

→ few other such-detailed examples in the world at the national scale

DK has relatively simple parameterization

→ combined with high-detail geometry makes this approach unique worldwide

High-level productivity already exists and is underway in this field, but this GEUS effort could become a potential world leader as an example of effective

- hydrogeologic data collection
- 3D database construction
- groundwater simulation modeling for management

DK model may become highly effective tool to:

- predict and manage groundwater withdrawals (impact on water supply or ecology)
- predict capture zones (protect groundwater well water supplies)
- predict contaminant travel paths (evaluate water quality and chemical processes)
- conduct research on site-specific conditions
  (e.g. hydrology, geochemistry, and remediation technology)
- optimize hydrologic and geochemical monitoring networks

DETAILED EVALUATION: HYDROLOGIC CYCLE (4/4)

Recommendations

- Establish the 3D geologic model of Denmark and refine the hydrogeologic model
  - Capture more geologic detail where achievable and where beneficial
- For practical projects in Denmark:
  - Demonstrate value of high geologic data density
  - Demonstrate value of highly detailed groundwater model
- Develop guidelines for characterizing and modeling groundwater systems
  - High data density provides unique opportunity for important research on appropriate levels of detail for various purposes
  - Guidelines would be beneficial to groundwater studies throughout the world

DK model system: Denmark's hydrogeologic database of the future!!

- Analogous to the spirit/intent of Jupiter
  but with fully 3D geology with groundwater physics simulation
- Should be fully supported as a basic function and public database of GEUS
- Provide regular funding for DK maintenance
- Provide regular funding for research on
  assessment of and improvement of
  geologic and physics models contained in DK

DETAILED EVALUATION: WATER QUALITY (1/3)

Preface

- Water quality (i.e., the chemical composition of groundwater) **cuts across** many of the "identified research topics" in the programme Water Resources.

Activities

- Identification and characterization of the **biogeochemical processes** that determine the chemical composition of groundwater with the **goal of explaining and predicting trends in groundwater composition**.

Observations

- Process-oriented field studies are supported by:
  - Analytical facilities for inorganic chemical analysis, organic chemical analysis and stable isotope measurements and additional analytical capacities (e.g., ICP-MS) at other GEUS locations/departments.
  - Capacity for complementary laboratory experiments
  - Reactive transport modeling capacity
- Two example projects were presented:
  - Natural occurrence and formation of chloroform in groundwater in a forested area
  - Field study to predict the concentrations and spatial distribution of arsenic in groundwater in the Red River Basin (Vietnam)

DETAILED EVALUATION: WATER QUALITY (2/3)

Scientific Quality

- 11 staff with primary affiliation in the Water Quality research topic (nearly all in the Department of Geochemistry). This research topic accounts for about 30% of the scientific output (2007-2014) of the Water Resources area with an average of 11 citations per paper.
- The two highlighted projects are of excellent quality and, moreover, take advantage of key strengths of GEUS. The chloroform project was initially stimulated by reports of unexplained chloroform occurrences in "clean" groundwater and project results had an influence on regulatory policy. The arsenic project is funded by a highly prestigious ERC Advanced Grant to Dieke Postma. This project benefits greatly from GEUS's strength in geologic and hydrologic modelling.

DETAILED EVALUATION: WATER QUALITY (3/3)

Recommendations

- The committee supports the stated future research directions in Water Quality to:
  - Expand investigations of biogeochemical processes to include the vadose zone
  - Address effects of tile-drain run-off on surface water quality
  - Continue to highlight inorganic geogenic constituents of groundwater with bearing on human health
  - Include investigations of geochemical conditions in the deep subsurface (note that these may be outside the Water Resources area)
- The committee recommends:
  - That the strong senior researchers in this area use their scientific networks to benefit GEUS and especially their junior colleagues and to ensure continuity in this area (i.e., succession)
  - That researchers in this area continue and intensify the efforts to integrate sophisticated geological and hydrological modelling with geochemistry, thus **leveraging a core strength** of GEUS.
  - That researchers in this area continue to **draw inspiration** for the research **from mandated tasks and major stakeholder concerns** regarding water quality.

DETAILED EVALUATION: WATER AND ENVIRONMENTAL TECHNOLOGY (1/2)

Activities

- Bioremediation of xenobiotics in soil, groundwater and water treatment facilities (waterworks) is the current focus
- Nutrients /Cities in water balance: startup of R&D is happening

Observations

- There is plenty of potential in the technology theme for GEUS. Yet, the limits of certain approaches (e.g., bioremediation down to levels below 0.1 µg/L) must be addressed.
- Development of this theme would benefit from:
  - Strengthening the engineering approach
  - Coordination and empowerment

Scientific quality

- Above average in terms of publications
- Implementation in the field must be stepped up and used as an important criterion of success

DETAILED EVALUATION: WATER AND ENVIRONMENTAL TECHNOLOGY (1/2)

Recommendations

- Deal with the nexus: technology + geology-hydrology + need for long term engagement
- Maintain molecular expertise (at the senior level)
- Develop topics such as:
  - N containment in agriculture
  - Urban soil and groundwater pollutants
  - Mitigation of climate change impacts by management of microbial processes in surface and deep soils (i.e., the soil as reactor system)
  - Closing of the water cycle by recharging treated water
  - Flooding to cool urban areas
  - Other…
- Scout for cooperation with commercial partners

DETAILED EVALUATION: WATER RESOURCES (1/2)

Activities

- efforts are designed to support optimal management of Danish water resource utilization
- Activities bring the science to the interface with users through integration of hydrogeology, engineering, epidemiology, economics, social science, and ecology
- focus is on new approaches for integrated and adaptive management of water resources
- goal is to ensure that land use activity will not unacceptably degrade water quality, while confirming that abstraction for domestic, agricultural, and industrial use is at a distribution and a rate that is compatible with sustainable use as well as maintenance of landscape features and aquatic biodiversity – in relation to both groundwater levels as well as quality, including saltwater intrusion
- important role for consultation and consensus building
- carried out within EU directives
- international activity brings benefits to Denmark through information exchange and commercial opportunities

Observations

- will ideally consist of coordinated multi-agency projects that contribute to a well-planned broader strategy toward national water security

DETAILED EVALUATION: WATER RESOURCES (2/2)

Scientific Quality

- research is being conducted at a high level of quality
- GEUS is well engaged in broad dialogue

Recommendations

- The panel endorses the research directions
- Needed water resource investigations will focus on human health and prosperity, as well as biodiversity maintenance
- much remains to be done to optimize usage, protect quality, and maintain aquatic ecosystems
- further preparedness is needed for sustained drought and salt water intrusion
- The activity will benefit from enhanced capabilities in national hydrological cycle and water use scenario modeling, as well as national syntheses of the controls on, status of, and scenarios for contaminants

OVERALL EVALUATION (1/4)

Observations

- GEUS has established a collaborative and productive working environment. This is especially appreciated by the PhD students.
- The previous external review included an explicit focus and discussion of expanded work in low- and middle-income countries (LMICs). Such work is now well integrated into the GEUS research portfolio.
- The GEUS research staff is strongly motivated to increase scientific output but sometimes feel constrained by working conditions (i.e., pressure to attract external funding, lack of time needed for writing, uneven support (across Departments) from senior colleagues with professorial appointments).
- GEUS research staff express the perception that research with scientific output is more highly valued than contributions to fulfilling GEUS's national mandates.
- The Geocenter Denmark consortium appears to be a very successful instrument to promote collaboration and leverage capabilities.

OVERALL EVALUATION (2/4)

Scientific Quality

- GEUS has a strong portfolio of research projects in the Water Resources area, with excellent international visibility.
- GEUS researchers are internationally active (i.e., in publishing, presence at scientific conferences, collaborative projects, etc.). One senior researcher at GEUS (Postma) was awarded a very prestigious ERC Advanced Grant.
- Areas of strength:
  - Groundwater monitoring. Sensor-based, high-resolution monitoring, especially for nutrients. Link between monitoring and DK model.
  - Groundwater mapping. Airborne EM surveys and integration of resulting geophysical data into geological and hydrologic maps.
  - Hydrologic cycle. Unprecedented detail in geologic data integrated into DK model.
  - Water quality. Integration of biogeochemistry and pollutant dynamics with sophisticated (3D) geological and hydrological modelling
  - Water and environmental technology. Top-level work on bioaugmentation; molecular methodology established.
  - Water resources management. Integration of DK model into ecological flow modelling. Innovative tools (e.g., Bayesian belief networks) for stakeholder engagement.

OVERALL EVALUATION (3/4)

Recommendations

- Management issues
  - Develop instruments to acknowledge and appreciate work related to mandated tasks (survey, consultancy, advisory); be wary of untended consequences of sole emphasis on scientific output (e.g., disincentives for open access, publications for practitioners); seek mechanisms that would promote leveraging of advisory and research activities (e.g., specified research time allocation for staff with large advisory responsibilities)
  - Professional development for GEUS research staff – clear and consistent (i.e., across Departments) articulation of expectations and opportunities for advancement (especially promotion to senior researcher); support senior researchers in building visibility through networks, achieving recognition as (e.g.) Adjunct Research Professors
  - Align professorial planning with research opportunities (e.g., in solution-oriented innovation)
  - Carefully monitor and evaluate current business model for external funding – this seems to be at the limit (perhaps already over the limit)

OVERALL EVALUATION (4/4)

Recommendations

- Strategic positioning
  - Identify and exploit competitive advantages (i.e., uncommon combinations of expertise; unusual access to "real world" concerns)
  - Increase leveraging between research activities and mandated tasks
  - Develop principles for prioritizing research in LMICs
- Considerations for future research directions
  - Currently there is a strong focus on agriculture and relatively little attention to urban hydrology (including both quality and quantity). Urban hydrogeology could be a productive area of future research.
  - Completion of a consistent nationwide 3D geology model would position GEUS to develop the next-generation national water resource (DK) model, which would permit further dramatic improvement in groundwater vulnerability assessment and resource protection protocols.