Scientific audit

RIVM COVID-19 data analytics and modelling for scientific advice to policy makers

Report of the external audit committee

July 2023

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List of Abbreviations

AC	Audit committee
BAO	*Bestuurlijk afstemmingsoverleg* (Administrative Coordination Consultation implemented to test the substantive advice for administrative feasibility and practicability)
CBS	*Centraal Bureau voor Statistiek* (Statistics Netherlands)
CDC	Centers for Disease Control and Prevention (in the USA)
CFA	Center for Forecasting and Outbreak Analytics (of CDC)
CIb	*Centrum voor Infectieziektebestrijding* (Centre for Infectious Disease Control of RIVM)
COVID-19	Coronavirus disease 2019
DAM	Data analytics and modelling
ECDC	European Centre for Disease Prevention and Control
EPI	*Centrum Epidemiologie en Surveillance van Infectieziekten* (Centre for Infectious Diseases Epidemiology and Surveillance within the CIb)
EPI-DIS	Data Information and Signalling within EPI
EPI-DIS-DARA	Data Analytics, Research, and Automated Reporting team within EPI-DIS
EPI-MOD	Modelling of Infectious Diseases team within EPI
EPI-NIP	National Immunisation Programme department within EPI (team dedicated to COVID-19)
EPI-RES	Respiratory Infections team within EPI
EU4S	European Sewage Sentinel System for SARS-CoV-2
FTE	Full-time equivalent
GDPR	General Data Protection Regulation
GGD	*Gemeentelijke of Gemeenschappelijke Gezondheidsdienst* (Municipal Public Health Service)
HPC	High-performance computing
ICU	Intensive care unit
INSERM	*Institut national de la santé et de la recherche médicale* (French National Institute of Health and Medical Research)
IT	Information technology
KNAW	*Koninklijke Nederlandse Akademie van Wetenschappen* (Royal Netherlands Academy of Arts and Sciences)
LCPS	*Landelijk Coördinatiecentrum Patiënten Spreiding* (National Coordination Centre for Patient Distribution)
LO	Liaison Officers of the SAB
MIDAS	Models of Infectious Disease Agent Study
Ministry of Health	Ministry of Health, Welfare, and Sport
MIT	*Maatschappelijk Impact Team* (Societal Impact Team)
MSc	Master of Science
NICE	National Intensive Care Evaluation
NIH	National Institutes of Health (USA)

NRS	National Sewage Surveillance
NWO	*Nederlandse Organisatie voor Wetenschappelijk Onderzoek* (Dutch Research Council)
OMT	Outbreak Management Team
OSIRIS	Online system for registering notifiable diseases
PhD	Doctor of Philosophy
PL	Project leader audit
RAMP	Royal Society's Rapid Assistance in Modelling the Pandemic (in the UK)
RIVM	*Rijksinstituut voor Volksgezondheid en Milieu* (Dutch National Institute for Public Health and the Environment)
R_t	Effective reproduction number
SAB	Scientific Advisory Board of RIVM (*Commissie van Toezicht*)
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SEIR	Susceptible-Exposed-Infected-Removed
SEP	Strategy Evaluation Protocol
SPI-M	Scientific Pandemic Influenza Group on Modelling (in the UK)
SWOT	Strengths, Weaknesses, Opportunities, Threats
TNO	*Nederlandse organisatie voor toegepast natuurwetenschappelijk onderzoek* (Netherlands Organisation for Applied Scientific Research)
UK	United Kingdom
UMC	University Medical Centre
USA	United States of America
VWS	*(Ministerie van) Volksgezondheid, Welzijn en Sport* (Ministry of Health, Welfare, and Sport)
WHO	World Health Organization
Z&O	*Centrum Zoönosen en Omgevingsmicrobiologie* (Centre for Zoonoses and Environmental Microbiology within the CIb)
Z&O-NRS	*Nationale Rioolwater Surveillance* (National Sewage Surveillance Department within Z&O)

1. Summary

This report presents the evaluation of the scientific quality, resources, relevance, independence, and viability of the COVID-19 data analytics and modelling (DAM) activities for scientific advice to policy makers performed by the Dutch National Institute for Public Health and the Environment (RIVM) in the period 1 January 2020 to 1 June 2022. This audit was commissioned by the Scientific Advisory Board of RIVM and was performed by an external international audit committee. The committee based its conclusions on a self-evaluation report compiled by RIVM; a stakeholder evaluation report written by an independent agency; and a series of interviews with RIVM representatives and experts, external experts, and external stakeholders during a four-day hybrid site visit in March 2023.

Research quality

In circumstances of high pressure and given limited resources, RIVM's COVID-19 DAM experts produced work of excellent quality, also compared to national agencies and advisory bodies with similar missions in other countries. RIVM's modelling approaches were adequate, and uncertainties were appropriately taken into account. Priorities had to be set, but RIVM's DAM experts did this in a sensible way, ensuring robust support for decision-making. While there was much international scientific cooperation, there was relatively limited cooperation with Dutch academic modelling groups during the audit period. While this was understandable given the time pressure, intensifying such cooperation and use of expertise could have contributed to the replicability of and the public trust in the modelling work. RIVM made substantial efforts to share data and model source codes as openly as possible and as far as privacy legislation allowed but did so at a relatively late stage. As reproducibility is a core aspect of research quality, this should be improved in the future, and RIVM is already taking steps to achieve this.

Human resources

The excellent performance of the remarkably small DAM teams reflects RIVM's investments to recruit, train, and retain top scientists prior to the pandemic. However, the human resources available during the audit period were not optimal. A larger team could have done more DAM work and thus have answered additional (lower priority) questions that were also important. In addition, RIVM would have had more time and capacity to share information about the models, facilitating overall transparency and independent external validation, and accelerating scientifically documented model comparisons. The societal and time pressure on the staff was immense, so additional staff is also needed to prevent burnouts in the long term. Many teams across the world experienced difficulties in hiring and training DAM experts; this was nearly impossible during the acute phase of the pandemic. In addition, there are structural obstacles that hinder the recruitment of high-quality external senior DAM experts at RIVM. These difficulties must be urgently addressed.

Access to data streams

Timely access to comprehensive and valid data is crucial for high-quality modelling for policy advice. Overall, RIVM's data access and data flows were much better than in many other countries. However, the DAM teams had to spend a disproportionate amount of time on collecting and linking some types of data and were unable to obtain others. This was due to a variety of reasons, including very strict interpretations of the GDPR in the Netherlands, scattering of data sets over different

sources, delays in the availability of some types of data, and non-structural funding for some data collection efforts. These issues should be evaluated and resolved before a new pandemic occurs.

Relevance to society

Overall, the COVID-19 DAM work performed by RIVM allowed the Ministry of Health to make public health decisions based on high-quality scientific information. The DAM teams produced an impressive range of outputs, and responded to a multitude of questions that arose. Some stakeholders other than policy makers did not always get the specific input they needed, as RIVM's COVID-19 DAM teams had to set priorities due to time constraints. The RIVM modellers continuously put forward uncertainties in their analyses and outputs. Nevertheless, uncertainties and assumptions could have been communicated more clearly. At a global scale, research is needed to explore and develop best practices in communicating uncertainties and assumptions, and in helping policy makers and other stakeholders to understand the possibilities and limitations of modelling approaches.

Scientific integrity and independence

RIVM's system to prevent undue external influence is robust and appears to have performed well during the audit period. There was some public confusion about the distinction between the roles of RIVM, the OMT, and the Ministry of Health during the pandemic. While intensive interaction between policy makers and the advising RIVM heads has been conducive to a timely and adequate response to the crisis, the different roles and RIVM's firmly entrenched independence with the associated checks and balances should be communicated better in the future.

Viability and future proofing

Now that the acute phase of the pandemic has ended, it is time to evaluate the experiences, secure the acquired knowledge, and make organisational adjustments to ensure that the Netherlands will be optimally prepared for a next pandemic. Several vulnerabilities in the organisation of infectious disease DAM at RIVM were identified, some of which cannot be addressed by RIVM alone but require concerted action by a broader group of relevant institutions and policy makers in the Netherlands that the DAM work of RIVM depends on. Moreover, a new pandemic will undoubtedly include unforeseen novel elements. RIVM's and the Dutch national ability to flexibly respond to such challenges in the future will depend on the actions that are taken now.

Strategic recommendations

1. Structurally strengthen the capacity of RIVM's infectious disease DAM teams.
2. Prioritise training of new infectious disease DAM experts in the Netherlands and attract more master and PhD students to RIVM.
3. Structurally improve the access to all data streams that are relevant for DAM at RIVM.
4. Improve the transparency of and communication about RIVM's infectious disease DAM work.
5. Establish a national network of collaborating institutions based on pre-existing memoranda of understanding, within which data and models can be shared more easily.
6. Strengthen the endeavour to incorporate behavioural data and the wider societal impact of pandemics into the DAM work.
7. Strengthen the internal collaboration between RIVM departments involved in DAM work.
8. Ensure sustainable funding for RIVM's infectious disease DAM work and for collaborative research to improve future pandemic preparedness.

2. Introduction

This report presents the evaluation of the Coronavirus disease 2019 (COVID-19) data analytics and modelling (DAM) activities for policy advice performed by the Dutch National Institute for Public Health and the Environment (RIVM) in the period from 1 January 2020 to 1 June 2022. In this period, the Netherlands reported the first case of COVID-19, the pandemic was declared, control measures were implemented, a large-scale vaccination program was rolled out, and – in the end – most measures were relaxed. The COVID-19 DAM work conducted at RIVM was used to inform the Ministry of Health, Welfare and Sport, the Outbreak Management Team (OMT), and the Health Council of the Netherlands. The OMT advice based on this information was subsequently used by the Dutch government to decide on its policy for infectious disease control. The evaluation (audit) was commissioned by the Scientific Advisory Board (SAB, *Commissie van Toezicht*) of RIVM, and was performed by an external audit committee (AC, described in section 2.5) using the guide for external evaluations at the Dutch National Institute for Public Health and the Environment (section 2.4).

2.1 COVID-19 data analytics and modelling at RIVM

Dutch National Institute for Public Health and the Environment (RIVM)

RIVM works towards a healthy population living in a sustainable, safe, and healthy environment, and has done so for more than a century. It is an agency of the Ministry of Health, Welfare and Sport (*Volksgezondheid, Welzijn en Sport, VWS,* referred to as 'Ministry of Health' in this report). Commissioners of work conducted by RIVM include national ministries, inspectorates, and international organisations such as the European Union and the United Nations. In addition to its role as a research institute in the field of public health and the environment, RIVM has a role as a trusted advisor to the government, professionals, and the public. The institute has five operational roles (policy advice, information provision, monitoring & surveillance, crisis & incident management, and programme coordination), supported by research. Scientific knowledge constitutes the basis for the execution of RIVM's tasks. This knowledge is gathered by RIVM itself, commissioned by RIVM, or collected from elsewhere by RIVM. The DAM activities that are evaluated in this report contribute particularly to the RIVM roles of research, scientific policy advice, and monitoring & surveillance, so the audit focused on these three roles. RIVM's COVID-19 DAM activities ranged from data collection and data curation to mathematical and statistical analysis and visualisation of the results. In other words, it constituted the process of transforming raw data into information that can be used to advise decision makers.

Center for Infectious Disease Control (CIb)

The COVID-19 DAM activities were carried out by experts of the Center for Infectious Disease Control (CIb) of RIVM. The CIb coordinates infectious disease control in the Netherlands by developing prevention strategies, ensuring high vigilance, and facilitating rapid responses to outbreaks. The CIb experts perform scientific research, develop technologies, and engage in international collaborative projects. In the event of a major outbreak, the CIb coordinates communication about infectious disease control in consultation with the relevant authorities. The DAM activities that are evaluated in this report were performed by experts based in two centres within the CIb: (i) the Centre for Infectious Diseases, Epidemiology and Surveillance (EPI) monitors the occurrence, burden, and trends in infectious diseases in the Netherlands. In addition, it studies the impact, effectiveness, and

cost-effectiveness of control measures; (ii) the Centre for Zoonoses and Environmental Microbiology (Z&O) focuses on early warning and risk assessment of the transmission of pathogenic microorganisms from animals, food, and the environment to humans in the Netherlands. Most of the COVID-19 DAM work that is discussed in this report was performed by the two EPI groups and one Z&O group described below.

Modelling of Infectious Diseases department (EPI-MOD)

The Modelling of Infectious Diseases department within EPI (EPI-MOD) consists of DAM experts who conduct research and epidemiological analyses on all infectious diseases that are relevant to the Netherlands. EPI-MOD supports all departments within EPI. During the audit period, EPI-MOD performed COVID-19 DAM work for policy advice by collecting data on contact patterns in the Dutch population; developing and using methods for assessing the transmission of the SARS-CoV-2 virus; developing and using nowcasts to assess the current situation; and developing models to perform short-term projections and scenario analyses for options of infectious disease control. EPI-MOD worked on 21 different DAM topics for COVID-19 policy advice during the audit period, with the most frequently addressed topics being:

- Effective reproduction number (R_t) based on notified cases (i.e., persons with positive tests), hospital admissions through the Online system for registering notifiable diseases (OSIRIS), and hospital admissions through the National Intensive Care Evaluation (NICE), broken down by virus variants and safety regions (output produced twice weekly);
- Projections[1] of the number of COVID-19 intensive care unit (ICU) admissions and hospitalisations, as well as the number of occupied beds in ICUs and wards, including scenario analyses on the effect of measures, vaccinations, and new virus variants (output produced weekly);
- Projections[1] of hospitalisations and ICU admissions based on positive test reports with a one-week horizon (output produced weekly);
- Projections of proportions of new SARS-CoV-2 variants (output produced weekly);
- Community mobility trends (output produced weekly);
- Number of contagious people (output produced weekly in 2020 and 2021);
- Vaccination coverage (output produced weekly from January 2021).

Data Analytics, Research and Automated Reporting team (EPI-DIS-DARA)

The Data Information and Signalling department within EPI (EPI-DIS) established a team dedicated to COVID-19 early in 2020. This Data Analytics, Research and Automated Reporting team (EPI-DIS-DARA) conducted automated reporting and data analytics activities to provide EPI-MOD with dataflows and data quality checks, and to facilitate open data. Daily, EPI-DIS-DARA provided:

- Information on clusters of infections according to source and contact tracing, including breakdown by potential settings of infection;
- Identification of probable nursing home residents among persons that tested positive (assessment based on registration in OSIRIS or a combination of postal code and age), to estimate the number of (newly) infected nursing home and disability care locations;
- Number of potentially reinfected cases.

[1] A projection is a statement about what is expected in the future if the current dynamics continue to play out. Scenario projections are statements about what could happen in the future under different 'what if' scenarios.

National Sewage Surveillance department (Z&O-NRS)

From February 2020, the National Sewage Surveillance (NRS) department within Z&O provided data and data analytics on the prevalence of SARS-CoV-2 particles in sewage wastewater to the Ministry of Health. By September 2020, more than 300 sewage treatment plants in the Netherlands provided wastewater samples to RIVM to facilitate wastewater-based SARS-CoV-2 surveillance in all municipalities. Z&O-NRS provided concentrations of coronavirus particles in sewage water daily from February 2020. In addition, the department calculated the delay between viral load in sewage water and hospitalisations for the delta variant once.

Staff

During the audit period, an average staff capacity of approximately 8.8 full time equivalents (FTE) was available for the COVID-19 DAM activities of EPI-MOD and approximately 7.7 FTE for the COVID-19 related work of EPI-DIS-DARA.[2] The staff composition of EPI-MOD and EPI-DIS-DARA changed over the audit period but there were only small changes in the *total* amount of FTE within these teams. The work of EPI-MOD was supported by data scientists from EPI-DIS-DARA and by epidemiologists affiliated with two other EPI teams: a team dedicated to COVID-19 within the Respiratory Infections (EPI-RES) department and a team dedicated to COVID-19 within the National Immunisation Programme (EPI-NIP) department. The precise FTE contribution of EPI-RES and EPI-NIP to the COVID-19 DAM work could not be quantified because it could not be differentiated from the other activities that were part of the operational pandemic response. The capacity of Z&O-NRS dedicated to COVID-19 increased from 5.0 FTE in 2020, to 11.7 in 2021, and 30.0 FTE in 2022.

Funding

The CIb's primary funding source is an annual lump sum payment from the Ministry of Health. During the audit period, the Ministry of Health provided extra direct funding specifically for COVID-19 activities. EPI-MOD and EPI-DIS-DARA spent respectively €2,935,763 and €3,514,067 on COVID-19 work over the period 2020-2022. Z&O-NRS spent €29,853,031 on COVID-19 surveillance until September 2022. Further details about staff capacity and funding can be found in RIVM's self-evaluation report that is made publicly available simultaneously with this audit report.

2.2 Organisation of COVID-19 policy advice in the Netherlands

RIVM is governed by special Dutch legislation ('Act on the RIVM'), which states that the director of the CIb is expected to deliver medical-epidemiological advice to the Minister of Health in the event of a crisis. To this end, a multidisciplinary OMT is composed by the CIb. During the audit period, the OMT consisted of ten permanent members and up to fifty other experts, most of whom were not affiliated with RIVM. The director of the CIb acted as the OMT chair and another CIb employee acted as the OMT's scientific secretary. The Ministry of Health frequently asked the OMT for advice on the development of the SARS-CoV-2 virus during the audit period. The OMT chairman passed requests from the Ministry of Health to the relevant teams, who then performed the DAM work and presented the results to the OMT.

[2] Based on Table 5 and 6 on page 41 and 42 of the self-evaluation report, using updated information about the EPI-DIS-DARA staff: the total staff FTE of EPI-DIS-DARA was 6.0 instead of 8.0 in the year 2020.

The OMT met almost weekly during the audit period and EPI-MOD delivered DAM results for nearly all these meetings. The head of EPI and the head of EPI-MOD presented graphs showing the actual development and graphs showing the prediction for upcoming days/weeks, considering historical data and analysis of models of potential intervention scenarios. The degree of uncertainty was also displayed in these graphs, presenting optimistic and pessimistic scenarios. The calculation and assumptions were explained verbally. An additional quality check on the predictive power of the modelling was performed regularly, by statistically or visually comparing former prediction graphs and actual realisation over the recent past. This constituted the basis for further discussion on which the final OMT advice was based. In addition to RIVM's DAM results, the OMT also used scientific evidence from various (inter)national parties in its deliberations. The minutes of OMT meetings were confidential, but uncertainties and differences in assessment within the OMT were explicitly reported in the OMT advice. The Ministry of Health decided on the timing of publication of the OMT advice. Some of the OMT advice was published within one or two days after the OMT meeting; other advice was published several days later. The formal OMT advice was also sent to the Administrative Coordination Consultation (BAO), who performed an administrative evaluation for feasibility. The OMT advice plus BAO advice were sent to the Minister of Health and the Parliament, who made policy decisions. These decisions were then implemented by the Dutch security regions and other responsible actors in the field.

During the audit period, the Ministry of Health also asked the Health Council of the Netherlands for advice on vaccination strategies. The Health Council subsequently asked RIVM to provide DAM results to inform this advice. RIVM provided DAM results to answer eight policy questions related to vaccination strategies.

In addition to the formal requests from the Ministry of Health, the OMT, and the Health Council, RIVM had the task of answering questions from other stakeholders, such as other governmental sectors, public organisations, private institutes, and citizens. Such requests were triaged within RIVM and allocated to the most relevant experts.

2.3 Scope and function of the audit

The SAB of RIVM regularly commissions independent evaluations (audits) to assess whether the RIVM activities comply with current scientific standards. These audits fulfil a duty of accountability towards government and society. The main function of the audit described in this report was to assess the scientific quality and independence of the COVID-19 DAM activities that RIVM performed for policy advice. The audit was expected to result in specific lessons to improve the process of DAM and its use in policy advice, i.e., to learn for the future. The scope of the audit concerned RIVM's COVID-19 DAM for scientific policy advice in the Netherlands in the period 1 January 2020 up to 1 June 2022, primarily focusing on advice provided to the Ministry of Health, the OMT, and the Health Council of the Netherlands.

Importantly, the audit explicitly did not address:

- The COVID-19 control policy by the government of the Netherlands;
- The organisation of the scientific advice in the Netherlands with respect to infectious disease control;
- RIVM research projects on COVID-19 that were not intended for policy advice;

- COVID-19-related research and advice carried out by other actors than RIVM.

It should also be noted that this audit was not conducted at the level of specific data sets, models, and outcomes, but at a higher level, focusing on scientific and methodological approaches and processes of COVID-19 DAM for advice to policy makers. The AC focused on the information that was presented in the documents described in section 2.4, supported by interviews conducted during a site visit.

Five main questions summarize the scope of the audit:

1. What is the scientific quality of RIVM's COVID-19 DAM work for advice to policy makers?
2. Were the resources adequate for conducting this work?
3. Did the advice allow for informed public-health decision making by the government?
4. Was the outcome of RIVM's COVID-19 DAM work affected by influences from external actors who have an active interest in specific outcomes, such as the government, ministries, or industry?
5. Are RIVM's infectious disease DAM teams properly equipped to contribute to the future pandemic preparedness of the Netherlands?

Further details about the purpose and criteria of the audit are described in the 'Terms of reference' document (see 2.4).

Note that the SAB has commissioned two earlier evaluations that are relevant to the audit described in this report: (i) a scientific audit of RIVM-wide mathematical health modelling work, performed by an international external audit committee in 2016, and (ii) an interim evaluation ('quickscan') of the scientific quality and independence of RIVM's COVID-19-related activities from March to September 2020. The latter took place in 2021 and had a broader scope than the current audit.

2.4 Followed procedures

The executive board of RIVM appointed an internal audit project team that organised the audit process and programme under responsibility of and in close consultation with the SAB, with moments of feedback from the chair and the scientific secretary to the AC. Two members of the SAB were appointed as liaison officers who were involved in the preparation of the audit.

Instructions

In January 2023, the AC scientific secretary sent the following documents, provided by RIVM's internal audit project team, to the AC to provide instructions about the audit procedure:

- Terms of reference, which specified the purpose and criteria of the evaluation, the overall schedule and planning of the evaluation procedure, and the responsibilities of the AC;
- Strategy evaluation protocol 2021-2027 (SEP), which was drawn up by the Universities of the Netherlands, Royal Netherlands Academy of Arts and Sciences (KNAW), and the Dutch Research Council (NWO). The primary aim of SEP assessments is to evaluate the research quality, societal relevance, and viability of a research unit considering its own aims and strategy, and to suggest improvements where necessary. The SEP is geared towards the evaluation of research conducted at Dutch universities, University Medical Centres, and NWO or KNAW institutes;

- Guide for external evaluations at RIVM, which is based on the SEP, transformed into a guide for evaluations to accommodate the evaluation of the broader tasks of RIVM, i.e., its role as a trusted advisor for the government in addition to its role as a research institute.

Documents

In February 2023, the AC scientific secretary sent the following documents to the AC to prepare for the audit:

- Self-evaluation report by RIVM, which described key aspects of the organisation of COVID-19 DAM at RIVM, a critical reflection (by the CIb) on the main questions posed to the AC, a critical discussion of the viability and future proofing including a SWOT (strengths, weaknesses, opportunities, threats) analysis, and several appendices with case studies and background information;
- Stakeholder assessment report, which described the conclusions from structured interviews with 19 stakeholders of RIVM's COVID-19 DAM activities, conducted by an independent agency (Andersson Elffers Felix);
- Draft site visit programme, based on which AC members were invited to suggest additional interviewees for the site visit.

In March 2023, the AC received from the AC scientific secretary:

- Final version of the site visit programme (see Appendix 1);
- Addendum to the self-evaluation report, which contained a supplementary explanation of the scope of the audit (regarding departments and data streams), a preprint manuscript about modelling for COVID-19 hospital and ICU admissions in the Netherlands that was recently submitted to a scientific journal, supplementary information about societal impact, a translation of a newspaper article on a national platform for corona research, a supplementary explanation of one of the figures in the self-evaluation report, an English translation of the response of RIVM's directorate to the 2021 quickscan of RIVM's COVID-19 work, an overview of follow-up actions in reaction to the 2016 scientific audit of RIVM's mathematical health modelling, the Netherlands Code of Conduct for Research Integrity, and a draft version of the 'Quality assurance for quantitative analyses, including models and data analytics' system that EPI-MOD developed recently.

The self-evaluation report and its addendum, the stakeholder assessment report, and the Terms of Reference are made publicly available simultaneously with this audit report and RIVM's response to this report.

Pre-evaluation and site visit

AC members were invited to send their first impressions after reading the above-mentioned documents, as well as questions to be asked during the site visit, to the scientific secretary of the AC. The input of the AC members was used for preparing the site visit. In March 2023, a site visit was organised as a hybrid event. Three AC members joined this site visit online (Professor White, Professor de Blasio, and Dr Colizza) and the others were present in person. The AC conducted a series of interviews with RIVM experts and representatives, external experts, and external stakeholders. Most of these persons were interviewed in a physical face-to-face setting in groups of

two to four interviewees. Some persons were interviewed in an online setting. During the site visit, no video or audio recordings were made of conversations between the AC and interviewees.

Drafting the report and fact check

The AC comprehensively weighed all information that was provided to the committee, including the self-evaluation report, the stakeholder assessment report, and the input of the interviewees, and based its conclusions on the combination of these sources. This audit report was drafted by the AC scientific secretary in close consultation with the AC chair. The AC members and Professor Haines gave feedback on the draft report, after which the draft was finalized. The AC scientific secretary sent the final draft report to RIVM on 10 May 2023 for a check on factual points, after which the committee finalized the report as submitted to RIVM on 3 July 2023. The working notes and correspondence regarding the preparations by the AC, any written material on the interviews and the draft (incomplete) versions of this audit report are confidential.

2.5 Members of the audit committee

The SAB of RIVM appointed as members of the AC:

- Professor André Knottnerus, *chair* (Maastricht University, the Netherlands);
- Dr Vittoria Colizza (INSERM & Sorbonne Université, France);
- Professor Birgitte Freiesleben de Blasio (Norwegian Institute of Public Health & University of Oslo, Norway);
- Dr Wilbert van Panhuis (National Institute of Allergy and Infectious Diseases, USA);
- Professor Juliet Pulliam (Stellenbosch University, South-Africa);
- Professor Peter White (Imperial College London, UK & UK Health Security Agency).

The SAB of RIVM additionally invited two professors to provide feedback to the AC, given their outstanding expertise and important international roles in the fields of infectious diseases and public health:

- Professor Marc Lipsitch (CDC Center for Forecasting and Outbreak Analytics (CFA) & Harvard School of Public Health, USA) provided written feedback on the self-evaluation report and stakeholder assessment report prior to the site visit;
- Professor Andy Haines (London School of Hygiene & tropical Medicine, UK) provided feedback from the public health perspective on the draft audit report after the site visit.

The SAB of RIVM appointed as independent scientific secretary to the AC:

- Dr Linda van den Berg (Washoe Life Science Communications, the Netherlands).

All AC members, the AC scientific secretary, and Professor Haines declared that, to the best of their knowledge, they had no affiliation or relationship to the entity to be assessed which could lead to a biased assessment, and that they had no conflict of interest regarding the research unit to be assessed**.** Professor Lipsitch declared the same, apart from reporting a personal friendship with the head of EPI-MOD. They also were co-authors on several joint scientific publications. This transparency was appreciated, and no impediments were seen to the intended role of Professor Lipsitch to provide scientific feedback prior to the site visit. The AC members, Professor Haines, and Professor Lipsitch were offered an allowance and reimbursement of their expenses according to the RIVM regulations. Short biographies of the AC members and the additionally invited experts are

provided in Appendix 2, along with an overview of their current positions, ancillary positions, and interests. The evaluation and recommendations in this report constitute the AC's consensus. 'Currently' refers to the time of the site visit; 'we' refers to the AC members.

3. Findings

3.1 Research quality

Overall scientific quality

In circumstances of high pressure and given limited resources, RIVM's DAM experts produced work of excellent quality, also compared to national agencies and advisory bodies with similar missions in other countries. Examples of high-quality work include the early assessments of parameters using international data, R_t estimates, projections of hospital and ICU admissions that were updated weekly, and the work on vaccination strategies. RIVM adopted an integrated approach to data collection, data analysis, and modelling to interpret the status of the pandemic, predict the effectiveness of control measures, and advise on infectious disease control. The close collaboration between modellers, data scientists, and epidemiologists contributed to the high quality of the work. The DAM work was conducted under immense societal and time pressure: modellers often had less than two days to perform the work following a formal policy request, while being responsible for safeguarding the quality required to respond to such requests. Modellers generally included uncertainties in their outputs, which is crucial for the correct interpretation of the results.

We also found the work of the Z&O-NRS department impressive. This team built a pipeline to analyse sewage water surveillance data within a short timeframe. Using sewage water data allows for a rapid scale-up of surveillance activity. Sewage water can provide timely information at a relatively fine spatial resolution. This informed authorities about the local epidemiological situation and allowed local authorities to decide on for instance vaccine distribution.

Types of models used

Three main analyses were carried out repeatedly throughout the audit period: (i) estimations of the effective reproduction number R_t, (ii) one-week horizon statistical projections of the number of hospitalisations and ICU admissions with COVID-19 based on reported number of positive tests, and (iii) short-term projections (up to three weeks ahead) of the daily number of COVID-19 hospitalisations and ICU admissions, as well as the number of occupied beds in ICU and wards, resulting from an age-stratified transmission model with scenario analyses. For the latter, RIVM used a deterministic, age-structured, Susceptible-Exposed-Infected-Removed (SEIR) model with a range of input parameters and a Poisson observation model. This is an appropriate choice for situational awareness and short-term forecasting, given that the models had to be rerun and queried repeatedly with varying input data. Other modelling approaches were also used, for instance to assess the impact of testing and digital contact tracing and transmission in specific settings such as schools. Repeated collection of behavioural data (e.g., contact patterns) by EPI-MOD through the pandemic supported the modelling work.

Predictive performance

For short-term projections, the EPI-MOD experts routinely compared the projections with last week's actual observed data. For some other types of DAM work (e.g., estimating the R_t), EPI-MOD compared a data-driven and model-driven approach, to evaluate whether the model assumptions were not too restrictive. The predictive performance of the models varied from highly accurate to

reasonably good given the limited time, the evolving epidemiological context, and the progressive updates of knowledge on the virus and the epidemic. The predictive performance appeared to be adequate to respond to the needs of decision makers during most of the audit period. As the pandemic progressed, the predictive performance of the models decreased, because the epidemiological situation became complicated with build-up of immunity in the population, novel variants, multiple vaccination rounds, interventions, and their interactions. The decline in predictive performance was recognized and communicated. A formal scientific comparison of the predictive performance of the RIVM models and models developed by other Dutch institutions was in progress at the time of the site visit.[3]

Scientific output

Peer-reviewed publication is challenging during a crisis, requiring substantial additional human resources, and for RIVM, we do not consider publishing peer-reviewed papers a priority over providing high-quality scientific advice to policy makers during the acute phase of a public health crisis. RIVM produced several peer-reviewed articles about its COVID-19 DAM work during the audit period. For instance, RIVM's DAM experts published an article analysing early data from Wuhan, providing baseline parameter estimates, showing alertness and capacity to respond to emerging threats. This paper was frequently cited. However, the number of peer-reviewed scientific articles is currently still relatively low compared to the massive volume of work that has been performed by RIVM's DAM experts. RIVM published most reports and updates in Dutch, and during the evaluated period, much of this work did not yet result in scientific articles or technical reports in English. More peer-reviewed articles about RIVM's COVID-19 DAM work are starting to be published now. Relatively low output through traditional peer-reviewed publications signals a lack of human resources that would otherwise have been devoted to preparing the modelling outputs for rapid communication to the national and international scientific community. Rapidly making more reports and updates available in English and publishing more peer-reviewed papers would have been highly valuable for other countries worldwide to assess the epidemic situation and learn from the estimated impact of interventions. Many research groups in other countries were uploading papers on preprint servers during the pandemic so that these were in the public domain and could be critiqued.

Academic reputation and recognition by peers

RIVM's COVID-19 DAM experts operate at the international forefront and have an outstanding academic reputation. RIVM has been among the few top institutes in the world in the field of infectious disease DAM since long before the COVID-19 pandemic, with a stable presence in scientific networks, consortia, and public health groups. The researchers have participated in international scientific studies and were actively involved in several collaborative publications during the audit period. An example of a frequently cited collaborative publication is a 2020 Lancet paper on the influence of country-based mitigation measures on the course of the COVID-19 pandemic. In

[3] In this formal comparison, RIVM's model is being compared with models developed by the Netherlands Organisation for Applied Scientific Research (TNO) and the National Coordination Centre for Patient Distribution (LCPS) by calculating a weighted interval score. This score is a relative measure that compares the performance of different models using the same input data. In this case, it compares how well the projections of ICU admissions captured the actual observations in the Netherlands. TNO and the LCPS are the only other teams that have produced such projections in the Netherlands.

addition, RIVM's DAM experts participated in prestigious scientific events, where they were invited to give presentations.

Involvement in research collaborations

RIVM's DAM teams were actively involved in several international consortia and collaborations during the audit period. For instance, EPI-MOD experts joined meetings of the World Health Organization (WHO), WHO/Europe, and European Centre for Disease Prevention and Control (ECDC), where they contributed to the discussions and provided their insights and results. In addition, RIVM's DAM experts performed comparisons with models developed in other countries for components of the transmission model that the team felt uncertain about (e.g., vaccine efficacy and seasonal influence). These international collaborations helped to compare the RIVM methodology with approaches in other countries, and scientific publications on these comparisons are now being prepared.

We learned that the CIb has developed an international strategy in response to one of the recommendations made by the 2016 audit committee that evaluated RIVM-wide mathematical health modelling work. This strategy includes comparative studies at an international level. The CIb has established a framework service contract with the ECDC for international projects on infectious disease modelling for policy making. During the audit period and thereafter, the CIb participated in two projects funded by the European Commission that focused on informing COVID-19 control (EpiPose) and pandemic preparedness (ESCAPE). The EpiPose consortium has worked on the inference of key characteristics of COVID-19, set-up a survey of contact patterns that was implemented in twenty European countries and set up participatory surveillance systems for COVID-19 (*Infectieradar* in the Netherlands). ESCAPE aims to enhance Europe's preparedness for a pandemic of pathogen X by improving the efficiency and scalability of early pandemic response plans. Z&O-NRS participates in the European Sewage Sentinel System for SARS-CoV-2 (EU4S) platform, which facilitates exchanging knowledge about wastewater-based epidemiology. EU4S intends to broaden its scope to emerging pollutants, pathogens, drugs, and antimicrobial resistance.

We observed that RIVM's DAM experts had more scientific collaboration with international than with national scientific partners, largely benefiting from pre-existing collaborations. This is not surprising because the field of infectious disease modelling is relatively small globally and there are well-established international networks of collaborators who have assisted each other over many years. Nationally, from early 2020, RIVM developed new contacts with partners TNO and LCPS, that also produced model projections on COVID-19 ICU admissions and hospitalisations. Comparisons with these results were presented in RIVM's technical briefings for the Health Committee of Parliament. Scientific publications on this are currently in preparation. There was not enough time to build additional new national collaborations because of the severe time pressure and the small size of the groups involved in RIVM's COVID-19 DAM work. A considerable time investment is required to coordinate collaborative activity and some countries had entire secretariats dedicated to this task during the crisis. However, more national collaboration between RIVM and university-based researchers could have contributed to the confidence among the academic and public health community that the RIVM modelling was robust by facilitating the comparison of independent models for cross-validation. It could also have facilitated regional stratification of model fitting and output, allowed more questions to be answered, and perhaps alleviated the pressure on the small

RIVM DAM teams (although coordinating collaboration also requires dedicated capacity). National collaboration could also have helped with code optimisation, documentation, and communication. Moreover, more national scientific cooperation could have contributed to the transparency and replicability of RIVM's work, which could have been beneficial for public trust. Multiple academic infectious disease research groups in the Netherlands were highly motivated to contribute to COVID-19 DAM for scientific policy advice during the audit period.

We acknowledge that establishing novel collaborations with academic modelling groups is challenging during a crisis because there are multiple obstacles to overcome. For instance, there is a distinction between infectious disease modelling for scientific purposes and for scientific policy advice, and the specific requirements for operational modelling need to be considered to establish fruitful collaborations between experts in these two fields. Moreover, modelling for policy advice has a very rapid turnaround and is customer-focused. Now that the pandemic-related pressure on RIVM has decreased, we encourage the institute to investigate ways to overcome these obstacles and promote and establish structural scientific exchange with the Dutch academic modelling community.

Transparency and reproducibility

Reproducibility is a core aspect of research quality. RIVM made substantial efforts to share data and model source codes as openly as possible. However, for the highly policy-relevant DAM work of projecting the COVID-19 healthcare burden, it did so at a relatively late stage. A basic brief description of the transmission model was published on the RIVM website in March 2020. A living document with a more complete description in Dutch, targeting a broader audience, was first published on the RIVM website in March 2021 and was later updated several times. An explanation targeting non-modeller scientists in English was published later. At the time of the audit, most of the code was openly available. The documentation supporting the code was of variable detail-level and quality at the time of the audit, with several of the repositories having limited documentation. This lack of transparency regarding the code of the transmission model raised substantial criticism by external parties during the audit period and thereafter. Several external experts that we met, said that the scientific quality of RIVM's COVID-19 DAM work was impossible to assess during the audit period due to transparency issues. This is in line with observations described in the stakeholder assessment report.

RIVM justified not making all parameter values, data, and code available for several reasons. Parameter values such as those related to hospitalisation were not shared because they were continuously adjusted to the latest reports, i.e., they were estimated every week based on the available data. Furthermore, the code needs high-resolution data that cannot be shared for privacy concerns and regulations. Moreover, the code itself contains privacy-sensitive data because it includes data curation commands that filter out invalid entries. During the site visit, RIVM representatives explained that they are improving their software engineering practices, in part by developing a more modular code that would separate these data curation steps from the scripts needed to run the models. According to the audit committee, a detailed description of the models should preferably have been made available already during the first pandemic wave, and updated since then (e.g., for variants and vaccination), with new parameter values being available on a regular basis. Issues related to timely information sharing are not unique to RIVM, and they are understandable given the fact that the DAM experts were under severe time pressure to deliver

results for scientific policy advice, which is their core task. We also recognise that standard methods for model and code sharing have not been fully developed by the modelling community. RIVM could not be expected to develop such methods during the pandemic because they rightfully prioritised DAM work for scientific policy advice. The use of synthetic data – which is being explored by RIVM's DAM experts at present – relies on the use of validated algorithms, and this is particularly challenging during the early period of a pandemic, with high uncertainties related to data collection and natural history parameters. Increasing the size of the DAM teams would have enabled them to spend more time on properly documenting the models and making the code and data openly accessible as far as privacy legislation allows at a much earlier stage. We will discuss this further in section 3.2.

3.2 Resources

Access to data streams

All data used for the COVID-19 DAM work were either owned by RIVM or transferred to RIVM on a voluntary basis. The EPI-DIS-DARA team developed data pipelines that met the needs of stakeholders (in particular EPI-MOD and the EPI-RES and EPI-NIP teams dedicated to COVID-19). Timely access to sufficiently comprehensive and valid data is crucial for high-quality modelling for policy advice. Overall, RIVM's data access and data flows were much better than in many other countries. The Dutch data were particularly good with respect to behavioural information, collected for instance with contact surveys and surveys about behavioural changes and well-being. Nevertheless, there were severe limitations in data availability. The DAM experts had to spend a disproportionate amount of time on collecting or linking some data sets and failed to obtain access to some other data streams. This was due to a variety of reasons:

- *Privacy legislation:* Very strict interpretations of the General Data Protection Regulation (GDPR) in the Netherlands caused limitations in data access and – crucially – data linkage, that slowed down some projects. For instance, the teams were unable to obtain access to telecom data to estimate human mobility between regions, even at an aggregate level. In other instances, the teams could only use data sets after developing time-consuming workarounds. Strict interpretation of the GDPR in combination with informed consent for sharing vaccination data[4] resulted in difficulties in linking vaccination data at the individual level to other data sets;
- *Voluntary data sharing:* External data sets are shared with RIVM on a voluntary basis, so RIVM had to negotiate with universities, hospitals, and other data owners. The strict interpretation of the GDPR in the Netherlands made such organisations hesitant to share data, because they feared legal ramifications. These data owners often negotiated that they would only share their data for the duration of the pandemic and on the condition that the data would exclusively be used for a specific purpose. This created several problems. First, it implied that RIVM could not share the data with external collaborators or experts that wanted to reproduce the results. Second, it prevented RIVM from addressing unanticipated scientific questions that arose as events occurred and knowledge accumulated. Third, it hindered RIVM in continuously learning lessons and developing analytical techniques after the pandemic in order to be better prepared for the next pandemic;

[4] Data about the vaccination status of individuals could only be shared with RIVM if these persons had given informed consent for this.

- *Scattered data:* Some types of data were highly scattered over different data sources. Collecting and combining them required a disproportionate amount of time. For instance, data on vaccine coverage had to be distilled by combining data from many different data sources;
- *Delays in reporting:* Delays in data availability hampered the use of some types of data. For instance, RIVM could not use mortality data of Statistics Netherlands as an outcome measure to monitor the pandemic because there was a four-month delay in the availability of causes of death statistics;
- *Non-structural funding:* Collecting some types of data relied on non-structural funding. For instance, the valuable measurements of contact patterns partially relied on funding from the European Commission, having a limited duration.

Now that the acute phase of the pandemic has ended, we recommend evaluating the limitations described above and taking measures to ensure more efficient data access during future crises, by establishing technical infrastructure and data use agreements that are both scientifically adequate and ethically acceptable for better pandemic preparedness.

Human resources

The size of the EPI-MOD team is small considering the amount of high-quality work that it produced at the reporting rhythms during the audit period. The excellent performance and expertise of RIVM's COVID-19 DAM experts reflect the investments to recruit, train, and retain top scientists that RIVM has made prior to the pandemic. RIVM would not have been able to facilitate an adequate crisis response if these foundations had not been laid in the last decade. This also indicates that many processes have successfully been standardized and automated, to speed up some tasks.

The working atmosphere in the teams that we met appeared to be very positive and collegial. Some staff members that we spoke to were in close contact while working from home and helped each other. Others have felt more alone. During a crisis, it is important to stay aware of how the staff is doing and this is particularly difficult when people are working from home. We noticed that the DAM staff is highly dedicated and understandably felt immense societal and time pressure because of their responsibility to produce reliable outcomes to facilitate and optimise policy decisions that affected the lives of millions of people within a very short time. RIVM structurally has support policies and interventions for its employees, including the services of a counsellor, an occupational physician, a corporate social worker, confidential advisors, and an ergonomics coach. During the audit period, all RIVM employees were offered extra workshops about healthy energy balance, and mental health check-ups by an external party. With 83% of EPI personnel making use of these mental health check-ups, these extra measures were well-received. We also had the impression that the staff felt supported by their heads.

Evidently, there is a need for additional staff to mitigate the risk of burnouts in the long term. In addition, we heard multiple examples of things that could have been done better if the team would have been larger. A larger team could have spent more time on quality control and documentation, addressed additional (lower priority) questions that are also important, and more rapidly shared the modelling methodology and outputs with the international and national scientific community and the public. In addition, the teams might have been more able to engage in potentially fruitful national collaborations if they had been larger.

It turned out to be very challenging to onboard qualified new team members during the crisis. Many teams across the world experienced difficulties in hiring and training DAM experts; this was nearly impossible during the acute phase of the pandemic. We also learned that at RIVM, there are structural obstacles that hinder the recruitment and retention of high-quality senior external DAM experts. RIVM was constrained to using standard hiring procedures during the pandemic and no special surge recruitment mechanisms were available to address the crisis. RIVM could only offer less favourable career prospects and a lower salary compared to academic employers. This is due to the salary system of the government ('*functiegebouw*'), which states that employees cannot progress to higher salary scales if the function itself does not change, even if they perform above expectations. This results in relatively low salaries given the quality of and the responsibilities associated with the work. This situation makes it difficult to retain and attract external high-quality senior experts. Indeed, several external infectious disease modellers who had a position at the level of assistant or associate professor at one of the Dutch universities expressed an interest in working on COVID-19 DAM at RIVM during the audit period but indicated that the substantially lower salary was an issue. These difficulties must be addressed before a new pandemic occurs.

The problem discussed above mainly applies to the EPI-MOD and EPI-DIS-DARA teams. The situation of the Z&O-NRS department is different: this team was created in February 2020 specifically to monitor SARS-CoV-2 particles in sewage water. The team was significantly scaled up during the pandemic. In the beginning, the team had to perform a lot of manual work. In 2021, the process was automated. While this could have been done more quickly if the team would have been larger from the start, the team had been scaled up substantially at the end of the audit period. However, it is a challenge also for Z&O-NRS to retain this capacity now that the pandemic-related pressure on RIVM has decreased, even though the team could address other viruses (e.g., monkeypox) and other public health challenges such as antimicrobial resistant bacteria, microplastics, and toxic chemicals in sewage water. Z&O-NRS therefore appears to be at risk of losing key competence, preparedness capacity, and its current international frontrunner status.

Financial resources

The overall availability of financial resources from the Ministry of Health was not described as a limiting factor in the self-evaluation report. However, we observed that limited capacity and human resources prevented RIVM's COVID-19 DAM teams to perform relevant tasks that would have been beneficial to the pandemic response (e.g., harmonising modelling approaches, focusing on regional models, and documenting the code to make methods and code available at an earlier stage). Baseline funding should be urgently improved to ensure future pandemic preparedness and responsiveness.

IT infrastructure

The IT infrastructure available to the COVID-19 DAM teams appears to have been largely adequate. Before the pandemic, RIVM had already installed improved computational facilities, including a high-performance computing cluster (HPC) and a data management system. The HPC is a virtual cluster that can be scaled up when needed. However, the required HPC capacity had to be reserved for performing particular tasks, which thus demanded quite some planning. The DAM teams at the CIb have converged to using the programming language R as a common software platform, although

Mathematica, Java, and Python are occasionally used for specific projects. Programming in R is fast compared to other programming languages, but computation times may be long. RIVM has created a vacancy for a software engineer who could assist the DAM experts in making the code more efficient, thereby reducing computation time.

Quality assurance procedures

Quality assurance was performed through internal and external checks, comparisons between models and observations, and comparisons between different models. As there was some overlap between the DAM work performed by the various RIVM experts, the results from one model could often be compared with the outcomes from another model to verify the quality of the results. In addition, RIVM's DAM experts compared their work with that of international colleagues, for instance within the EpiPose project, WHO modelling calls, the Nowcast Hub, and ECDC Scenario Hub, as well as with national colleagues from LCPS and TNO. In addition, following the recommendations of the 2016 audit committee of the RIVM-wide mathematical health modelling activities, the CIb has initiated the development of a quality assurance system for its DAM work using a bottom-up approach. This quality assurance system was based on the UK's Aqua Book guidelines and was implemented in a system designed to ensure that the guidelines are appropriate for the local situation and the required timeliness of the DAM work. The system is now being formalised.

As we discussed in 3.1, publishing details about the modelling methodology would have better enabled external investigators with the required expertise to reproduce RIVM's COVID-19 DAM work. Researchers in the community reported difficulties in timely access to this information for the important model on the projection of ICU occupancy used to inform policy recommendations. In the future, improving coding practices could facilitate the transparency of RIVM's DAM work, thus strengthening the quality assurance procedures.

3.3 Relevance to society and timeliness

Use of COVID-19 DAM for policy advice

During the first few months of the pandemic, RIVM mainly provided unsolicited advice. For instance, EPI-MOD already started analysing data from abroad before SARS-CoV-2 was detected in the Netherlands and before the Ministry of Health requested COVID-19 DAM work from RIVM. As the pandemic progressed, policy makers increasingly started to ask questions that had to be answered using DAM approaches. It is our impression that RIVM was highly responsive to policy makers' questions. The DAM teams produced an impressive range of routine outputs, and responded to a multitude of questions that arose. The OMT convened 85 times during the audit period and RIVM presented DAM results at 71 of these meetings. The turnaround time between a formal request and the delivery of results to the OMT was extraordinarily low: usually RIVM presented DAM results within 0.5-2 days following the request. In addition, RIVM contributed to 39 'Catshuis meetings' (i.e., meetings of the cabinet with relevant experts and advisers). The director of the CIb also presented public technical briefings for the Health Committee of Parliament weekly or biweekly in the midst of the pandemic. We heard many positive comments about these technical briefings. RIVM's COVID-19 DAM experts also advised the Health Council of the Netherlands on COVID-19 vaccination strategies five times during the audit period.

Overall, the COVID-19 DAM work performed by RIVM allowed the Ministry of Health to make public health decisions based on high-quality scientific information. This provided legitimacy to the policy measures that were implemented in the Netherlands. Modelling often provided the leading scientific input that was considered in OMT meetings. Here, we mention some examples:

- In April 2020, RIVM's COVID-19 DAM experts provided estimates of the potential number of persons with symptomatic respiratory infections in the Netherlands to guide policy decisions on the required testing capacity at test stations;
- In March 2021, they provided advice on relaxations of infectious disease control measures (e.g., opening of primary schools and day care centres) ;
- At the end of 2021, they provided predictions of the potential impact of testing for entry to social contact venues such as restaurants, to inform policy decisions on this testing for entry.

RIVM declined answering questions that could not be modelled within the required time frame or for which no adequate data were available. For instance, it will not be possible to answer the question *'Should the curfew start at 20:00 or 22:00?'* with modelling approaches. However, most of the questions asked by Dutch politicians appeared to have been interpretable by RIVM's DAM experts. This has been facilitated by the intensive interaction between the CIb heads and policy makers, which will be discussed further in section 3.4.

Use of COVID-19 DAM by other stakeholders

Stakeholders other than policy makers were generally very positive about RIVM's input, but did not always get the specific input they needed. For instance, the municipal public health services (GGDs) had to translate the national RIVM DAM results back to regional information to predict the testing and vaccination capacity needed in their regions. The Health Council of the Netherlands would have liked RIVM to develop additional 'what if' scenarios and compare interventions. It is understandable that such specific needs could not always be addressed during the COVID-19 crisis due to time constraints, but we suggest investigating if and how this could be achieved in the future.

Communication of uncertainties and assumptions

The RIVM modellers continuously calculated and reported uncertainties in their analyses and outputs. Explaining the inherent uncertainties associated with DAM work was a central part of the communication efforts of EPI-MOD. Uncertainties were described in the form of a set of scenarios, prediction intervals, or as a written or spoken statements to supplement the results. This is one of the most challenging aspects to communicate to non-experts but paramount for the correct interpretation of results. Many stakeholders that we met indicated that uncertainties were adequately presented by RIVM, which facilitated appropriate interpretation. Nevertheless, some types of uncertainty could have been visualised or communicated more clearly (e.g., unknowns about the virus and uncertainty in the source data). In addition, while model assumptions were regularly addressed,[5] these were not always explicitly documented. As a result, some stakeholders

[5] Examples of such assumptions derived from the DAM results presented to the OMT on 11 February 2022, as described in RIVM's self-evaluation report:

- Today's reported cases provide information about hospital admissions eight days from now;
- The probability of hospitalisation per reported case differs among age groups, changes over time due to vaccination and testing behaviour, and is fitted with flexible modelling (P-spline);
- The probability of ICU admission differs among age groups, is constant over time, and is fitted with a flexible model (P-spline).

experienced difficulties in explaining RIVM's COVID-19 DAM results to their own stakeholders and answering questions from the media. Although external organisations are not responsible for RIVM's work, they are responsible for their decisions, advice, or actions based on RIVM's work, so we recommend investigating how uncertainties and assumptions can be communicated more clearly.

Interaction with journalists and the public

As soon as the scale of the pandemic became apparent, RIVM established a multidisciplinary COVID-19 communication team consisting of experts with a range of communication specialities. This team was responsive to questions from journalists and the public and organised question-and-answer sessions to inform journalists. As the pandemic progressed, the public became more knowledgeable and started asking more complicated questions. It became challenging for the communications team to provide timely answers to each of these questions in layman's terms. The communication team developed information about RIVM's COVID-19 DAM for the RIVM website and other communication channels. This was done in close collaboration with the DAM experts. For instance, web pages about modelling were published on the RIVM website and explainer videos related to COVID-19 were published on YouTube. Information about key epidemiological parameters was made available on the 'Coronavirus Dashboard' that was developed by the Ministry of Health. This dashboard was updated daily with the most recent information about important indicators of the pandemic, such as the number of reported hospital admissions, the number of positive tests, and the viral load in sewage water. RIVM's media exposure was very high during the pandemic but limited to the group leaders (i.e., the director of the CIb, head of EPI, and head of EPI-MOD). RIVM employees who frequently appeared in the media were often confronted with hate mails and threats. In addition, the institute was confronted with misinformation and disinformation spread by other parties.

During the audit period, public confusion arose about the distinction between the roles of RIVM, the OMT, and the Ministry of Health (see 3.4). The scientific DAM results were sometimes equated with the policy decisions that were based on these results. Some of this confusion may have been caused by the timing of publication of the OMT advice. Early in the pandemic, the OMT advice was published shortly *after* press conferences in which the Minister of Health announced new policy measures. Later, OMT advice was sometimes published shortly before such press conferences.

RIVM's COVID-19 DAM results were incorporated in the OMT advice as written text, for instance the reproduction number (R_t), the expected date of the peak of the number of hospitalisations, and the expected date that a novel virus variant would become dominant. In addition, the public could learn about the COVID-19 DAM results on which the OMT based its advice by watching broadcasts of the (bi)weekly technical briefings by the director of the CIb or by inspecting the slides of these briefings that were published on the website of the Health Committee of Parliament. Moreover, RIVM organised a weekly epidemiological report and a weekly press gathering, where topics such as the epidemiological situation, vaccination coverage, and genomic surveillance results were presented. Data were made openly available on the RIVM website and the Coronavirus Dashboard as far as privacy legislation allowed, e.g., regarding the number of cases, the number of hospital & ICU admissions, the R_t, vaccination coverage, and sewage water surveillance results. It is our impression that RIVM addressed most of the criticisms it received, with strong commitment to the principles of scientific integrity. In view of the criticisms, we will provide suggestions on improving transparency and communication with the public in section 4.2.

3.4 Scientific integrity and independence

RIVM is governed by special Dutch legislation ('Act on the RIVM'), which states that the institute shall perform research, monitoring, and surveillance for policy advice and to safeguard public health. According to the Act on the RIVM, the government and ministries can commission research on specific topics, but they cannot determine *how* the research is carried out or how the outcomes are reported. RIVM has installed a system to ensure scientific integrity and independence, including codes of conduct for its personnel, guidelines on public-private partnerships, trainings for staff (integrity training, moral deliberation sessions, and a trusted advisor training), the appointment of an independent confidant for scientific integrity, peer review and audit procedures, and the supervision by the external SAB.

In theory, RIVM's COVID-19 DAM work could have been influenced by policy makers and other stakeholders in many ways, e.g., if modellers would be sensitive to politically desirable outcomes, or to pressure from industry. However, we did not observe evidence that this has taken place during the audit period. RIVM's system to prevent undue external influence generally is robust and appears to have performed well during the audit period, and we have no doubts about the independence of RIVM's DAM experts. We heard about a number of examples of resisting undue influence, and of declining to answer questions within unfeasible time frames. We also heard examples of requests that were declined because the available data or methodologies would not allow the DAM experts to produce scientifically sound results. For instance, estimates of the number of infectious people in the country became too unreliable when vaccination was implemented, because hospital admissions could no longer be used as a proxy for the underlying number of infections. In other DAM work, estimates of the differential effect of different curfew time options could not be made reliably using modelling approaches. RIVM openly responded to criticisms and the institute attempted to respond properly to disinformation and misinformation. This underscores the scientific independence of the institute. Importantly, the staff members doing the day-to-day work were shielded from politicians and journalists to protect them from external pressure and to avoid additional workload.

The director of the CIb chaired the OMT and the heads of EPI and EPI-MOD also participated in the OMT meetings to contribute their expertise. In combination with the intensive interaction between policy makers and the RIVM heads, this has caused some public confusion regarding the independence of the RIVM DAM experts. Some members of the public equated scientific DAM results with the policy decisions that were based on these results. At the same time, intensive interaction and dialogue between experts and decision makers is crucial to facilitate an adequate crisis response and can be achieved without compromising integrity. However, to avoid public confusion, the importance of this dialogue and the related checks and balances to safeguard independence should be better communicated in the future.

3.5 Viability and future proofing

Now that the acute phase of the pandemic has ended, it is time to learn from the experiences and make organisational adjustments to ensure that the Netherlands will be optimally prepared for a next pandemic. We identified several vulnerabilities in the organisation of infectious disease DAM at RIVM. We will discuss these here and provide recommendations for the near future in section 4.2.

Retaining and recruiting DAM experts

To ensure pandemic preparedness of the Netherlands, it is of utmost importance to maintain the DAM expertise that is currently present at RIVM, to recruit and train new experts, and to strengthen the network in which RIVM's infectious disease DAM experts operate. As discussed in 3.2, recruiting and retaining high-quality senior level DAM experts is hindered by limitations that are beyond RIVM's influence. In the scientific audit of the RIVM-wide mathematical health modelling activities that was conducted in 2016, it was recommended to retain experienced modellers, with their rare knowledge and skills. The 2016 committee advised to introduce career progression paths to create a long-term perspective for these experts. However, this is hampered by the so-called '*functiegebouw*' system that we mentioned in section 3.2. EPI-MOD is currently exploring ways to make its recruitment process and the remuneration of personnel more flexible through secondment and through competitive salaries and career paths. We were informed that several staff members were already promoted to permanent positions. In addition, RIVM intends to develop a structure to scale-up modelling capacity and organise additional support to decrease the workload of DAM experts during a crisis. These ambitions and developments should be supported.

Training DAM experts

Bringing in additional junior personnel is important to create a pipeline for capacity for the future. More in general, a broader base of modelling skills is needed in the Netherlands. EPI-MOD halted recruiting new master (MSc) students in 2020 and froze new PhD positions because the team did not have time to properly supervise MSc and PhD students. The first post-pandemic PhD student was recruited at the end of 2022, and there are four new PhD positions in 2023. In line with the recommendations of the 2016 audit committee of mathematical health modelling at RIVM, we encourage RIVM to attract more MSc and PhD students as a mechanism to recruit future staff members and to ensure sufficient capacity during future pandemics.

National collaboration

Instigating national collaboration is another way to create extra capacity. Now that there is less time pressure due to pandemic conditions, RIVM's DAM experts are open to strengthen the collaboration with Dutch academic partners, in addition to their vast international cooperation. For this purpose, they have recently started an internal discussion on how to optimally engage academic modelling groups in future crises. Furthermore, they have launched some innovative national collaborations, for instance with earthquake modellers at TNO. We encourage RIVM to continue along this line and establish structures to collaborate and share scientific information with the Dutch academic community, including infectious disease modellers. There are multiple examples of successful collaborations between public health institutes and academic research groups in other countries. Examples from the countries of origin of the AC are:

- In France, the Coordinated Action on Modelling (*Action Coordonnée Modélisation*) was created early 2021 as a framework to promote collaboration across modelling teams and with the national public health agency (*Sante Publique France*);
- In Norway, Open Knowledge Meetings were organised during the pandemic; these operated as a sounding board;
- In the UK, the National Institute for Health Research funds health protection research units that are partnerships between the Health Security Agency and different universities funded on a competitive basis. The long-established Scientific Pandemic Influenza Group on Modelling (SPI-

M) coordinates work of multiple independent modelling groups, from both academia and public health agencies, to advise the UK government. The Royal Society's Rapid Assistance in Modelling the Pandemic (RAMP) initiative coordinated support from academic volunteers to assist public health during the COVID-19 crisis;

- In the USA, the Models of Infectious Disease Agent Study (MIDAS) network (funded by the National Institutes of Health, NIH) worked with cooperative agreements that could pivot from routine research activities to pandemic response modelling in times of crisis. During the pandemic, the MIDAS network organised multiple working groups in collaboration with modellers at the CDC to discuss COVID-19 modelling;
- In South-Africa, a COVID-19 Modelling Consortium was established, but the public health institute involved (the National Institute for Communicable Diseases) did not have in-house modelling capacity.

Access to data streams

Getting access to and linking required data sets was very time-consuming during the audit period. In addition, access to certain types of data (e.g., hospital or clinical data) was negotiated for a limited period. i.e., the COVID-19 crisis. In other instances, access was never obtained (e.g., telecom data). The importance of high-quality data sets and data linkage for modelling purposes cannot be overemphasised, especially during a pandemic. A robust data framework is a crucial element of a strong pandemic preparedness plan. In addition, access to data needs to be continued, so that methods of analysis can be developed and refined to be better prepared in the future. We recommend developing an effective strategy to achieve these requirements.

Regarding mortality data, we were informed that Statistics Netherlands (CBS) is now digitizing the process of collecting causes-of-death statistics, which is expected to decrease the delay in reporting to a few weeks in a few years from now. Legislation was recently adjusted to this end, allowing medical doctors to fill out digital cause of death certificates. One of the most urgent actions after the outbreak of a novel infectious disease is continuously assessing its severity, and real-time monitoring of mortality is an essential component of this assessment.

Transparency and communication

RIVM's COVID-19 DAM work received unprecedented attention from the public and the media during the audit period. As discussed in section 3.1-3.4, RIVM was criticised during the audit period for not making the code and data of crucial models used to inform policy decisions fully available, limited collaboration with Dutch academic modellers, and perceived mixing of roles. The interim evaluation ('quickscan') of the scientific quality and independence of RIVM's COVID-19-related activities that was commissioned by the SAB in 2021 identified transparency and communication as an important point of improvement. The SAB advised RIVM to clearly communicate the distinction between the results of research performed by RIVM and the policy advice generated by the OMT. In addition, the SAB recommended publication of the reports to the OMT in which predictions had been tested retrospectively, and the substantiation of statements made based on calculation models. In its response, RIVM explained that it strived for the greatest possible transparency and published its work on the RIVM website whenever possible, and that the OMT also integrated scientific evidence from various (inter)national parties in its final advice.

We acknowledge that RIVM had to set priorities given the immense workload during the audit period and that the institute has extensively invested in communicating about its COVID-19 DAM work despite this workload. We also acknowledge that the effectiveness of communication efforts depends on both sender and receiver. Nevertheless, we strongly recommend further improving the transparency and communication with various societal and stakeholder groups in the future. Points of attention include:

- RIVM has been involved in lawsuits, where the institute was summoned to share the code and data that it used for its COVID-19 DAM work. In fact, there is tension between relevant legislation (GDPR) on the one hand, and Open Science and Open Government on the other, with which other research institutions are also confronted. The EPI-MOD experts have now started changing their programming style, so that the code either does not contain privacy-sensitive information anymore or that this information can easily be removed from the code. In addition, the team intends to explore synthetic data as a solution to share privacy-sensitive data more broadly. We support these initiatives, while recognising that generating synthetic data during a crisis is a resource-intensive activity that would require dedicated expertise and staff time;
- RIVM's COVID-19 DAM results were made publicly available as written text incorporated in the OMT advice, as life broadcasts of the technical briefings in the House of Representatives, and in slides of the technical briefings by the director of the CIb. The timing of the publication of OMT advice was determined by the Ministry of Health. Often, the OMT advice was made public after policy decisions were announced. This may have added to public confusion about the independent role of RIVM;
- RIVM intends to invest more in explaining its roles and responsibilities to its stakeholders and the public. To this end, the institute plans to organise workshops and a summer school course on the science of infectious disease modelling and RIVM's role as public health institute. We support this initiative;
- In our view, international collaborative research is needed to explore and develop best practices in communicating uncertainties and assumptions, and in helping policy makers and other stakeholders to understand the possibilities and limitations of modelling approaches;
- Investigating whether processes for assessing misinformation and disinformation and tackling hate mail and threats could be further improved is an important point of attention.

Governance, processes, and internal collaboration

RIVM intends to develop and implement a structure that facilitates a rapid transition to 'crisis mode', including clearly defined roles, tasks, processes, and communication procedures. These plans include procedures to rapidly scale up capacity and support for the DAM teams, and more collaboration with Dutch modelling groups. In line with these plans, we also encourage RIVM to further promote internal collaboration, which has already proved effective in several cases. In this context, we have the impression that there could be more interaction between the EPI-MOD and Z&O-NRS teams. It is not surprising that more traditional epidemiological data sources were used for policy advice more frequently because the use of sewage water data for infectious disease surveillance is a novel approach. We recommend integrating sewage water surveillance data – having almost full population-based coverage – more into policy advice in the future. For instance, the results of sewage water surveillance may be used as input for modelling efforts or as a method of model validation. A random sample of the population doing regular self-testing would be a useful adjunct

because sewage water surveillance does not provide information about which subgroups in the population are infected.

Integrating behavioural data and other aspects of public health

During the COVID-19 pandemic, RIVM established a dedicated corona behavioural unit. Among other activities, the unit repeatedly carried out a survey about behavioural changes and well-being of the Dutch population during the pandemic. EPI-MOD used input from the corona behavioural unit for modelling work on disease burden estimation, scenario analyses for the effectiveness of testing, contact tracing, and the CoronaMelder app. Data on contact patterns were collected by EPI-MOD for use in the COVID-19 DAM work. Unfortunately, the DAM teams did not obtain access to telecom data to estimate human mobility between regions, due to very strict interpretations of the GDPR in the Netherlands. One of the recommendations made by the 2016 audit committee that evaluated RIVM-wide mathematical health modelling work was to investigate how behavioural sciences could contribute to developing relevant scenarios to help stakeholders make policy decisions. The CIb recently obtained funding for a new project in which epidemiologists, modellers, and behavioural scientists will collaborate. This project, called 'BEHAVE', aims to include behavioural data into transmission models, with a specific focus on COVID-19 and sexually transmitted diseases. We encourage the CIb to increase its efforts along this line.

Public health impact is much broader than the direct effects of COVID-19; it also includes the direct and indirect effects on the physical and mental health of the population caused for example by the disruption of working life, social life, school routines, and the economy. A 'societal impact team' (*Maatschappelijk Impact Team*, MIT) was therefore recently established in the Netherlands. The MIT has the task to advise the Dutch cabinet on the social and economic consequences of pandemics and how to deal with them. In the future, the Dutch government will consult the MIT about the social and economic consequences of new policy measures before policy decisions are made, and the MIT and OMT will have complementary roles as advisors to the Dutch cabinet. It should be explored whether and how the assessment of broader societal impacts can be integrated into the DAM work in the future.

Securing sustainable funding

We observed limitations in the resources of the teams – including human resources – that should be urgently addressed to ensure pandemic preparedness. In this context, we note that the different groups that were evaluated in this audit vary in size, maturity, and vulnerabilities. EPI-MOD is a mature team with excellent international standing. This team should be enlarged. Z&O-NRS was established only recently and needs support to consolidate its development, because RIVM and the Netherlands are a frontrunner in this rapidly evolving novel type of surveillance and the competence will be valuable to the international community in general. Importantly, most of the available funding for RIVM's COVID-19 DAM work (and in fact, pandemic-related research in general) has a temporary nature. This also applies to funding for support structures such as facilities to provide access to data streams. Now that the acute phase of the pandemic has ended, the sense of urgency of investing in research into infectious disease DAM tends to fade away. We would like to stress the importance of structurally investing in research to improve infectious disease DAM to ensure future pandemic preparedness, which is an important government responsibility.

4. General conclusions and recommendations

4.1 General conclusions and answers to main questions

We appreciated the audit process, which was well-organised. The discussions with interviewees took place in an open atmosphere and were transparent and constructive. This enabled us to formulate the following general conclusions (4.1), resulting in several specific recommendations (4.2).

Main question 1: What is the scientific quality of RIVM's COVID-19 DAM work for policy advice?

In circumstances of high pressure and given limited resources, RIVM's COVID-19 DAM experts produced work of excellent quality, also compared to national agencies and advisory bodies with similar missions in other countries. RIVM's DAM experts have an excellent international reputation. The modelling approaches were adequate, and uncertainties were appropriately taken into account. The work was conducted by a remarkably small team under immense societal and time pressure. Getting access to the required data sets was a very laborious task in some instances. Priorities had to be set, but RIVM's DAM experts did this in sensible way, ensuring robust support for decision-making.

RIVM produced several peer-reviewed articles about its COVID-19 DAM work during the audit period. but the number of publications was relatively low compared to the massive volume of work that has been performed by RIVM's DAM experts. This signals a lack of human resources that could have been devoted to preparing the modelling outputs for rapid communication to the national and international scientific community. There was much international scientific cooperation, but relatively limited cooperation with Dutch academic modelling groups during the audit period. While this was understandable given the time pressure, such cooperation could have contributed to the replicability of and the public trust in RIVM's work. RIVM made substantial efforts to share data and model source codes as openly as possible and as far as privacy legislation allowed but did so at a relatively late stage. As reproducibility is a core aspect of research quality, this should be improved in the future, and RIVM is already taking steps to achieve this.

Main question 2: Were the resources adequate for conducting this work?

Access to data streams: Timely access to sufficiently comprehensive and valid data is crucial for high-quality modelling for policy advice. RIVM's access to various data streams was scaled up rapidly. Overall, RIVM's data access and data flows were much better than in many other countries. However, the DAM teams had to spend a disproportionate amount of time on collecting and linking some types of data and was unable to obtain others. This was due to a variety of reasons, including very strict interpretations of the GDPR in the Netherlands, scattering of data sets over different sources, delays in the availability of some types of data, and non-structural funding for some data collection efforts. These problems should be evaluated and resolved before a new pandemic occurs.

Human resources: The excellent performance of the small DAM teams reflects RIVM's investments to recruit, train, and retain top scientists prior to the pandemic. RIVM would not have been able to facilitate an adequate crisis response if these foundations had not been laid in the last decade.

Having said that, the human resources available during the audit period were not optimal. A larger team could have done more DAM work and could thus have answered additional (lower priority) questions that were also important. In addition, RIVM would have had more time to share information about the models and engage in collaborations, thus facilitating model comparisons and external validations and improving overall transparency. The societal and time pressure on the staff was immense, so additional staff is also needed to prevent burnouts in the long term. Many teams across the world, including RIVM's teams, experienced difficulties in hiring and training DAM experts; this was nearly impossible during the acute phase of the pandemic. In addition, there are structural obstacles that hinder the recruitment of high-quality external senior DAM experts at RIVM. These difficulties must be urgently addressed.

Financial resources, IT infrastructure, quality assurance procedures: Limited human resources likely prevented RIVM's COVID-19 DAM teams to perform additional tasks that would have been beneficial to the pandemic response. This should be urgently addressed to ensure future pandemic preparedness. The IT infrastructure available to the COVID-19 DAM teams appears to have been largely adequate. A quality assurance system based on the UK's Aqua Book guidelines was developed for the DAM work. Limitations in publishing all essential details of the modelling methodology hindered external researchers with the required expertise to independently reproduce RIVM's COVID-19 DAM work during the audit period. In the future, using synthetic data and different coding practices could improve the transparency of RIVM's DAM work, thus strengthening the quality assurance procedures. For some analyses, providing aggregated data rather than synthetic data may be appropriate for the sake of timeliness during a crisis.

Main question 3: Did the advice allow for informed public-health decision making by the government?

Overall, the COVID-19 DAM work performed by RIVM allowed the Ministry of Health to make public health decisions based on high-quality scientific information. This provided legitimacy to the policy measures that were implemented in the Netherlands. The DAM teams produced an impressive range of routine outputs, and responded to a multitude of questions that arose. Modellers often had less than two days to deliver the results following a formal policy request, while being responsible for maintaining the quality and rigor needed to respond to such requests. Some policy questions could not be answered due to a lack of capacity; others could not be answered because modelling was not a suitable approach. Some stakeholders other than policy makers did not always get the specific input they needed because RIVM's COVID-19 DAM teams had to set priorities due to time constraints. This was done in a conscientious way.

The RIVM modellers continuously put forward uncertainties in their analyses and outputs. This is one of the most challenging aspects to communicate to non-experts, but paramount for the correct interpretation of DAM results. Many stakeholders indicated that uncertainties were adequately presented, which facilitated appropriate interpretation. Nevertheless, uncertainties and assumptions could have been communicated more clearly. International collaborative research is needed to understand and develop best practices in communicating uncertainties and assumptions, and in helping policy makers and other stakeholders to understand the possibilities and limitations of modelling approaches.

Main question 4: Was the outcome of RIVM's COVID-19 DAM work unduly influenced by external actors?

RIVM's system to prevent undue external influence generally is robust and appears to have performed well during the audit period. There was some public confusion about the distinction between the roles of RIVM, the OMT, and the Ministry of Health during the pandemic. As a result, the scientific COVID-19 DAM results were sometimes equated with the policy decisions that were based on these results. We consider intensive interaction between policy makers and the advising RIVM heads to have been conducive of a timely and adequate response to the crisis. Dialogue is important and integrity does not need to be affected by that. However, in order to prevent confusion about the role of RIVM, better communication on roles in relation to RIVM's firmly entrenched independence with the related checks and balances is strongly recommended.

Main question 5: Are RIVM's infectious disease DAM teams properly equipped to contribute to the future pandemic preparedness of the Netherlands?

Now that the acute phase of the pandemic has ended, it is time to evaluate and document the experiences, secure the acquired knowledge and expertise, learn from what happened and what could have been done better, and make organisational adjustments to ensure that the Netherlands will be optimally prepared for a next pandemic. We identified several vulnerabilities in the organisation of infectious disease DAM at RIVM, some of which cannot be addressed by RIVM alone, requiring concerted action of several institutions. Moreover, a new pandemic will undoubtedly include unforeseen novel elements. RIVM's and the Dutch national ability to flexibly respond to such challenges in the future will depend on the actions that are taken now.

4.2 Strategic recommendations for the near future

1. **Structurally strengthen the capacity of RIVM's infectious disease DAM teams.**

In line with the actions that RIVM has already initiated (described in 3.5), we recommend increasing the basic size of the EPI-MOD team and taking measures to retain the excellent staff of EPI-MOD, EPI-DIS-DARA, and Z&O-NRS. We also support RIVM's ambition to create a structure that facilitates a rapid upscaling of capacity during a new crisis. We urgently advise RIVM to engage in negotiations with the government to solve the structural issues regarding recruiting and retaining high-quality senior DAM experts – including more competitive salaries and better career prospects – before a new pandemic occurs. Additionally, a system to deviate from the normal rules during exceptional crisis situations should be considered to enable rapidly recruiting temporary surge capacity.

2. **Prioritise training of new infectious disease DAM experts in the Netherlands and attract more master and PhD students to RIVM.**

Training junior infectious disease DAM experts is crucial to ensure sufficient basic and surge capacity in the future. In addition, a broader base of modelling skills is indispensable in the Netherlands. We recommend attracting more MSc and PhD students and investing in DAM-related training and education programmes.

3. Structurally improve the access to all data streams that are relevant for DAM at RIVM.

We recommend evaluating the limitations regarding data access and developing a strategy including an overview of data sets required for infectious disease control, both during a pandemic and in non-pandemic circumstances. We also recommend setting up technical infrastructure and an ethical/legal governance framework to improve access to relevant data sets for pandemic preparedness and control (i.e., a streamlined system and framework), so that data access will consume less time and will be less of a limitation in future crises. Of course, this should be done in close cooperation with the data owning organisations. As regards mortality data, we encourage the Dutch government to promote (or, if necessary, enforce) the use of digital cause of death certificates while solving the practical limitations that doctors experience when filling out the digital forms. Overcoming the difficulties in gaining access to data, linking data sets, and sharing data with collaborators while adhering to the relevant legislation requires joint action by RIVM, the government, and other actors. A taskforce should be convened to investigate ways to facilitate sharing and linking data sets without violating data protection requirements or the privacy of the persons from whom the data were derived, both in crisis and non-crisis times.

4. Improve the transparency of and communication about RIVM's infectious disease DAM work.

We recommend investigating the various challenges related to transparency and communication that RIVM experienced during the pandemic. Based on this analysis, RIVM can undertake actions to improve transparency and communication with various societal and stakeholder groups. Points of attention include:

- We applaud EPI-MOD's initiative to change its programming style, so that the code either does not contain privacy-sensitive information anymore or that this information can easily be removed from the code. This will facilitate making the code openly available. In addition, we support the team's ambition to explore synthetic data as a solution to share privacy-sensitive data more broadly. This is expected to substantially improve transparency and reproducibility of RIVM's DAM work in the future, but will require dedicated staff time;
- As will be explained further in recommendation 5, we encourage RIVM to continue exploring ways to establish structures to collaborate and share scientific information with the Dutch research community. Such collaborations may also contribute to the transparency of and public trust in RIVM's infectious disease DAM work;
- Acknowledging that the timescales may be extremely short, we recommend making RIVM's infectious disease DAM results publicly available at the earliest possible stage;
- We suggest investing more in addressing questions from stakeholders other than national policy makers to ensure that their specific needs can be better met by RIVM in the future, while acknowledging that doing so will require additional personnel and dedicated staff time;
- In line with RIVM's ambition to invest more in explaining roles and responsibilities to its stakeholders and the public, we recommend investing in communication about internal procedures to ensure scientific independence, including the supervision by the SAB and audits by independent committees;
- International collaborative research is needed to understand and develop best practices in communicating uncertainties and assumptions, and in helping policy makers and other stakeholders to understand the possibilities and limitations of modelling approaches. We also recommend investigating how international best practices and learning points can be

implemented at RIVM, using input from communication experts. In addition, we recommend contributing RIVM's experience and learning points to the international body of best practices;
- We recommend investigating whether the processes for assessing misinformation and disinformation and tackling hate mail and threats could be further improved. We expect that worldwide exchange of best practices and international collaborative research on this topic will have added value.

5. Establish a national network of collaborating institutions based on pre-existing memorandums of understanding, within which data and models can be shared more easily.

We recommend establishing a formal collaboration structure that supports high quality feedback and integration of expertise from other national (academic) modelling groups that meet the expertise requirements into RIVM's infectious disease DAM activities. Pre-arranged agreements with academic collaborators (e.g., through honorary or combined positions) may provide a way to rapidly scale up infectious disease DAM capacity during a future crisis. In addition, such agreements could help ensure that collaborators operate according to the same principles of independence and integrity as RIVM employees (e.g., shielded from pressure from commissioners and other entities such as industry). This would further broaden and enrich the scientific basis of RIVM's infectious disease DAM work in support of policy making. Depending on the nature of the collaborations and how these are used in a crisis setting, such collaborations could also be leveraged to increase the transparency of and probably also public trust in this work. At RIVM, such a national network could be established at a higher institutional level than the individual DAM teams.

6. Strengthen the endeavour to incorporate behavioural data and the wider impact of pandemics into the DAM work.

In line with the recommendations made by the 2016 audit committee that evaluated RIVM-wide mathematical health modelling work and in line with RIVM's ambitions described in the self-evaluation report, we encourage the institute to explore ways to incorporate additional types of behavioural data in the modelling efforts in the future. Public health impact is much broader than the direct effects of an infectious disease, and infectious disease modelling alone does not address effects such as the impact on the care for other medical conditions, mental health, and education. Decision makers often must balance multiple endpoints and trade-offs in their decisions, so it would be good to investigate what other data they would have found helpful in retrospect. It should be explored whether and how the assessment of broader societal impacts can be integrated into the DAM work in the future, to more comprehensively understand and assess the benefits and trade-offs of different policy options.

7. Strengthen internal collaboration between RIVM departments involved in DAM work.

We recommend building on the existing collaborations of the CIb with other departments and services within RIVM, which facilitates rapidly scaling up resources in the event of a new crisis. This is in line with RIVM's ambition as formulated in the self-evaluation report. In this context, we also advise that the sewage water surveillance data will be more integrated in scientific policy advice in the future.

8. Ensure sustainable funding for RIVM's infectious disease DAM work and for collaborative research to improve future pandemic preparedness.

The sense of urgency of investing in research into infectious disease DAM tends to fade away now that the acute phase of the pandemic has ended. We recommend safeguarding funding to sustain and improve the innovations developed for pandemic preparedness so far. It is essential to ensure that the funding available for RIVM's infectious disease DAM work has a permanent rather than temporary nature. In addition, it is important to negotiate better funding opportunities for research and expertise development in infectious disease DAM for scientific policy advice, as sufficient structural funding for both fundamental and operational DAM research is crucial to ensure future pandemic preparedness. This recommendation obviously transcends RIVM's mandate, but the government has an important responsibility to ensure pandemic preparedness.

Appendix 1: Site visit programme

Day 1: Monday 20 March 2023

	Start	End	Activities	Attendees *All AC members were present in all sessions, unless indicated otherwise. Online attendees are presented in Italics.*
	12.00	12.30	Phone call: Interview in Dutch with chair of the House of Representatives Committee on COVID-19 (*Vaste Kamercommissie VWS*)	Bart Smals (chair, House of Representatives Committee on COVID-19), AC chair, AC secretary
	12.15	12.30	Set-up the video meeting in T0.04 & T0.19	
	12.30	13.15	Kick-off working lunch meeting to introduce AC members to each other and to the RIVM participants and the SAB in T0.04	SAB chair, SAB LO, director general RIVM, director CIb, head CIb-EPI, head EPI-MOD, head Z&O-NRS, PL
	13.15	13.20	5-minute break & move to T0.19	
01	13.20	14.30	Preparatory AC meeting in T0.19	AC members
	14.30	14.35	5-minute break	
02	14.35	14.50	Introduction and interview: The broader context of the audit. SAB chair	SAB LO, director general RIVM, director CIb, head CIb-EPI, head EPI-MOD, head Z&O-NRS
03	14.50	15.10	Introduction and interview: Tasks and responsibilities of RIVM and illustration of the broader context of the audit. Presentation by director general RIVM + discussion	SAB chair, SAB LO, director CIb, head CIb-EPI, head EPI-MOD, head Z&O-NRS
	15.10	15.15	5-minute break	
04	15.15	15.35	Introduction and interview: The organisation of infectious disease control in the Netherlands, the role of the CIb, the scope of the audit. Presentation by director CIb and head CIb-EPI + discussion	SAB chair, SAB LO, director general RIVM, head EPI-MOD, head Z&O-NRS
	15.35	15.40	5-minute break	
05	15.40	16.20	Introduction and interview: CIb staff in lead of COVID-19 DAM, to provide context and illustrate the interdependency of their departments and projects. Presentation by head EPI-MOD + discussion	team leader EPI-DIS-DARA project leader Infectieradar head Z&O-NRS
	16.20	16.45	25-minute break	
06	16.45	17.15	Interview: OMT members, external to RIVM	Prof. Marion Koopmans, DVM, PhD (virologist, Erasmus University Rotterdam; National Influenza Centre) *Károly Illy, MD, MBA (President, Netherlands Association for Paediatrics)*
	17.15	17.20	5-minute break	

07	17.20	17.50	Interview: OMT chair & secretary from within RIVM	Prof. Jaap van Dissel, MD, PhD (Role: OMT chair) Prof. Aura Timen, MD (Role: OMT secretary)
	17.50	17.55	5-minute break	
08	17.55	18.25	Interview: Representatives from two Dutch Ministries	*Stephanie Wiessenhaan (Coordinating Policy Advisor Public Health, Ministry of Health, Welfare and Sport)* Wijnand Stevens, LLM (Counsellor to the Prime Minister of the Netherlands, Ministry of General Affairs)
09	18.25	18.45	Reflection on day 1 sessions, preview day 2	AC members
	19.30	21.00	Dinner at the hotel for AC	AC members

Day 2: Tuesday 21 March 2023

	Start	**End**	**Activities**	**Attendees** *All AC members were present in all sessions, unless indicated otherwise. Online attendees are presented in Italics.*
	11.30	12.00	Video call in meeting room at the hotel: Interview with Statistics Netherlands on past and future availability of death statistics and causes of death statistics.	Danny van Elswijk, PhD (head Health care and Wellbeing, deputy director Quarterly Statistics) AC chair, AC secretary, Prof. Pulliam, Prof. van Panhuis
	12.00	12.45	Lunch at the hotel for AC	AC members
	13.15	13.30	Set-up the video meeting	
01	13.30	13.40	Welcome & opening by AC chair	AC members
02	13.40	14.05	Interview staff: Data flows and data analytics by DARA team and EPI-NIP team on vaccination data	team leader EPI-DIS-DARA employee of EPI-DIS-DARA project leader for monitoring & evaluation COVID-19 vaccination, EPI-NIP
	14.05	14.10	5-minute break	
03	14.10	14.40	Interview staff: EPI-MOD department on testing capacity prognoses, contact detection app	three EPI-MOD employees
	14.40	14.45	5-minute break	
04	14.45	15.25	Interview staff: EPI-MOD department on vaccination advice including burden calculation for Health Council of the Netherlands	three EPI-MOD employees, head EPI-MOD *
	15.25	15.40	15-minute break	

05	15.40	16.20	Interview staff: EPI-MOD department on need for medical care & transmission models including Dutch Caribbean islands, and contact patterns	three EPI-MOD employees, head EPI-MOD *
	16.20	16.25	5-minute break	
06	16.25	16.55	Interview staff: senior legal advisors of the CIb	two senior legal advisors of the CIb
	16.55	17.00	5-minute break	
07	17.00	17.20	Interview staff: head EPI-MOD	
	17.20	17.30	10-minute break	
08	17.30	18.00	Interview: independent scientific experts from University Medical Centre Amsterdam, University Medical Centre Utrecht, Erasmus Medical Centre	*Prof. Patrick Bossuyt, PhD (Clinical Epidemiology, Amsterdam UMC)* *Maarten van Smeden*, PhD (Assoc. Prof. Epidemiologic Methods, UMC Utrecht) *Prof. Sake de Vlas, PhD (Infectious Disease Modelling, Erasmus Medical Centre)*
09	18.00	18.30	Reflection on day 2 sessions, preview day 3	AC members
	19.30	21.00	Dinner at the hotel for AC	AC members

* EPI-MOD head left the session after 30 minutes.

Day 3: Thursday 23 March 2023

	Start	**End**	**Activities**	**Attendees** *All AC members were present in all sessions, unless indicated otherwise. Online attendees are presented in Italics.*
	12.00	12.45	Lunch at the hotel for AC	
	13.15	13.30	Set-up the video meeting	
01	13.30	13.40	Welcome & opening by AC chair	AC members
02	13.40	13.55	Introduction and interview: NRS activities Presentation by head Z&O-NRS + discussion	
	13.55	14.00	5-minute break	
03	14.00	14.30	Interview staff: Z&O-NRS department on surveillance of COVID-19 in sewage water	three employees of Z&O-NRS
	14.30	14.40	10-minute break	
04	14.40	15.20	Interview: municipal public health services (GGD) of Amsterdam and Brabant regions GGD-GHOR Netherlands, overarching organisation for the GGD	Ewout Fanoy, MD (GGD region of Amsterdam) *Ariene Rietveld, MD (GGD region of Brabant)* *Sjaak de Gouw, director Public Health and infection disease control GGD GHOR*

	15.20	15.40	20-minute break	
05	15.40	16.10	Interview: Confidant for scientific integrity and independence at RIVM, and coordinator of integrity at RIVM.	
	16.10	16.15	5-minute break	
06	16.15	16.45	Interview: chair of Health Council of the Netherlands	*Prof. Bart-Jan Kullberg, MD (chair of Health Council)*
	16.45	16.55	5-minute break	
07	16.55	17.25	Interview: external independent communications expert and social sciences expert	*Prof. Andrea Evers, PhD (Health Psychology; scientific director, Institute of Psychology, Leiden University)*
	17.25	17.30	5-minute break	
08	17.30	18.00	Interview staff: CIb communication on modelling & RIVM corporate communication strategy	two communications advisors of RIVM
09	18.00	18.30	Reflection on day 3 sessions, preview day 4	AC members
	19.30	21.00	Dinner at the hotel for AC	AC members

Day 4: Friday 24 March 2023

	Start	**End**	**Activities**	**Attendees** *All AC members were present in all sessions, unless indicated otherwise. Online attendees are presented in Italics.*
	12.00	12.45	Lunch at the hotel for AC	AC members
	13.15	13.30	Set-up the video meeting	
01	13.30	13.40	Welcome & opening by AC chair	AC members
02	13.40	14.40	Interview staff: head EPI-MOD	
	14.40	14.50	10-minute break	
03	14.50	16.10	Final AC meeting to determine preliminary conclusions and recommendations.	AC members
	16.10	16.30	20-minute break	
04	16.30	17.00	AC chair summarises preliminary confidential conclusions and recommendations. Closing by director CIb	SAB chair, SAB Liaisons, director-general RIVM, head CIb-EPI, head EPI-MOD, head Z&O-NRS, project leader audit, RIVM staff members interviewed during the site visit

Appendix 2: Short biographies of the audit committee members

Professor André Knottnerus (chair)

André Knottnerus is emeritus professor of general practice and primary care research at Maastricht University (the Netherlands). His scientific work is focused on clinical epidemiological and quality of care research, especially in primary and community care. He worked as general practitioner in Amsterdam and was staff member at the Vrije Universiteit. He was trained as an epidemiologist at Maastricht University and delivered his PhD thesis on the development and application of clinical epidemiological methods in diagnostic research. He was appointed as professor of general practice and primary care research at Maastricht University in 1988. In 1990-1991, he was dean of the Faculty of Medicine in Maastricht, and subsequently research executive of the board of the Maastricht Medical School until 1994. From 1994, he was founding scientific director of the university's primary care research institute (until 2000) and the Netherlands School of Primary Care Research (until 2002). From 2001 to 2010, he was president of the Health Council of the Netherlands (where he was also responsible for scientifically advising the Dutch government on its vaccination policies) and from 2010 to 2017, chair of the Scientific Council for Government Policy (*Wetenschappelijke Raad voor het Regeringsbeleid*, WRR). As an independent expert, Professor Knottnerus was member of the independent Scientific Advisory Board of RIVM from 1996 to 2017. In the period 1998 -2020, he has been editor-in-chief of the Journal of Clinical Epidemiology. In 2004, he was elected as a member of the Royal Netherlands Academy of Sciences (KNAW), and from 2009 to 2013 he was chair of the medical section of the Academy. He was awarded with several national and international scientific prizes. Professor Knottnerus was nominated (not elected) for the Dutch senate for the Dutch sociodemocratic party. He is not involved in corona policies or COVID-19-related modelling issues in this party. All his publications have been written on the basis of scientific independence.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Emeritus professor of general practice and primary care research, Maastricht University, the Netherlands (emeritus since 2018);
  - Medical epidemiologist;
- Current ancillary positions:
  - Chair of the Committee Scientific Integrity, Maastricht University (since end of 2019 member, since 1-1-2023 chair; attendance fee per meeting);
  - Visiting professor of clinical epidemiology, University of the Philippines, Manilla (attendance fee per (online) meeting);
  - Co-chair Biosciences Steering Panel, European Academies Science Advisory Council (unpaid);
  - Honorary Member, Health Council of the Netherlands (unpaid);
  - Member, Royal Netherlands Academy of Arts and Sciences (KNAW) (unpaid);
  - Chair Advisory Board, KWF Dutch Cancer Society (unpaid);
  - Member Advisory Board, CORPUS – Journey through the human body (unpaid);
  - Member (Advisory) Board, Dutch Foundation for Biosciences and Society (unpaid);
  - Member (from 2019) and chair of Supervisory Board (from 2022), The Investigative Desk (unpaid);
  - Member Advisory Board, Institute for Positive health (unpaid);

    - Member Supervisory Board, International Primary Care Research Leadership Programme, University of Oxford, UK (unpaid);
    - Member Advisory Board, Amsterdam Public Health (unpaid);
    - Member Forum A to Z, Reading and Writing Foundation (unpaid);
    - Member, Royal Holland Society of Sciences and Humanities (*Koninklijke Hollandsche Maatschappij der Wetenschappen*, KHMW) (unpaid);
    - Honorary member, Dutch Society of General Practitioners (*Nederlands Huisartsen Genootschap*, NHG) (unpaid);
    - Frequently acting as chair or member of advisory committees, audit committees, evaluation panels, editorial boards (sometimes paid, sometimes unpaid);
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: none;
- Interests pertaining to intellectual property and reputation relevant to this audit: involved in (currently unfunded) independent academic research on influenza vaccination since the early 1990s, no academic interests regarding the COVID-19 data and modelling work under review;
- Other interests relevant to this audit: none. As noted in the short biography, Knottnerus was member of the independent Scientific Advisory Board of RIVM as an independent expert from 1996 to 2017.

Dr Vittoria Colizza (AC member)

Vittoria Colizza is head of research at INSERM (French National Institute for Health and Medical Research) & Sorbonne Université, Faculty of Medicine, working in the Pierre Louis Institute of Epidemiology and Public Health, within the Communicable Diseases Surveillance and Modelling team where she leads the EPIcx lab (Epidemics in complex environments). She is an expert in modelling to assess epidemic and pandemic risks and propagation, accounting for the role of social contacts and mobility. Trained as a physicist (PhD in statistical and biological physics in 2004 at the International School for Advanced Studies in Trieste, Italy), she worked at Indiana University (USA) in the School of Informatics as postdoc (2004-2006) and visiting assistant professor (2007), and joined Institute for Scientific Interchange (ISI) Foundation (Turin, Italy, 2007-2010) after being awarded an European Research Council (ERC) Starting Grant in Life Sciences in 2007. In 2011, Colizza joined INSERM in Paris and was promoted head of research in 2017. In 2020-2022 she was visiting professor at the Tokyo Institute of Technology in Japan. She has been active in the response against COVID-19 pandemic, advising French public health agencies and authorities. For her work, in 2020 she received her Knighthood of the Order of Merit of the Italian Republic by the Italian president, and in 2021 she was awarded the Prix Irène Joliot Curie – Prix spécial de l'engagement by the French Academy of Sciences and the French Ministry of Research. Colizza has been a fellow of the Network Science Society since 2022, and currently is vice-president and secretary of this Society.

Current positions, ancillary positions, and interests

- Principal position(s):
    - Head of research at INSERM and Sorbonne Université;
- Current ancillary positions:

    - Co-President of the Coordinated Action on Modelling of the *Agence nationale de Recherche sur le SIDA et les Hépatites Virales – Maladies infectieuses émergentes* (ANRS-MIE), since 2021 (unpaid);
    - Member of the Academic Council of Sorbonne Université, since 2022 (unpaid);
    - Member of the Monkeypox International Health Regulations (IHR) Emergency Committee of WHO for the declaration of the Public Health Emergency of International Concern (PHEIC), since 2022 (unpaid);
    - Visiting professor at the Tokyo Institute of Technology in Japan, 2020-2022 (unpaid);
    - Member of the French Modelling Working Group on COVID-19 advising Public Health France, 2020-2022 (unpaid);
    - Member of the French Modelling Working Group on Mpox (monkeypox) advising Public Health France, since 2022 (unpaid);
    - Scientific Advisory Board member of OptimAgent of the Modelling Network for Severe Infectious Diseases funded by the German Federal Ministry of Education and Research, since 2022 (unpaid);
    - Vice-president and secretary of the Network Science Society, since 2022;
    - Fellow of the Network Science Society, since 2022;
    - Frequently acting as member of advisory committees and evaluation panels (unpaid);
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: involved as academic partner in a Horizon Europe-funded project (ESCAPE) on pandemic preparedness also listing RIVM as partner, since January 2023;
- Interests pertaining to intellectual property and reputation relevant to this audit: none;
- Other interests relevant to this audit: none.

Professor Birgitte Freiesleben de Blasio (AC member)

Birgitte Freiesleben de Blasio is department director at the Norwegian Institute of Public Health and professor II at the University of Oslo. She was educated in theoretical physics at the Niels Bohr Institute, University of Copenhagen (MSc 1997; PhD 2003). Her research focuses on developing mathematical models to study the spread of infectious diseases and the effectiveness of various control strategies. Primarily, her work is applied with a strong emphasis on advising public health authorities in Norway and internationally, and she works on social network analysis. Since 2002 she has worked at the University of Oslo, and in 2013 she became professor at the Department of Biostatistics. In 2012, she became a senior advisor at the Norwegian Institute of Public Health, and since 2016 she has worked as department director, first at the Department of Infectious Disease Epidemiology and Modelling (~20-30 employees), and from 2019 she heads Department of Methods Development and Analytics (~50-60 employees). During the COVID-19 pandemic, she has chaired the Norwegian Institute of Public Health (NIPH) COVID-19 modelling team, a collaboration of University of Oslo (UiO), Norwegian Computing Center, and Telenor Research, providing operational modelling on situational awareness, short-term forecasting, and scenarios to support Norwegian health authorities.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Director Department Methods Development and Analytics, Norwegian Institute of Public Health (NIPH);
  - Professor II, Department of Biostatistics, University of Oslo;
- Current ancillary positions:
  - Head of the NIPH COVID-19 modelling team, a collaboration between NIPH, University of Oslo, Norwegian Computing Center, Telenor Norway;
  - Member of Crisis Management Group at NIPH (2020-2022);
  - Member of the Nordic COVID-19 Modelling Meeting, update on activities/discussion forum with participation of modelling teams at the public health institutions in the Nordic countries;
  - Head of steering group, Norwegian Enhanced Paediatric Immunisation Surveillance (NorEPIS) (unpaid);
  - Board Member BigInsight center for research-based innovation (unpaid);
  - Member of the Norwegian Academy for Science and Letters (unpaid);
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: Involved in (funded and unfunded) independent academic research on COVID-19 modelling, social contacts patterns during the pandemic, analysis of contact tracing data, and mobility indicators derived from mobile phone data in Norway; no research is connected to the modelling work under review;
- Interests pertaining to intellectual property and reputation relevant to this audit: involved in the ongoing pandemic evaluation at NIPH;
- Other interests relevant to this audit: participated in the mathematical health modelling audit of RIVM in 2016-17, as a committee member.

Dr Wilbert van Panhuis (AC member)

Wilbert van Panhuis received his MD from the Free University Medical Center in Amsterdam, the Netherlands, and a PhD in infectious disease epidemiology from the Johns Hopkins Bloomberg School of Public Health. He has served as assistant and then associate professor of epidemiology and biomedical informatics at the University of Pittsburgh for 12 years before joining the National Institute of Allergy and Infectious Diseases (NIAID) in 2021 as the inaugural director for the NIAID Office of Data Science. He envisioned and established Project Tycho, a data repository for notifiable infectious disease data that comprises over 125 years of detailed, standardized data for all US notifiable diseases ever reported and for dengue fever from many countries around the world. Wilbert used the data to estimate the impact of US vaccination programs in a study. Globally, Wilbert has led the development of an international network of researchers and government agencies in Southeast Asia to integrate and study over 20 years of dengue surveillance data. Most recently, Wilbert established and directed the inaugural Coordination Center for the NIH-funded Models of Infectious Disease Agent Study (MIDAS), the largest network of modellers for infectious diseases in the world. Wilbert coordinated the MIDAS network during the COVID-19 pandemic, including collaborations with the US CDC and state and local health departments, helped establish multiple model comparison and combination projects, such as the COVID-19 Scenario Modelling Hub and the Multi Model Outbreak Decision Support (MMODS) project, and published a framework for improving the reproducibility of computational models of infectious diseases.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Director, Office of Data Science, NIAID;
- Current ancillary positions: none;
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: none;
- Interests pertaining to intellectual property and reputation relevant to this audit: none;
- Other interests relevant to this audit: none.

Professor Juliet R.C. Pulliam (AC member)

Prof Juliet Pulliam is the director of the South African Centre for Epidemiological Modelling and Analysis (SACEMA), a national centre of excellence that is funded by the Department of Science and Innovation, managed by the National Research Foundation, and hosted at Stellenbosch University. She also holds the academic rank of professor in applied mathematics at Stellenbosch University. Her research focuses on applications of mathematical modelling to epidemiology and control of infectious diseases, particularly emerging, re-emerging, and zoonotic diseases. Since March 2020, she has served as a member of both the Ministerial Advisory Committee (MAC) on COVID-19 and the core modelling team for the South African COVID-19 Modelling Consortium (SACMC). Prior to moving to SACEMA in July 2016, she spent five years as a faculty member in the Department of Biology and the Emerging Pathogens Institute at the University of Florida, where she was also the inaugural director of the International Clinics on Infectious Disease Dynamics and Data (ICI3D) Program. Professor Pulliam received a PhD in ecology and evolutionary biology from Princeton University in 2007, with a dissertation entitled *Determinants and Dynamics of Viral Host Jumps* and she spent three years as a Research and Policy for Infectious Disease Dynamics (RAPIDD) Program fellow at the US National Institute of Health's Fogarty International Center.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Director, South African Centre for Epidemiological Modelling and Analysis (SACEMA);
  - Professor in applied mathematics, Stellenbosch University;
- Current ancillary positions:
  - Co-director, International Clinics on Infectious Disease Dynamics and Data (ICI3D, undertaken as part of job as director SACEMA);
  - Member, Ministerial Advisory Committee on COVID-19, National Department of Health, South Africa (unpaid);
  - Member, Core Modelling Group, South African COVID-19 Modelling Consortium (unpaid);
  - Member, Medical Advisory Committee on COVID-19, Stellenbosch University (undertaken as part of job as director SACEMA);
  - Member, Clinical / Epidemiology Working Group, South African National Variants Consortium (unpaid);
  - Member, Scientific Committee, Epidemics (Bologna, 2023, unpaid);
  - Member, MIDAS Network (unpaid);
  - Editorial Board Member, *Epidemics* (unpaid);
  - Associate Editor, *Proceedings of the Royal Society Series B* (unpaid);

    - Editorial Board Member, *Philosophical Transactions of the Royal Society Series B* (unpaid);
    - Member, Wellcome / Bill & Melinda Gates Foundation Network Workshop Organising Committee (unpaid);
    - Program Committee Member, Lessons and Experiences on Viable Epidemic Response Strategies (LEVERS), National Science Foundation - Pandemic research for preparedness & resilience (NSF-PREPARE) (2022-February 2023);
    - Member, Scientific Advisory Committee, PHIRST-C Study, National Institute for Communicable Diseases, South Africa (2020-2021, unpaid);
    - Chair, Independent Advisory Group, NIHR Global Health Research Group on the Application of Genomics and Modelling to the Control of Virus Pathogens (GeMVi) in East Africa at the University of Warwick (2018-2022, unpaid);
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: research grants related to COVID-19 modelling and analysis from the Bill and Melinda Gates Foundation (BMGF) and the Wellcome Trust; core funding from the South African Department of Science and Innovation – National Research Foundation; research grants related to poliovirus risk modelling and analytic methods for environmental surveillance from BMGF;
- Interests pertaining to intellectual property and reputation relevant to this audit: independent research related to modelling and analysis for COVID-19 and other infectious diseases;
- Other interests relevant to this audit: none.

Professor Peter White (AC member)

Professor Peter White models a range of infectious diseases to improve understanding of their epidemiology, assess the expected effectiveness and cost-effectiveness of intervention options, and evaluate interventions post-implementation. He uses techniques of Bayesian evidence synthesis, transmission-dynamic modelling, health-services research, and economic analysis, applied to data from surveillance, surveys, cohort studies, and trials. He was originally a laboratory scientist and performed ecological fieldwork as part of his PhD. Currently, he is professor of public health modelling in the Medical Research Council (MRC) Centre for Global Infectious Disease Analysis at Imperial College London, head of the Modelling & Economics Unit at the UK Health Security Agency, and co-director of the National Institute for Health Research (NIHR) Health Protection Research Unit in Modelling & Health Economics. He is a former expert consultant to the CDC's National Center for HIV, Viral Hepatitis, STD, and TB Prevention. Professor White's work has been funded by the UK Department of Health and Social Care (DHSC), Department for International Development (DfID), UK Medical Research Council, UK National Institute for Health and Care Excellence (NICE), UK National Institute for Health and Care Research (NIHR), Wellcome Trust, and the WHO. He has advised the UK Department of Health and Social Care (DHSC), Department for International Development (DfID), National Institute for Health and Care Excellence (NICE), Australian Department of Health, ECDC, US White House Office of Science and Technology Policy, Wellcome Trust, World Bank, and WHO. Professor White has published more than one hundred peer-reviewed papers and has written several book chapters.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Professor of public health modelling, MRC Centre for Global Infectious Disease Analysis, Imperial College London;
  - Co-director, NIHR Health Protection Research Unit in Modelling and Health Economics;
  - Head, Modelling & Economics Unit, UK Health Security Agency;
- Current ancillary positions:
  - Received payment from Pfizer for teaching of mathematical modelling of infectious disease transmission and vaccination, 2021;
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: none;
- Interests pertaining to intellectual property and reputation relevant to this audit: none;
- Other interests relevant to this audit: participated in the mathematical health modelling audit of RIVM in 2016-17, as a committee member.

Professor Marc Lipsitch

Dr Lipsitch is professor of epidemiology at the Harvard University T.H. Chan School of Public Health (HSPH) with a joint appointment in the Department of Immunology and Infectious Diseases. He directs the Center for Communicable Disease Dynamics and the Interdisciplinary Program on Infectious Disease Epidemiology and has been a member of the faculty at HSPH since 1999. Since 2021 he has been on part-time secondment to the US CDC as director for science of the newly established Center for Forecasting and Outbreak Analytics. His research concerns the effect of naturally acquired host immunity, vaccine-induced immunity, and other public health interventions (for example, antimicrobial use) on the population biology of pathogens and the consequences of changing pathogen populations for human health. He is an author of more than 350 peer-reviewed publications on antimicrobial resistance, epidemiologic methods, mathematical modelling of infectious disease transmission, pathogen population genomics, and immunoepidemiology of Streptococcus pneumoniae. Professor Lipsitch is a global leader in COVID-19 research, with over 80 scientific publications on the topic. He has also been active in science communication on the subject, with over 20 op-eds and popular articles published since the start of the outbreak. Professor Lipsitch received his BA summa cum laude in philosophy from Yale and his DPhil from Oxford as a Rhodes Scholar. He did postdoctoral work at Emory University and CDC. Honours include mentoring awards from Harvard Chan, the Robert Austrian Lectureship, the Rothman Prize, the Wade Hampton Frost Award from the American Public Health Association, and election to the American Academy of Microbiology and National Academy of Medicine.

Current positions, ancillary positions, and interests

- Principal position(s):
  - Professor of epidemiology and director, Center for Communicable Disease Dynamics, Harvard TH Chan School of Public Health;
- Current ancillary positions:
  - Member, Scientific Advisory Committee, Coalition for Epidemic Preparedness Innovations;

    - Director for Science (2021-3), now Senior Advisor (2023-), Center for Forecasting and Outbreak Analytics, US CDC;
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: Head of EPI-MOD is a friend and a sometime collaborator;
- Externally funded research relevant to this audit: none;
- Interests pertaining to intellectual property and reputation relevant to this audit: none;
- Other interests relevant to this audit: none.

Professor Andy Haines

Andy Haines was formerly a family doctor and professor of primary health care at University College London (UCL). He developed an interest in climate change and health in the 1990s and was a member of the Intergovernmental Panel on Climate Change for the second and third assessment exercises and review editor for the health chapter in the fifth assessment. He was director (formerly dean) of the London School of Hygiene & Tropical Medicine from 2001- October 2010. He chaired the Scientific Advisory Panel for the 2013 WHO World Health Report, the Rockefeller /Lancet Commission on Planetary Health (2014-15), and the European Academies Science Advisory Council working group on climate change and health (2018-19). He was a member of the Lancet COVID-19 Commission. He chaired the Royal Society, Academy of Medical Sciences project on climate change mitigation and health. He recently co-chaired the InterAcademy Partnership (140 science academies worldwide) working group on climate change and health and is currently co-chairing the Lancet Pathfinder Commission on health in the zero-carbon economy. He participates in the US National Academy of Medicine initiative on climate change and health.

Current positions, ancillary positions, and interests

- Principal position(s):
    - Professor of environmental change and public health, Centre on Climate Change and Planetary Health, London School of Hygiene & Tropical Medicine;
- Personal financial interests in the outcomes of audit: none;
- Personal relationships relevant to this audit: none;
- Externally funded research relevant to this audit: not applicable;
- Interests pertaining to intellectual property and reputation relevant to this audit: not applicable;
- Other interests relevant to this audit: not applicable.

Dr Linda van den Berg (AC scientific secretary)

Linda van den Berg is an independent science writer and scientific secretary with a background in the life sciences. She obtained a MSc in fundamental biomedical sciences in 2000 (*cum laude*) and a PhD in behavioural genetics in 2006, both from Utrecht University (the Netherlands). In the period 2006-2012, she was a postdoctoral researcher at VU University Medical Center (the Netherlands), the Broad Institute of Harvard and MIT (USA), and Leiden University Medical Center (the Netherlands). Since 2012, she has worked as a professional science writer and scientific secretary, with a focus on health & life sciences. Her company Washoe Life Science Communications offers a variety of communication services to academic institutes, research consortia, and governmental organisations.

Since 2015, she has served as an independent scientific secretary to almost twenty audit committees of a variety of Dutch scientific institutions. For RIVM, she previously served as the scientific secretary to the 2022 audit committee of RIVM's Public Health Foresight Study (VTV).