Nordic Experiences in Climate Change Analysis in Modelling Mining Area Environmental Impacts

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Abstract

Modelling environmental impacts of mining generally requires a set of interconnected models, which all use climatic input data. Inclusion of climate change analysis to each model may seem self-evident but, in practice, selection of suitable climate modelling scenarios requires holistic understanding of the modelling chain. An analogous approach to climate change is needed through the whole modelling chain, therefore, the process of choosing modelling scenarios should include analysing previous models in the model chain and assessing requirements of subsequent models. This paper presents experiences in inclusion of climate change in modelling sequences in Nordic mining environment.

Keywords: Climate Change, Modelling, Modelling of Environmental Impacts

Introduction

Due to climate change, in the Nordic countries, temperatures will rise, precipitation will increase, snow cover season will become shorter, and the amount of soil frost will decrease. This paper focuses on the Nordic countries of Finland and Sweden. During the next few decades, projected changes for Finland (Ruosteenoja *et al*. 2016) and Sweden (SMHI 2022) are fairly similar under all greenhouse gas (GHG) emission scenarios. Conversely, in the second half of this century, the evolution of climate is highly dependent on GHG emissions. Current round of climate modelling, called Coupled Model Intercomparison Project version 6, or CMIP6, embeds Shared Socioeconomic Pathways (SSPs) (O'Neill *et al*. 2014), which provide a set of emission scenarios driven by socioeconomic assumptions concerning population, economic growth, education, urbanisation and the rate of technological development. CMIP6 is used in preparation for the Intergovernmental Panel on Climate Change (IPCC)'s sixth assessment report. The SSPs are based on five narratives describing alternative socio-economic developments, being SSP1 Sustainability – Taking the Green Road; SSP2 Middle of the Road; SSP3 Regional Rivalry – A Rocky Road; SSP4 Inequality – A Road Divided; SSP5 Fossil-fueled Development – Taking the Highway (Riahi et al. 2017).

In Finland, based on global numerical climate models i.e., General Circulation Models (GCMs), under the high-emission SSP5-8.5 ensemble for the period 2040–2059, mean annual temperature is projected to increase from the current average (1991-2020) of 2.9 °C (Jokinen et al. 2021) with approximately +3 °C to 4.1-6.5 °C (fig. 1). Annual precipitation is projected to increase from the current average (1991-2020) of 609 mm (Jokinen et al. 2021) with approximately 24% to 635 – 851 mm (fig. 2). At the end of the century, under the high-emission SSP5-8.5 ensemble, the mean annual temperature is projected to be even 9.0 °C indicating approximately +6 °C increase to current average (fig. 1). Annual precipitation is projected to increase with 43% from current average to 868 mm (fig. 2).

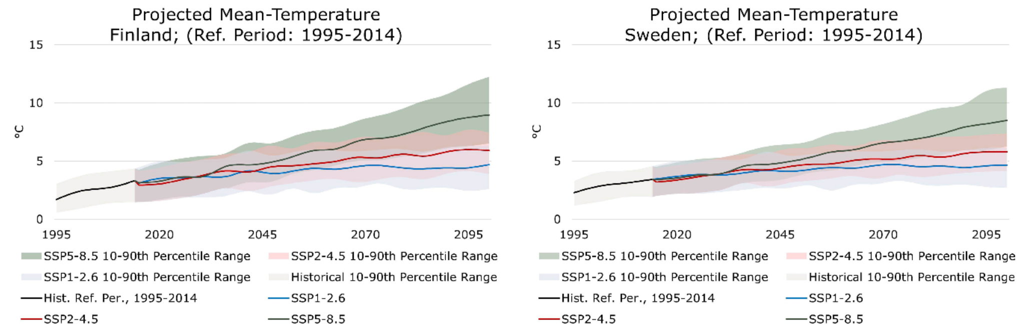

Figure 1 Projected Mean Temperature for Finland and Sweden with Varying SSPs. Data Sourced from The World Bank Group (2021).

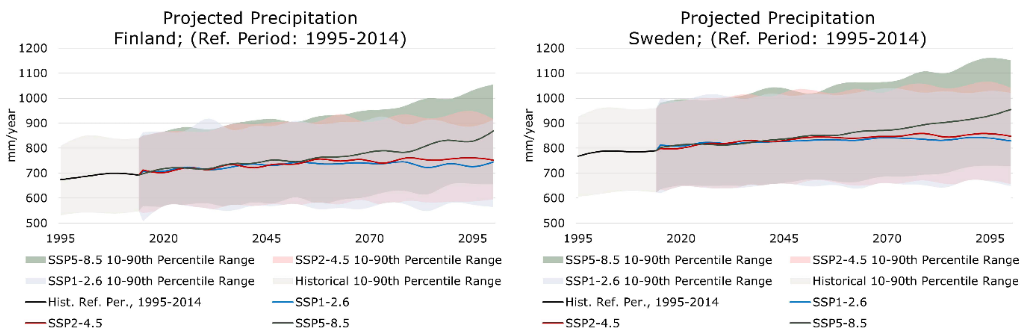

Figure 2 Projected Precipitation for Finland and Sweden with Varying SSPs. Data Sourced from The World Bank Group (2021).

In Sweden, under the high-emission SSP5-8.5 ensemble for the period 2040–2059, mean annual temperature is projected to increase from the current average (1991-2020) of 5.1 °C (SMHI 2022) to even 6.4 °C (fig. 1). The lesser increase in comparison to Finland is due to already increased average temperature during past decades and the fact that the presented projection data is based on GCMs. Annual precipitation is projected to increase from the current 681 mm (SMHI 2022) with approximately 25% to 726 – 973 mm (fig. 2). At the end of the century, under the high-emission SSP5-8.5 ensemble, the mean annual temperature is projected to be even 8.5 °C indicating approximately +3 °C increase to current average (fig. 1). Annual precipitation is projected to increase with 40% from current average to 954 mm (fig. 2).

The shift from cold to warmer climate is expected to influence the annual water budget both in Finland and Sweden. Temperature doesn't control only evapotranspiration, but also conditions like snow storage and ground frost, which have a major impact on infiltration and percolation (Barthel et al. 2021). Thus, also groundwater recharge and groundwater storage patterns will be impacted (Barthel et al. 2021, Nygren et al. 2020).

Modelling environmental impacts of mining generally requires a set of inter-connected models, which all use climatic input data. This model set, where one model often provides input data for the next model, may include hydrological, hydrogeological and geochemical models, pit lake models, site water balance models and different pollution dispersion models. All environmental models deal with representations of processes that occur in the real world in space and time. Inclusion of climate change scenario for each model is often set as a prerequisite by the authorities. In this paper, we don't argue the importance of analysing and describing the modelled system behaviour for the future climate. Quite the contrary, preparing for varying climate is important part of mine preparedness planning and even a legal prerequisite as the relevant European framework directives require continuous monitoring of unforeseen environmental impacts (European Commission 2001, 2014). Our recommendation is, that before adding a climate change scenario to each model in a complex modelling chain, modelling objectives and model qualifications should be carefully assessed to avoid unproductive use of resources and to have a consistent and defendable approach to climate change in the whole modelling chain.

Chain of Models in Modelling Mining Area Environmental Impacts

Interconnected Models

On the set of interconnected models (fig. 3, fig. 4), individual models represent different timeframes and technical approaches. A model for mine operational period often spans over next 10-30 years whereas post-closure models may cover hundreds of years. Individual models can be steady-state models, predicting a time-independent year or a season, or they can be transient. Site water balance models use often probabilistic approach with extensive future climate analysis, as they're tools assisting in the critical mining industry task of water management planning. Other environmental models are

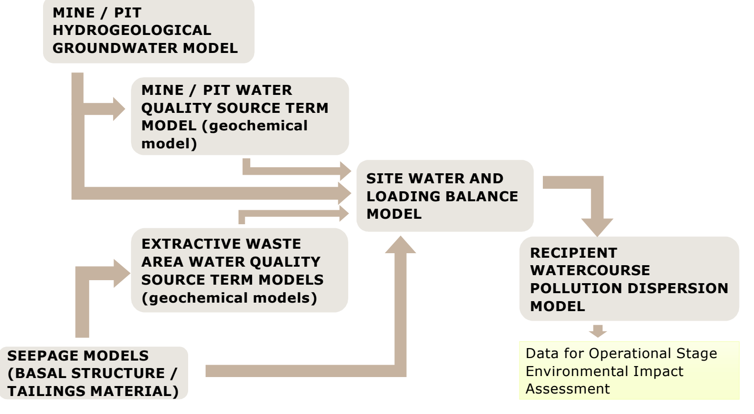

***Figure 3** Example of the Set of Interconnected Models in Modelling of Mine Site Operational Stage Environmental Impacts.*

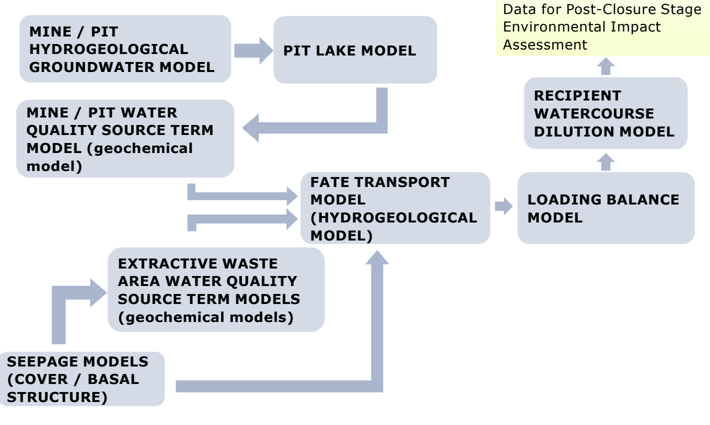

***Figure 4** Example of the Set of Interconnected Models in Modelling of Mine Site Post-Closure Stage Environmental Impacts.*

usually deterministic. Despite the modelling time frame, modelling software or technical approach, all the models use climatic data as input data.

In our recent modelling sequences, selection of approaches for climate change inclusion to various models has required a lot of evaluation. Whether an inclusion of a particular climate change scenario to a mining environmental assessment model is applicable or not, can be outlined with four questions: what are the used hydrological model inputs and how well those can be predicted in climate change scenarios; does the modelling interval or the modelling point in time allow for climate change scenario modelling; which model will use the model outcome as an input and how; will exceptional climate scenario analysis, like exceptional year scenario or exceptional inter-annual climatic event scenario or other exceptional weather scenario, be included and does this provide enough information for adaptation to climate change?

The reason for not using a climate change scenario may derive from unavailability of regional level climate projection data, uncertainty in critical model parameters that are impacted by climate change, subsequent model data and scenario requirements, or planned inclusion of exceptional climate scenario analyses that will cover the climate change impacts.

Hydrological Inputs to Each Model

Nearly all environmental models, that are used in modelling of mining area environmental impacts, use temperature, precipitation and evaporation as inputs – directly or indirectly. Some models, like pit lake models, require use of wider range of climate variables that affect the hydrodynamics of the pit lake. Such parameters include, in addition to precipitation, evaporation and air temperature: dewpoint; solar radiation; cloud cover; and wind speed and direction (Vandenberg *et al.* 2011). For successful climate change scenario inclusion to any model, all required parameters should be available, based on Regional Climate Models (RCMs), and data sets should span until the modelling point in time.

Hydrogeological groundwater models do use direct meteorological inputs, but more important is the definition of groundwater recharge parameters. Direct measurement of groundwater recharge is impossible.

The natural groundwater recharge process is governed by a multitude of factors such as topography, land use and land cover, geology, depth to groundwater and climate. Regarding the latter, it is not only average values of climatic variables but also the temporal variability of these which is of utmost importance. Different climates and geological conditions result in huge differences in groundwater recharge. (Barthel *et al.* 2021)

Groundwater recharge is a good example of a parameter that is, even when estimated for the existing climate, very uncertain. For any future climate scenario, the current estimate may not be valid at all. Prediction attempts of groundwater recharge will require considerable human and computing resources and, possibly, even broader scientific understanding of recharge parameters under current state.

Modelling Interval and Modelling Point in Time

Modelling intervals vary between models and can be hourly, daily, weekly, monthly, seasonal, or annual. Modelling intervals, like in case of operational stage site water and loading balance models, can also change during the mining project development. On Preliminary Economic Assessment (PEA) stages the site water and loading balance models are often annual and are developed to daily models during the mine development stage.

Most operational stage models usually span until 2050. As during the next few decades projected changes for Finland and Sweden are fairly similar under all greenhouse gas (GHG) emission scenarios, operational stage models can easily settle with one predicted scenario for future climate, for example SSP2 (Middle of the Road). Post-closure models and their printouts are often annual, which is practical considering the expected long timespan. Recommendation concerning post-closure stage models is to analyse and include the future climate predictions at the end of the century where the current climate change predictions span. On the second half of this century, the evolution of climate in Finland and Sweden is highly dependent on GHG emissions. Thus, post-closure stage models should include at least two predicted scenarios for the future climate, for example SSP2 (Middle of the Road) and SSP5 (Fossil-fueled Development – Taking the Highway), latter of which could be managed as a sensitivity case.

Consideration of Subsequent Models

Even the modellers and modelling teams are highly specialized on their own competence field and have skills in their special software, more effort, in general, should be put to define the modelling objectives in co-operation with the team responsible of the next model in the chain. Visualising the set of interconnected models (fig.3, fig.4) is a good tool for identifying all necessary and compulsory dialogue-parties. The dialogue between the modelling teams of subsequent models must be concrete and detailed. Desired output/input flows between models should be defined in terms of each parameter, unit, time-step and data format. Additionally, discussion about modelling scenarios of each model is required, especially concerning climate change approaches. Questions to assist the dialogue could be:

- Does the subsequent model use same or different climatic input data? If different, where does the difference derive from? Do both models aim to model the same point in future time and is future climate, including future climate predictions, described and understood the same way?
- Which climatic scenarios will be included in the subsequent model? Which scenario results would be the recommended ones to be used on each of them? Should certain climatic scenarios be added to assist the subsequent model to meet the overall modelling objectives?

It is not a prerequisite that exactly same future climate variables are used for each and every model. However, using varying future climate variables should be a conscious decision and based on a dialogue.

Inclusion of Exceptional Climate Scenario Analysis

Some models, like operational stage site water balance models, often include extreme weather event analyses and exceptional year scenario analyses. Average or median assessment scenario results can, thus, be supplemented with presentations of 10-90th or 5-95th percentile confidence limits or other relevant exceptional scenario analyses. Additionally, other models are often run with sensitivity cases predicting change of direction and amount of change in results on exceptional climate conditions. As the historically varying climate and its exceptional conditions often cover expected climate change over mine operational stage, separate modelling of climate change scenario, in comparison to utilizing system behaviour based on historical recurrences, can be unproductive. In these cases, climate change analyses could be only verbal analysis of indicative direction of change.

Conclusions

Our proposed three-step path to prepare for project-wide systematic climate change analyses, in modelling mining environmental impacts are:

1. **Develop and describe long-term climate characteristics for the mine area** as part of project early-stage hydrological studies. Include future climate predictions. Our recommendation is to include pathway analyses from two SSPs. Practical approach could be to include SSP2 (Middle of the Road) and SSP5 (Fossil-fueled Development – Taking the Highway) pathways. Analyse the local future climate as far as the global numerical climate models span. Identify, even preliminarily, the duration of expected mine operational period. Describe the expected future climate, based on one chosen SSP, at the end of expected operational life of mine (LOM). Additionally, for post-closure assessment purposes, describe the expected future climate based on two chosen SSPs at the end of the analysed timeline. **During project development, keep the description and database of predicted long-term climate characteristics updated**.

2. **Conceptualize the modelling pathway**. Visualize the set of interconnected models (fig.3, fig.4) and put them on a timescale. Visual presentation or roadmap of interconnected modelling tasks assists the modellers in understanding all the interfaces that their model has on the modelling chain. It also assists project schedule development and communications. **Review and update the conceptualization along with the project**.
3. After steps 1 and 2 **start the actual modelling** – separately for each model. Define modelling objectives for the individual model. Review availability of climate change related hydrological inputs and **plan for climate change scenario inclusion/exclusion.** Consider model interfaces with other models and **have the climate scenario dialogue** with the party responsible of the subsequent models. Establish key output metrics. Select modelling software and understand its potential and limitation in managing and handling climate change related input parameters. Start actual modelling process from model-specific conceptual model development.

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