Hydrological Impact Assessment within a Natura 2000 Protection Area in Northern Scandinavia

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Abstract Numerical groundwater models, surface water catchment models and geochemical mixing models have been developed to simulate the pre-operational, operational and post-closure groundwater system, hydrological conditions and surface water quality at a mine site in northern Scandinavia. Baseline water quality is good with the exception of one watercourse that is negatively affected by uncontrolled releases of surface water from a historical tailings pond. Generally modelling predicts limited impacts on surface water flows and water quality for most key parameters.

Keywords Hydrological impact assessment, tailings, pit lake, Natura 2000 protection area

Introduction

A hydrological impact assessment (HIA) has been undertaken for the Hannukainen iron ore-copper- gold project in northern Scandinavia (Fig. 1). There is a long history of mining in the area with the most recent activity between 1969 and 1996. Disused facilities include waste rock dumps (WRDs), open pits and a tailings pile located 11km south of the mine site that contains approximately 6.6 Mt of tailings waste from iron, copper and gold ore processing.

It is proposed that the disused open pits will be dewatered and further exploited. Waste will be streamed; potentially acid forming waste (PAF), non acid forming rock (NAF) and overburden (OB). The tailings pile will be expanded to hold about 6 Mm^3 of high-sulphide (High-S) tailings, contained within a fully lined (base and sides) tailings management facility (TMF), and 43 Mm^3 of low intensity magnetic separation (LIMS) tailings, deposited directly above the existing tailings. During mine operations contact water will be treated where necessary and discharged to the Muonionjoki, a large regional river, via a 15 km pipeline. The Muonionjoki forms the border between Finland and Sweden making it of interest to both national and international regulatory bodies.

Rivers in the vicinity of the site comprise a known habitat for the endangered migrating Sea Trout (Salmo truter) and are within a Natura 2000 protection area under the 1992 EU Habitats Directive. The principle receptor for the purpose of the HIA is the surface water environment. Any future mining operations must be able to demonstrate that suitable management methods can be employed to mitigate against negative impacts.

Methodology

Impact management comprises several components; baseline characterisation, impact prediction, mitigation methods, and mine design. This paper focuses on the first three components although environmental considerations were incorporated into the mine design, for example:

- WRDs are located such that all seepage from PAF material and the majority from the NAF material is captured by pit dewa-

tering during operations or the pit lakes post closure;
- Expansion of the historical tailings site has been selected in favour of constructing a new facility; and
- The water management plan avoids any discharges of surface water to minor watercourses during mining.

WQO Standards

Site-specific Water Quality Objectives (WQOs) for river water quality were developed using the ANZECC methodology (ANZECC & ARMCANZ, 2000). ‘Trigger Values’ (TVs) and ‘Action Values’ (AVs) were derived for each chemical parameter. AVs are based on toxicological data and if exceeded there is an expectation of immediate remedial work. Under the ANZECC method exceedances of TVs should act as a warning of potential future exceedances of AVs. TVs are defined based on statistical analysis of baseline stream water quality data. However, at the project site baseline water quality is generally very good and for some larger rivers the baseline data shows limited seasonal and interannual variation resulting in a low standard deviation within the data set. Hence, in many cases TVs were significantly lower than AVs whereby a relatively small increase in baseline concentrations would result in an exceedance of a TV. Consequently, TVs were viewed as an indicator of change from baseline conditions rather than a potential risk to aquatic life.

Baseline Characterisation

Within the study area there are no long-term flow or surface water level records. Therefore baseline surface water hydrology was assessed through analysis of regional stream flow data from Finland’s environmental administration OVIA database, supplemented by on-site stream flow measurements. The analysis produced estimates of annual runoff, average monthly flow conditions, low flows and wetted area for the key rivers potentially impacted by the development.

Baseline surface water quality in rivers close to the development has been characterised through a monitoring program undertaken by the mine operator since mid-2007. Generally samples have been collected five times per year; monthly in the summer months and once in the spring and autumn. Sampling is not possible during the winter due to freezing of the rivers.

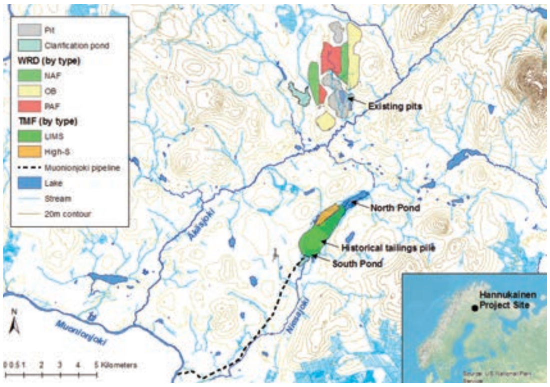

***Fig. 1** Proposed Hannukainen site layout*

There has been very limited groundwater monitoring at the existing TMF. A multi-level monitoring network was designed and installed as part of the HIA study and provided the majority of the groundwater baseline data. A more established monitoring network exists at the historical mine site with piezometers installed in both the overburden and bedrock. Regular groundwater sampling and water level monitoring began in mid-2011.

Surface Water Flow Modelling

The combined impact on river flow due to changes to baseflow and changes to surface water runoff have been estimated for both the local and regional rivers. Changes to baseflow were generated by numerical groundwater modelling. It was assumed that the lost runoff volumes to each river were proportional to the lost catchment area. The changes in catchment area were assumed to impact stream flows in open water/non-winter months (May to October) due to decreases in surface runoff.

Groundwater Modelling

Groundwater level data and mapped wetlands were used to calibrate a 3-D numerical groundwater model of the site area, constructed using MODFLOW-2005, a block-centred, finite-difference, groundwater flow model. The model was used to characterise the hydrogeological regime, including the interaction between groundwater and surface water bodies, and to estimate a water balance for the TMF ponds under different climatic conditions. Fractured zones were represented by zones of increased hydraulic conductivity.

Geochemical Modelling

Estimates of source term chemistry at the WRDs and TMF were determined through both geochemical mass balance calculations and thermodynamic equilibrium modelling using the USGS code PhreeqC version 2 (Parkhurst and Appelo 2012). Source term solution chemistry was then mixed with baseline groundwater quality, saturated minerals were allowed to precipitate and adsorption of metals to mineral phases was permitted to predict the solution chemistry discharged to the receiving watercourse.

A conservative mass balance approach was applied to predict metals concentrations within the local receiving rivers using GoldSim. This method is conservative in that it does not take into account processes such as mineral saturation, pH equilibrium, atmospheric gas equilibrium or attenuation through adsorption. Due to the short residence times and relatively low concentrations in the receiving watercourses, a mass balance approach is justified because it cannot be guaranteed that equilibrium will be reached or that precipitates will form a colloidal suspended load.

Water quality in the Muonionjoki at the proposed outfall was calculated using three methods:

- Box model: At the outfall where the effluent undergoes initial dilution.
- Plume model: Close to the outfall where the effluent has formed a plume but has not fully mixed across the river. This is modelled using a 2D advection-diffusion equation; and
- Complete mixing model: At a distance from the outfall when the effluent has fully mixed with the river flows. This is modelled using a conservative dilution modelling approach.

Upon cessation of mining the pits will be artificially flooded. Modelling incorporated a coupled mass balance – thermodynamic equilibration approach in which chemical loadings from various sources including high wall runoff, WRD seepage and precipitation were mixed.

Baseline Characterisation

River Network

There are marked seasonal variations in flows within rivers close to the site (Fig. 2). High flows follow snow melt in spring (May and June) and low flows occur in winter (December to April) when precipitation is held within catchments as snow and ice. These seasonal variations affect the amount of natural dilution available in the river systems through the year.

Baseline water quality in one local river, the Niesajoki, is negatively affected by uncontrolled releases of surface water from ponds at the historical tailings pile to the river. Water quality improves downstream of the TMF, as shown by the nickel concentrations presented in Fig. 3.

Groundwater

Groundwater monitoring indicates that the groundwater surface is generally 0–25m below

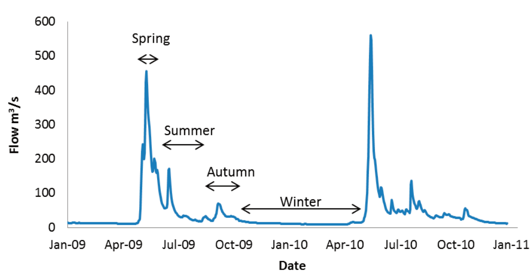

Fig. 2 *Typical annual flow hydrograph for the site (gauge number 65761 from OIVA database)*

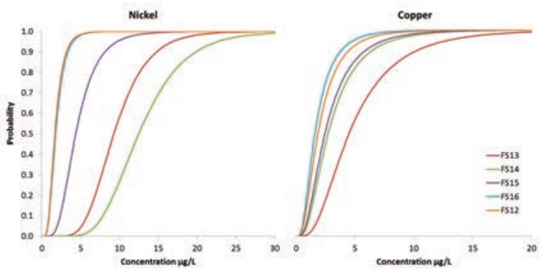

Fig. 3 *Water quality downstream of the existing TMF, fitted to a log-normal distribution. FS13=North Pond, FS14=South Pond, FS15=Niesajoki mid-point, FS16=Niesajoki close to mouth, FS12=Niesajoki at mouth*

ground surface (bgs) throughout the project site, broadly following topography, and the local groundwater system discharges to the wetlands and rivers, supporting base flows to these streams (Fig. 4). Geology at the site comprises intrusive igneous rocks, metasediments and metavolcanics overlain by Quaternary age glacial deposits with a measured thickness of up to 45m. Groundwater flow in the bedrock is primarily through open, connected fractures which persist to depths of at least 250 m.

Water quality is generally good however there is evidence of impact from the existing WRD and TMF characterised by elevated concentrations of sulphate, cobalt, copper and nickel. Suppressed pH (<6.5) was observed but since pH is often naturally low in northern Scandinavia this alone does not prove existing impacts; elevated sulphate is the strongest indicator.

Assessment of Potential Impacts

Construction Phase

Construction of mine facilities will include excavation of new stream diversion channels, development of water impoundment dams and construction of other infrastructure including a pipeline to the Muonionjoki. There are no planned releases to the local river network during dewatering of the existing pits and therefore there are no predicted impacts on water quality or flow. If construction works are undertaken adhering to best practise, for example effective sediment control, it is anticipated that impacts on water quality in the local rivers will not be significant.

Operational Phase

There will be small (<5 % during an average year) decreases in flows in the rivers located downstream of mining infrastructure due to a decrease in baseflow and a reduction of catchment area flowing to the rivers. However, hydraulic calculations indicated that these changes will result in a negligible change in channel wetted area; important for the maintenance of aquatic life.

During the operational phase there will be no uncontrolled releases of surface water from the TMF and river flows immediately downstream of the facility may decrease by approximately 40 %. The magnitude of flow reduction

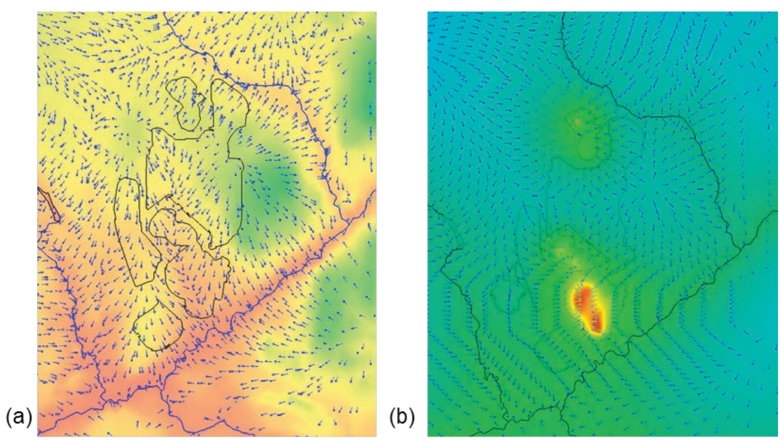

Fig. 4 *Groundwater contours at the mine site under (a) baseline and (b) life of mine conditions*

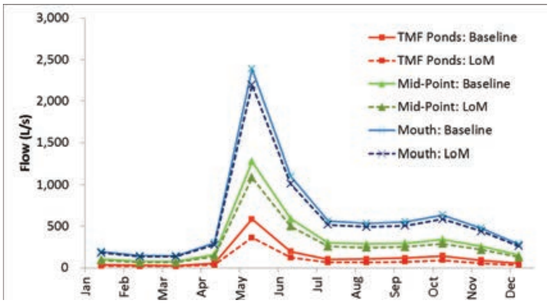

Fig. 5 *Baseline and life of mine (LoM) flow in the Niesajoki River, downstream of the TMF*

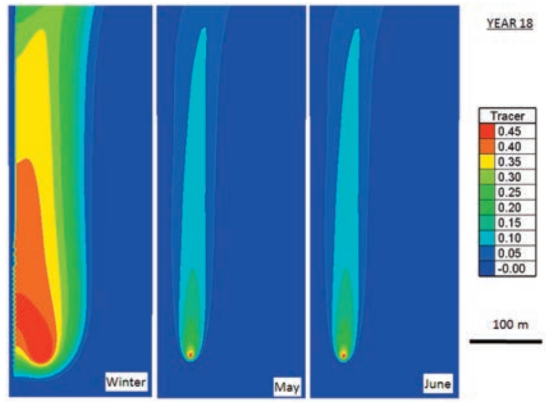

Fig. 6 *Plume prediction model for life of mine (Year 18)*

decreases with increasing distance from the TMF (Fig. 5).

The reduction of flows from the TMF should result in a marked improvement in the quality of water in the river. Elsewhere, modelling indicates that key parameter concentrations are predicted to remain within 16 % of baseline during the spring thaw, apart from chloride. During winter months exceedances of TVs for cadmium, chromium, mercury and uranium are predicted.

Discharge to the Muonionjoki will comprise less than 1 % of the baseline river flow and is not predicted to have a significant impact on flow. Modelling indicates that there will be a dilution zone downstream of the outfall within which there is a risk of AV exceedances for some parameters. For most parameters the main impacts are during winter months (Fig. 6) when flows in the river are at their lowest. The effluent plume is predicted to have fully mixed with river water within 1–2 km of the outfall. At this point modelling predicts no exceedances of AVs. However, exceedances of TVs for cadmium, cobalt, copper, molybdenum, nickel and uranium are predicted near the end of mine life.

Closure Phase

It is predicted pit lakes may overtop once fully recovered. There is negligible impact predicted on river flow. Calculations indicate that following the first over-spill of water to the rivers, TVs are predicted to be exceeded for a number of key parameters. Copper predictions are predicted to exceed AVs under some flow conditions. Steady state predictions highlight the potential for exceedances of some AVs with exceedance of TVs for the majority of key parameters.

Upon closure, seepage from the tailings will continue to report to the TMF ponds and local rivers. Ultimately, water from the South Pond will be discharged directly to the Niesajoki without treatment. River flow rates would be expected to return close to present day conditions. The water quality of the Niesajoki is predicted to deteriorate due to this release, with exceedances of TVs for a number of parameters, and the potential for exceedance of AVs for copper.

Potential Mitigation Measures

Operational Phase

Generally no mitigation is required for river flows, however flows immediately downstream of the TMF could be augmented using treated mine water or diverting natural catchments surrounding the TMF. At the Muonionjoki, potential mitigation options include improvements to proposed water treatment, optimisation of the site water management plan to reduce winter discharges, and engineering of the outfall. For example, a diffuser design would enhance mixing close to the outfall.

Closure Phase

There is predicted to be both groundwater and surface water discharge from the pit lakes and TMF site following closure of the mine and modelling has demonstrated potential detrimental impacts on the surrounding watercourses. Based on the current understanding and predictions the following options are being considered as long term solutions to potential water quality issues:

- Treatment of acidity in pit lakes through alkaline amendment (such as lime, CaO) addition;
- Treatment of the pit lake and TMF water at point of discharge with passive wetland, permeable reactive barriers and active systems being considered;
- Mitigation at source, for example addition of alkaline rock amendment (limestone, $CaCO_3$) to the PAF WRD to attenuate acidity or installation of a low permeability, oxygen limiting cover to PAF waste to decrease metals loading to the pit lakes; and
- Amending blasting strategies to ensure that waste rock fracturing is minimised.

Equally important to impact management methods are assessment criteria to quantify the success of mitigation.

It should be noted that a number of conservative assumptions have been made during water quality predictions including full mixing of the pit lakes, no sub-surface attenuation of solutes, and the use of static “NAG” testwork for prediction of WRD seepage. It is intended that water quality predictions will be updated as new information, such as fully matured kinetic test data, becomes available. Modelling of pit lake stratification is also planned to refine the pit lake water quality prediction.

Conclusions

This paper highlights the challenges and limitations of the methods used to characterise the baseline condition at Hannukainen and predict potential impacts of mining activities. It also underlines the multidisciplinary approach that is required for a study of this kind.

Generally there are limited impacts due to the mine on surface water flows in any of the rivers located immediately downstream of mining facilities. On cessation of mining WRD seepage will continue to flow into the pit voids, forming a point source rather than an uncontrolled diffuse source of seepage. This will aid post closure mitigation and seepage control. There is predicted to be both groundwater and surface water discharge from the pit lakes, therefore it is proposed that either long term active or passive treatment of pit lake discharge should be investigated to ensure discharge limits are achieved.

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