NITREM

NITROGEN REMOVAL FROM WASTE ROCK

2018-2020

WORK PACKAGE 5 SUSTAINABLE LANDSCAPE DESIGN

Cedervall arkitekter

RawMaterials
Connecting matters

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

WP5 Work Group

| Cedervall Arkitekter
Matt Baida, Frida Frogsjö

| Future Terrains
Pete Whitbread-Abrutat

| AL Miljökonsult AB
Anders Lundkvist

| Universidad Complutense Madrid
José Francisco Martin Duque, Pedro Martinez Santos, Ramon Sanchez

Project partners

LKAB Minerals · Uppsala Universitet · SLU · WSP · CSIC · Luleå Tekniska Universitet · Boliden

Funded by

EIT RawMaterials – Connecting matters

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation

contents

Abbreviations & Acronyms

EIT	**The European Institute of Innovation & Technology**
LKAB	**Luossavaara-Kiirunavaara aktiebolag (publ)**
HDPE	**high density polyethylene**
NITREM	**the nitrogen removal from waste rock-project**
NO_3	**nitrate**
WFD	**Water Framework Directive**
WP	**work package**
WRD	**waste rock dump**
Mt	**million tonnes**

CHAPTER 1

Introduction

Waste rock produced by mining activities often negatively affects surrounding areas leading to environmental and/or public health impacts. At LKAB's Kiruna iron mine in Sweden's Arctic north, waste rock derived from underground mining operations is contaminated with residual explosive chemicals, namely ammonium nitrate (NH_4NO_3). At the surface where the waste rock is stored in extensive waste rock dumps (WRDs), the highly soluble nitrate (NO_3) is readily leached from the waste rock by percolating water from rain or melting snow. The surrounding natural environment is notable for its numerous – and nutrient poor – water bodies and rivers and the purity of its water. Nitrates can have a significant impact on such nutrient poor aquatic systems and regulations are enforced to limit nitrate discharges from the mine.

The three-year EIT RawMaterials Nitrogen Removal from Waste Rock (NITREM) project has been developed to address this issue. EIT RawMaterials is a body of the European Union and consists of partners working to ensure the sustainable competitiveness of the European minerals, metals and materials sector along the value chain by driving innovation, education and entrepreneurship. Within the NITREM project there are six work packages:

- WP0 Feasibility study
- WP1 Project management
- WP2 Waste rock deposit and bioreactor construction
- WP3 Operations, monitoring and evaluation
- WP4 Knowledge transfer
- WP5 Sustainable landscape design

The focus of this report is Work Package 5 (WP5) – Sustainable Landscape Design. The following chapter introduces the project and the background to WP5.

NITREM Description

LKAB are a key partner to the project. They are driven by their own sustainability goals, the EU's Water Framework Directive (WFD) and Swedish environmental legislation. One of their objectives is to reduce emissions of nitrogen to water by at least 20% per tonne of finished product by 2021 compared with 2015. This will ensure LKAB meet future WFD requirements of the European mining industry. This objective led to an innovative project that commenced in 2014. Its purpose was to identify treatment techniques for reducing the nitrate loading of waters emanating from the Kiruna iron ore mine site. A product of this on-going research was the development and construction of a pilot-scale, subsurface bioreactor for nitrogen removal at the Kiruna mine (Figure 01). The pilot-scale bioreactor operated over a two-year period, successfully removing outgoing nitrate concentrations to below detection levels.

NITREM is a three-year (2018-2020) research and development project focusing on upscaling the pilot bioreactor project. The focus within the three years includes the design, monitoring and successful operation of the bioreactor system integrated into an operational WRD. The project goal is to develop a commercial service for an integrated waste rock landform and bioreactor design available for market introduction and implementation throughout the European mining sector.

2018

- Project kick-off
- Desktop analysis of existing reports
- Site analysis
- Literature review
- Field studies
- Develop landscape performance goals & criteria
- Conceptual geomorphic design
- Draft Landscape Design Report

2019

- Project kick-off
- Design Methodology development
- Field studies/data collection
- Hydrological modelling
- GeoFluv Level 1 training
- Level 1 Geomorphic Design
- Landscape Design Report

2020

- Project kick-off
- WRD cost analysis
- Field studies/data collection
- Social Transition methodology development
- GeoFluv Level 2 training
- Level 2 Geomorphic Design
- WRD hydrological modelling
- Visualizations

Work Package 5

LKAB plan to deposit 130Mt or 72,000,000m^3 of waste rock from 2021 at a location within the mine leasing area referred to as Area B at the Kiruna mine site (Figure 01). Their current plans and methods for deposition and rehabilitation are outlined in their rehabilitation plan and are detailed later in this report. The focus of WP5 is to design a WRD that considers WRD hydrology, aesthetics, post-mining land-use, landform function, biodiversity and ecosystem services in combination with NITREM bioreactors. This includes the identification of a suitable WRD design method to achieve successful bioreactor function and mine rehabilitation goals.

For a landscape design to be considered `sustainable', not only are environmental factors fundamental but socio-economic considerations are critical and need to be accommodated within, and allowed to influence, the plans and designs such that closure related risks to the well-being and livelihoods of workers, communities and the region are minimised and any opportunities are maximised. As such, WP5 is a multi-faceted work package that addresses not only the removal of nitrogen through the efficiency and function of the bioreactors but also the regulators' and wider societal concerns around waste rock management and mine closure planning. The objectives of WP5 are to:

1. Develop landscape performance goals and criteria
2. Design a WRD that incorporates the NITREM bioreactor technology
3. Develop a design methodology to guide the successful planning and implementation of future NITREM projects
4. Prepare a social transition methodology to guide development of a vision for addressing the socio-economic aspects of mine closure

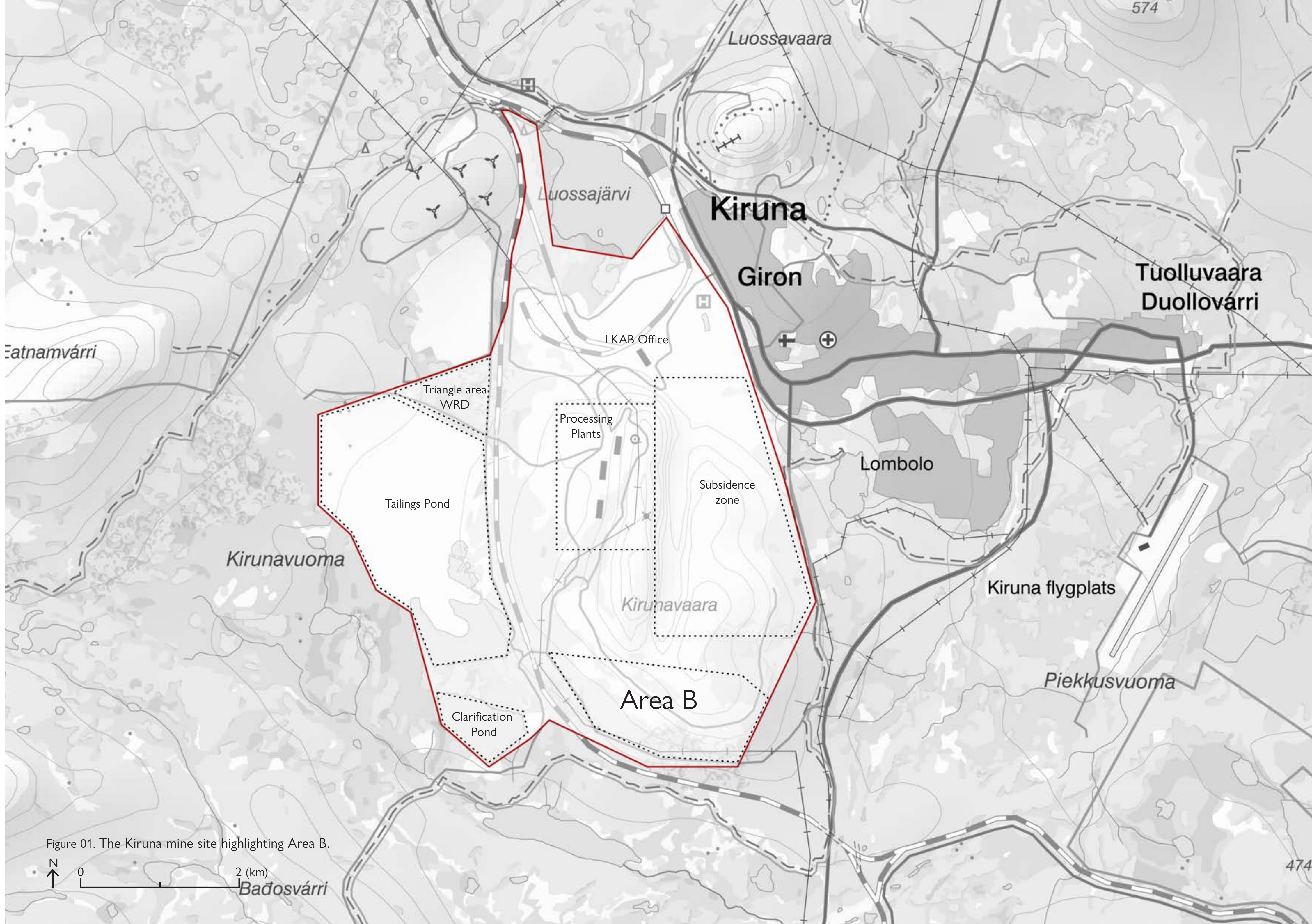


Figure 01. The Kiruna mine site highlighting Area B.

Figure 02. Bioreactor construction at the Kiruna mine Triangle Area waste rock dump.

Bioreactor Technology

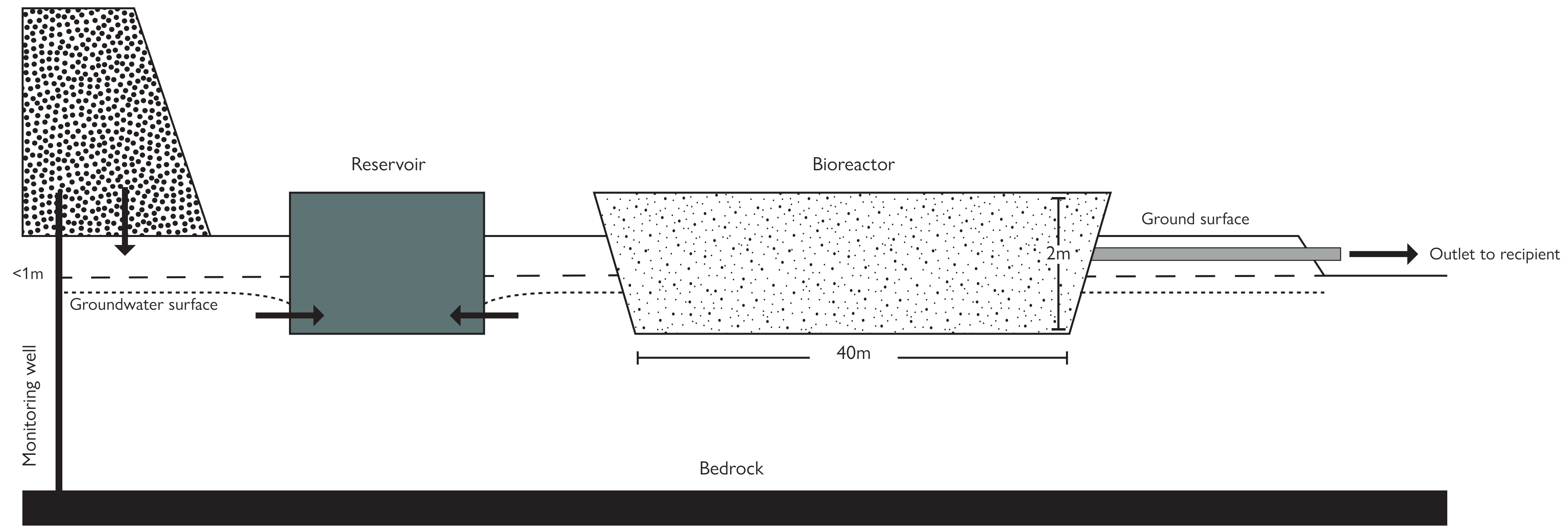
The NITREM bioreactors are a denitrifying woodchip system for removing nitrate by microbial denitrification. Denitrification is the process whereby nitrate is converted to relatively inert nitrogen gas, which is released harmlessly to the atmosphere, thus removing the risk of nitrate-enriched leachates from entering surrounding water bodies. The remediated water is fed via gravity to the recipient water system. Figure 02 shows the internal construction of a biorecator.

Bioreactor Parameters

Internal Temperature	Suitable biogeochemical environment for the promotion of denitrification at temperatures ranging from 0.8C to 17C.
Flow rates	Annual infiltration into waste rock calculated at L/s/km². Bioreactors require 0,1L/s minimal flow to function and too high flows can reduce the efficiency of the system.
Residence time	Optimal residence time 48-60 hours (24 hours at higher temperatures).
Bioreactor shape (WxLxD)	Aim to reduce/prevent no flow areas.
Location	Bioreactors location are site-specific based on where leachate water flows can be collected and where the remediated water needs to be discharged.

Bioreactor System

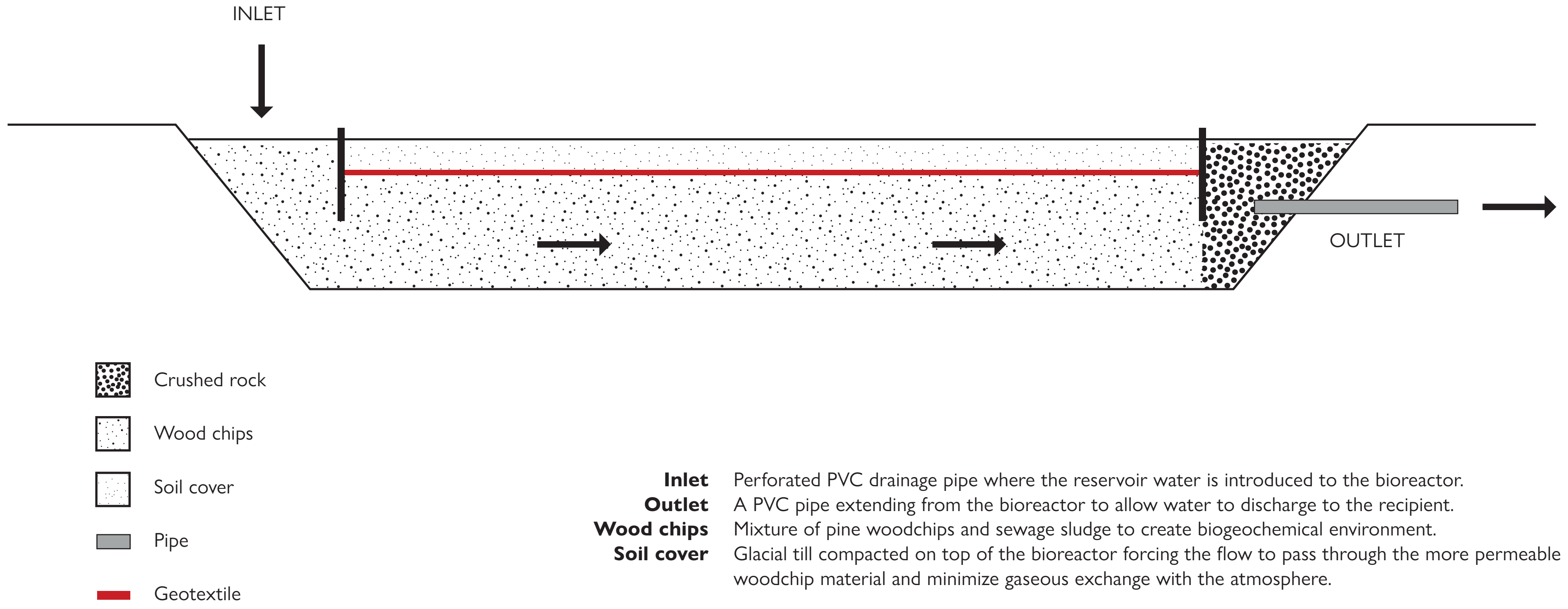
Waste rock dump | infiltration



Reservoir Water collection before being pumped/directed to the bioreactor
Bioreactor size 6m x 40m x 2m
Bioreactor materiality Plywood frame covered with a 1.5 mm impermeable geomembrane (high-density polyethylene, HDPE)

Figure 03. Bioreactor system.

Bioreactor Design



Inlet Perforated PVC drainage pipe where the reservoir water is introduced to the bioreactor.
Outlet A PVC pipe extending from the bioreactor to allow water to discharge to the recipient.
Wood chips Mixture of pine woodchips and sewage sludge to create biogeochemical environment.
Soil cover Glacial till compacted on top of the bioreactor forcing the flow to pass through the more permeable woodchip material and minimize gaseous exchange with the atmosphere.

Figure 04. Bioreactor design.

Waste Rock Dump Design Methods

An important foundation for the Work Package was the understanding of and research into waste rock dump design and construction methods. The conventional design of waste rock dumps often follows an approach with outcomes driven primarily by health and safety legislation relating to slope stability, planning restrictions on footprints and heights and mine planning (logistics efficiency). Designers and engineers subsequently design and build something to comply with these restrictions in a way that achieves regulatory requirements driven by economics. The resulting landforms, which are referred to in this report as conventional waste rock dumps (Figure 06), are often designed using a pyramidal form with straight lines and using maximum slopes and sharp angles to optimize the waste holding capacity. From a safety perspective such landforms generally achieve stability, but over the long term this approach is less successful in terms of socio-economic end-use or ecological integrity and fails to take into account the ongoing effects of wind and water erosion.

An important – but often over-looked – issue with the conventional approach is that over a prolonged period of time, it can be predicted that such landforms, under the influence of local climatic forces and physical erosion, would stabilize to a more natural form (Figure 05). Water erosion, safety liability, collapse and sediment deposition are long-term problems requiring consideration when considering a design for a waste rock dump integrated with bioreactors. Ultimately this creates a long-term liability risk and could lead to costly ongoing maintenance, which can make it more difficult for a company to achieve their remediation goals and the successful relinquishment of their site.

Conventional WRD designs are limiting in several ways – even if this approach is considered as good international industry practice, the practice is not progressive, and a paradigm shift is required. The nature of the design can restrict development of an ecologically sustainable and natural-looking vegetation cover and landscape, with knock-on effects for post-mining land-use options, water quality standards and social acceptance. This may eventually become manifested in permitting problems.

Some of the more progressive mining companies are starting to explore the geomorphic approach (Figure 07) to WRD design by creating landforms that mimic the function and aesthetics of more natural environments. The basis of a geomorphic design is to create a landform that does not require ongoing treatment to prevent erosion, is hydrologically stable, minimizes soil erosion, is visually appealing and promotes a self-sustaining ecosystem.

A key principle is that geomorphic design does not attempt to recreate original landforms or replicate past landscapes. It is accepted that pre-disturbance environmental conditions cannot be restored per se; the goal is to design landforms using available unconsolidated materials that adhere to geomorphic principles and behaviors of water flow on natural landscapes. Such landforms, although artificial, offer more topographic variation – even at a micro-level – than conventional designs. The valleys that result from establishing a functional drainage system provide a diversity of microclimates including slopes and slope aspects that result in varied water harvesting, soil conditions, sunlight exposure and ecological niches, which ultimately promote the development of a more resilient and diverse ecological composition.

By mimicking both the appearance and function of nature such landforms are designed to efficiently convey water without excessive erosion or sediment loading on the surrounding environment. Landform designs that are demonstrably stable in the medium to long term are also important for a wider range of rehabilitation goals, including future land productivity and a return to traditional land uses. Geomorphic landform design has advanced considerably over the last 10 years and, while still in its infancy, it is becoming identified as Best Technology Currently Available (BTCA, United States) or as Best Available Technique (BAT, European Union).

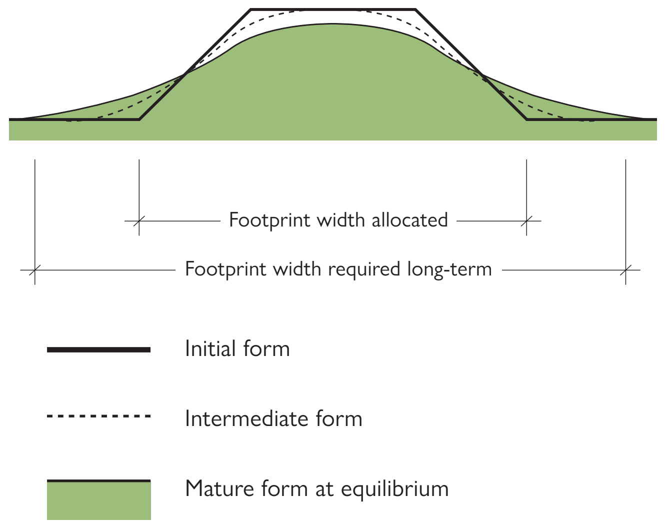


Figure 05. Generalized degradation of conventional WRD landforms due to physical erosion over time.

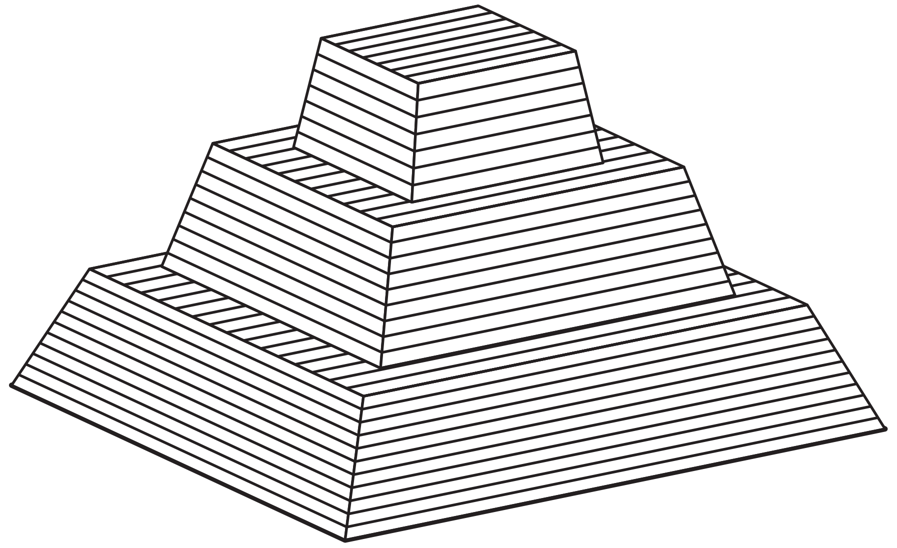


Figure 06. Conventional waste rock dump design.

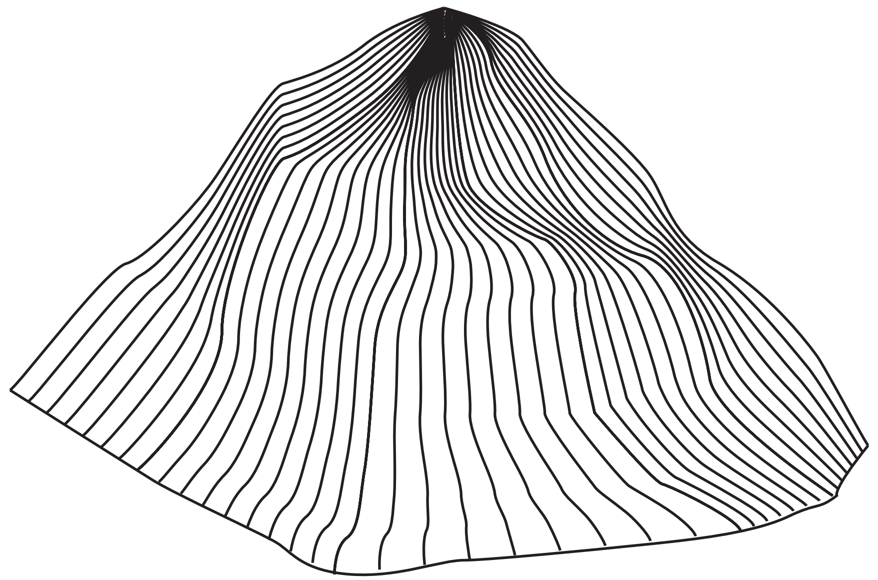


Figure 07. Geomorphic waste rock dump design.

WP5 Waste Rock Dump Design Approach

It is understood that the structure and composition of a waste rock dump determines how water will move through it, affecting runoff and groundwater flows and, hence, the function and success of the bioreactors. An important consideration was the ability to control these components, where possible. As such, WP5 addresses the link between waste rock and water management issues over the lifetime of the mine and seeks to build opportunity for long-term landscape sustainability post-closure.

To successfully achieve the desired outcomes of the NITREM project along with LKAB's rehabilitation goals, the proposed conventional WRD for Area B was not seen as the best design solution. It was hypothesized that a geomorphic design would be the most integrated approached to enable nitrate enriched leachates to be remediated and also assists the company to achieve other environmental and land-use goals associated with WRD design, such as long-term stability, re-establishing vegetation, increasing biodiversity and creating a landscape accessible to reindeer herding.

The adoption of a geomorphic design requires a paradigm shift in thinking by mining companies to understand and view the potential and value of their WRDs from a perspective that currently focusses on waste rock management as a safety and economic issue.

WP5 Project Process

The WP5 Work Process

The project has adopted a research by design approach. This means that the project process itself, irrelevant of the outcome, is critical in assisting to develop a commercial and adaptable methodology that can be implemented at other sites across Europe and further afield. As such the working process has been recorded throughout the project to ultimately shape the design methodology that is discussed further in chapter 4. The process undertaken for this this project is outlined in figure 08.

Project Feedback

NITREM is a project with many stakeholders ranging from the mining company, to the other work package teams and to EIT RawMaterials. It has been important to keep all informed to gain feedback on the direction of the project and to incorporate knowledge and thinking from outside the WP5 team. In order to obtain feedback and share knowledge and lessons learnt within the project, the following meetings and workshops have been undertaken:

- Quarterly meetings with LKAB including members of the environmental, hydrological and transport/logistics teams
- Bi-annual consortium workshops including all the NITREM work package teams
- Study trip to Spain with LKAB to visit mining sites that have implemented geomorphic reclamation, 2019
- Audit meeting with EIT RawMaterials, 2018
- Conference presentation – 'Creating Value through Closure', Luleå, Sweden 2019
- 2020 Knowledge transfer seminar (market introduction)

Limitations

The project was affected by the following limitations:

- Owing to WP5 holistic approach towards sustainable landscape design thinking including consideration for WRD stability, socio-economic factors, ecological restoration and aesthetic aspects there was limited timeframe and budget to thoroughly research, model, and collect field data. As such the purpose of the project was not to deliver a sustainable landscape design to be implemented but rather a method that can be replicted to acheive this.
- Time on site was relatively limited. The landscape input parameters for the design require further validation.
- Language barrier: most of the reports reviewed relating to the site were in Swedish. This presents several issues including the misinterpretation of information and additional time to review the information. The project is to be delivered in English.
- NITREM is focusing on one small section of the Kiruna site. This may affect the replicability of the technology to other areas of the site where there may be insufficient knowledge.

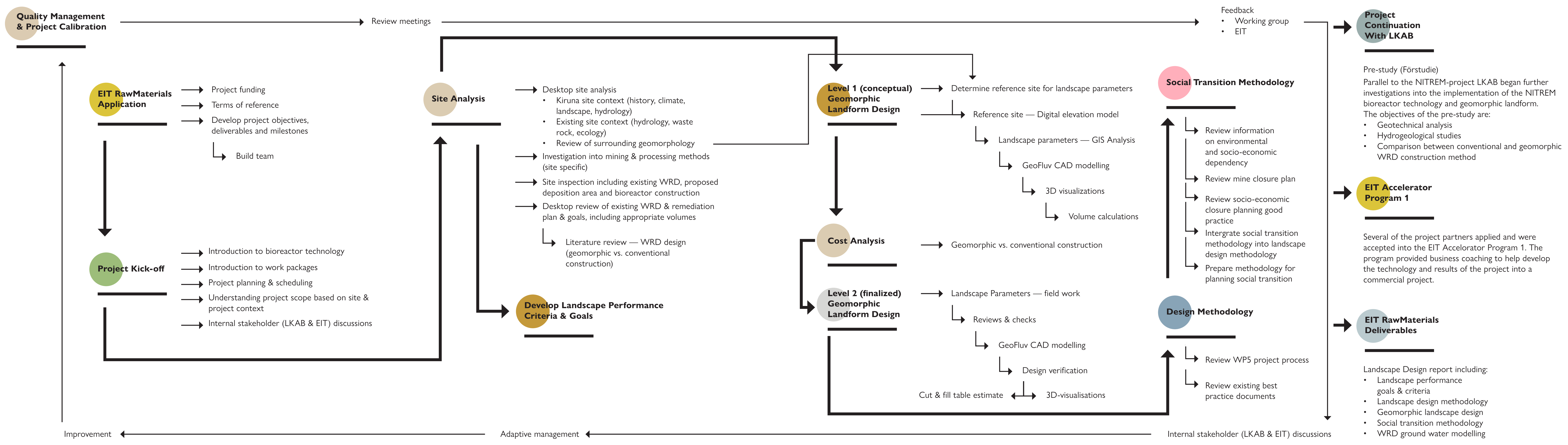


Figure 08. WP5 Project Process.

CHAPTER 2

Site Knowledge

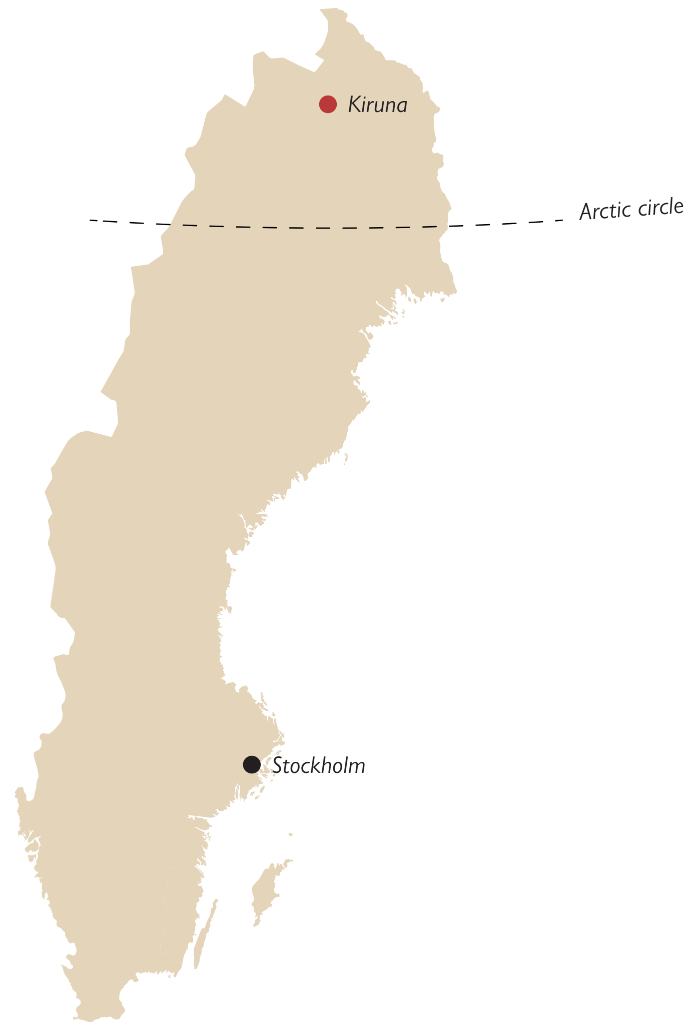
Work Package 5 is required to focus not only on the placement of the bioreactors in the landscape, but also to consider WRD stability, ecological restoration and aesthetic aspects. The complexities of such considerations require a thorough understanding of the existing site conditions and the wider Kiruna context.

This section considers Kiruna's cultural, environmental and geographical context along with the existing site conditions and LKAB's proposed rehabilitation plans for the mining lease area in general and more detail for Area B, see figure 01.

This review was undertaken to improve the team's knowledge of the issues and opportunities that might influence the project's sustainable landscape design and determine how the design might integrate more successfully with its surrounding context. The investigations were informed by consultation with LKAB personnel, research and desktop analysis of existing reports and plans for the mine site (see appendix A).

Kiruna Context

Area 20.530km^2
Population 23.196 inhabitants
Business sector Mining (the LKAB Kiruna iron ore mine, the biggest underground iron ore mine in the world), space technology and tourism.
Tourism Mainly associated with hunting, fishing, skiing and other outdoor pursuits. The country's highest peak is Kebnekaise at 2111m.



Understanding landforms

During August 2020, the WP5 team along with Professor José Francisco Martin Duque from Complutense University of Madrid undertook field investigations around the town of Kiruna in Northern Sweden, to gain a better understanding of the geomorphology and highly sensitive landscapes and ecosystems of the tundra. The intention was to learn more about the landforms from a regional perspective in order to be able to better replicate a WRD landform that is representive of the local landscape.

The last ice age ended in the Kiruna area approximately 10,000 years ago. Today its landscape is dominated by the landforms produced by the glaciers and ice-sheets of the ice age, which are exhibited in the mountains to the west and north of Kiruna (e.g. cirques, glacial troughs, paternoster lakes, lateral and ground moraines, arêtes) and the glaciated plains to the east and south (e.g. ground moraines, erratics, fluvio-glacial deposits, drumlins, eskers, kame deposits, kettle lakes).

Geomorphologically the landscape is described as relatively young and consists of surficial materials of high permeability, which impedes the accurate determination of drainage networks. It appears that alluvial channels mostly follow the glacial troughs and are developed also in the lowest parts of the plains between lakes.


Figure 09. Pulsas


Figure 10. Bedrock nob


Figure 11. Esker


Figure 12. Subglacial gorge


Figure 13. Thermo cirque


Figure 14. Talus deposit


Figure 15. The team exploring Tundra polygons (patterned ground) east of Nikkaluokta.

Kiruna's Landscape

Kiruna is located in the Arctic region of north Sweden, which is characterized by extensive high plateaus and low mountains with the occasional high mountain. The nearest surrounding low mountains are Eatnamvárri, Peuravaara in the west and Luossavaara in the north. The Kirunavaara mountain, containing the mine, is located to the west of the town.

The terrain varies from a low point in the valley of the Torne River at 329m to Luossajärvi at 499m, Kiruna at 500-570m and the peak of Luossavaara at 726m high.

The area surrounding Kiruna possesses several important ecological areas, including Natura 2000 sites, nature reserves, wetlands with high natural value and key biotopes (Figure 18). The areas reflect both the importance of the NITREM project to help protect the natural pristine environment and also the areas provide ecological cues to what can hopefully be replicated post-mining at the Kiruna mine site.

Figure 16. Hummocky topography on fluvioglacial deposits (no drainage network is developed). The depressions are closed depressions.

Figure 17. Fluvioglacial deposits common for the area.

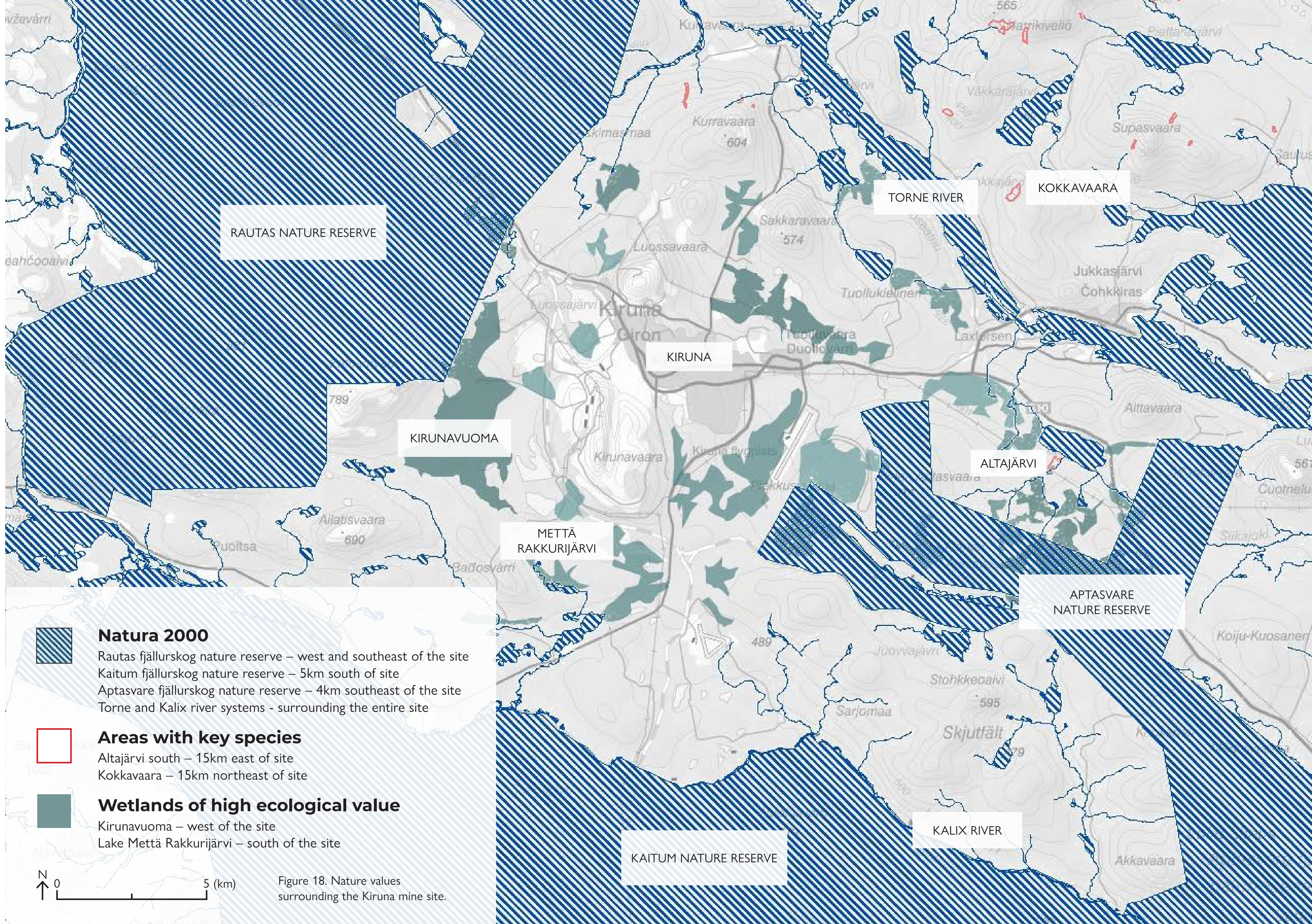


Figure 18. Nature values surrounding the Kiruna mine site.

Climate

Kiruna's location, some 140 km north of the Arctic Circle, means an Arctic climate, with extreme winters for more than half the year and extreme differences in solar radiation between summer and winter. This harsh climate is rendered more hospitable by the warming effects of the North Atlantic Drift ocean current which moderates the climate in northern Scandinavia.

Inland dry air, caused by very low winter temperatures, helps make the freezing temperatures more bearable, compared to the damper air of coastal towns. Summer temperatures are low and fall rapidly in the mountain areas. Most precipitation falls in July, with an average of 82mm. The driest month is March, with approximately 24mm of precipitation.

Climate	Sub-Arctic
Polar nights	The sun is absent from 15th December until 10th January
Midnight sun	30th May and 14th July
Altitude	Average altitude of the area is 465 m. a.s.l.
Temperature	Average annual temperature is -2.2°C January -14.80°C and July + 12°C
Precipitation	Approximately 504mm/year
Wind direction	Predominant southerly winds during winter and northerly winds during the summer

Climate change

The Arctic is the part of the planet that is warming most rapidly due to anthropogenic climate change. The County Administrative Board of Norrbotten has prepared a climate change report which presents the predicted impacts of warmer temperatures, sea level rise and changing precipitation patterns for the period 2069-2090. From a baseline period of 1960–1990, it discusses two scenarios based on high or low greenhouse gas emissions. Of interest to the future planning, design and rehabilitation of waste rock dumps are the following climate predictions:

Increased mean annual temperature	Approximate increase of 3.6–5.6°C
Increased mean annual precipitation	Approximate increase of 28-52%

The specific effects of the climate prediction include:

- A longer growing season - increase from 140 days to 150-180 days
- Changed maximum snow cover may stay constant or decrease slightly by 0-10% (this refers to the maximum amount of water that is stored in the snow cover in winter, which is significant to the water flow in spring)
- Increased precipitation in spring by 36-56%
- Between 6 and 11 days with more than 10mm precipitation (a measure of the occurrence of large quantities of rain, which can lead to flooding)
- Maximum 24-hour precipitation event range between 30 and 35mm (a measure of the risk of downpours)

These predictions have long-term implications on waste rock dump design that could affect the following:

- Increased rainfall together with heavier predicted rainfall events means a stronger spring flood as the snow masses melt. This could lead to increased erosion from the existing waste rock dumps.
- The ability to establish vegetation quicker as the growing season is expected to lengthen from 140 days to between 150 and 180 days. Increasing temperatures will also affect the choice of species that can be established, given the migration of vegetation zones with increasing altitude and latitude.

Ecology

Kiruna

An understanding of the local ecology is important in enabling the WP5 team to develop a landform design that act as a catalyst for the establishment of appropriate biodiversity and integration it into the surrounding ecosystem. Ecologically, Kiruna is surrounded by forest, which is characterized by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and birch (*Betula spp.*), aspen (*Populus tremula*), rowan (*Sorbus aucuparia*) and willow (*Salix spp.*) found along rivers and lakes. A herbaceous layer of mosses, lichens and ericaceous shrubs on shallow soils are also found. Wetland vegetation includes species such as moss and *Equisetum*, common cotton-grass (*Eriophorum angustifolium*) crowberry, blackberry and sedges and sub-shrubs such as dwarf birch and bog bilberry.

The topsoils of the Kiruna area are generally thin, varying from a few centimetres to a metre in thickness. The dominant soils are moraine (till) and peat and are underlain by bedrock consisting of metamorphosed volcanic rocks, with a smaller component of sedimentary rocks and greenstones. The predominant subsoil is podzol, which aligns with mountain pine forest vegetation.

Mining Lease Area

An ecological inventory of the entire mine site conducted in 2017 by Ecogain shows that the area is part of a larger system with a similar natural environment to the surrounding mountain range of Kirunavaara. It is concluded that the species that are present on the mine site are also likely to be found in the surrounding areas. The study indicated that the populations of plants and animals affected by mining operations would have low significance for the species' long-term survival, since these habitat types are common in the region.

Area B

Area B is not covered by any protection requirements. The wetlands south of the site have been classified as natural value class 3 or to be of 'considerable natural value'. Mountain birch populate the undisturbed area of the site, which is cut off by the transport road and rail line to the south before wetlands extend all the way to Lake Mettä Rakkurijärvi, Area B's recipient for water.

It should also be noted that there is a national interest in reindeer herding just south of Area B.

Figure 19. Nature values by the Kiruna mine site.

History and Sámi Culture

6000 b.c — Arrival of the first people more than 6,000 years ago, after the inland ice cap retreated

1600 — Settlers, and the very first miners, came at the beginning of the 17th century during the first mining era (the first iron ore mine was opened in 1647).

1850 — In the mid-1880s the first test drilling took place on Kiirunavaara Mountain

1900 — Kiruna counts 1900 as its birth year, when the Crown approved the town plan. The town was founded by the state-owned LKAB mining company.

1910 — Population increased dramatically, and by 1910 Kiruna already had 7,500 inhabitants.

1975 — Kiruna's population was at its greatest in the mid-1970s, with just over 31,000 inhabitants.

1980 — Revenue from Sweden's mines formed the basis of Sweden's economic success.

2019 — The underground mining operations are causing surface subsidence resulting in parts of the city being relocated over a 20-year period, including the homes of over 4,000 people.

The Sámi culture and the Finnish-speaking culture have lived together in the area for all recorded history.

The Sámi are the recognised indigenous peoples of the Arctic and sub-Arctic parts of northern Norway, Sweden, Finland and into northwestern Russia. Much of the indigenous Sámi culture is preserved in the Kiruna area through the active use of the North Sami language and thriving reindeer husbandry. The surrounding landscape forms part of Sápmi – a cultural region inhabited by the Sámi people. It is used by Sámi reindeer herders and, despite the vast areas of open land around the town and mine, wetlands, rivers and lakes constrict the migrating reindeer to relatively narrow areas that skirt the mine's permit boundary. The reindeer are culturally important for the indigenous Sámi people, who have lived and herded reindeer in the area for thousands of years. In addition, the Sámi culture and herding practices contribute to tourism for Kiruna. It is a requirement of the mining permit that the waste rock dumps are to be restored to an ecologically-appropriate vegetation cover that includes areas of reindeer moss, to enable grazing by reindeer on these sites after they have been relinquished.

Figure 20. The mine offices and subsidence zone, photo taken from north of the mine site facing south.

Kiruna Mine’s Waste Rock Management

Mining Lease Area

Mining at Kiruna began in 1898. The mining lease area covers approximately 4126ha (Figure 21). In total one billion tonnes of iron ore have been produced with two-thirds of the ore body remaining to be extracted.

The magnetite-apatite ore body dips at 50-60° towards the town of Kiruna and is 4km long, 80-120m thick and up to 2km deep. The first decades of extraction were from the Kirunavaara open pit, which is still visible. The mine currently operates at 1365m below the surface. The ore is processed on-site into magnetite pellets with approximately 27Mt produced per annum (2017 figures).

Currently the mine site holds a total of 265Mt of existing waste rock. Older deposition sites include the Kirunavaara open pit. Dumping presently occurs at three locations. At current production rates of approximately 10Mt of waste rock produced each year the existing dumps will be at full capacity by 2021. As such, LKAB plan to deposit 130Mt of waste rock from 2021 onwards at a location within the mine leasing area referred to as Area B. As discussed in chapter 1, this is also the test site for the NITREM project. The area includes existing WRDs and landfill sites containing waste material and contaminated sludge from the processing plant.

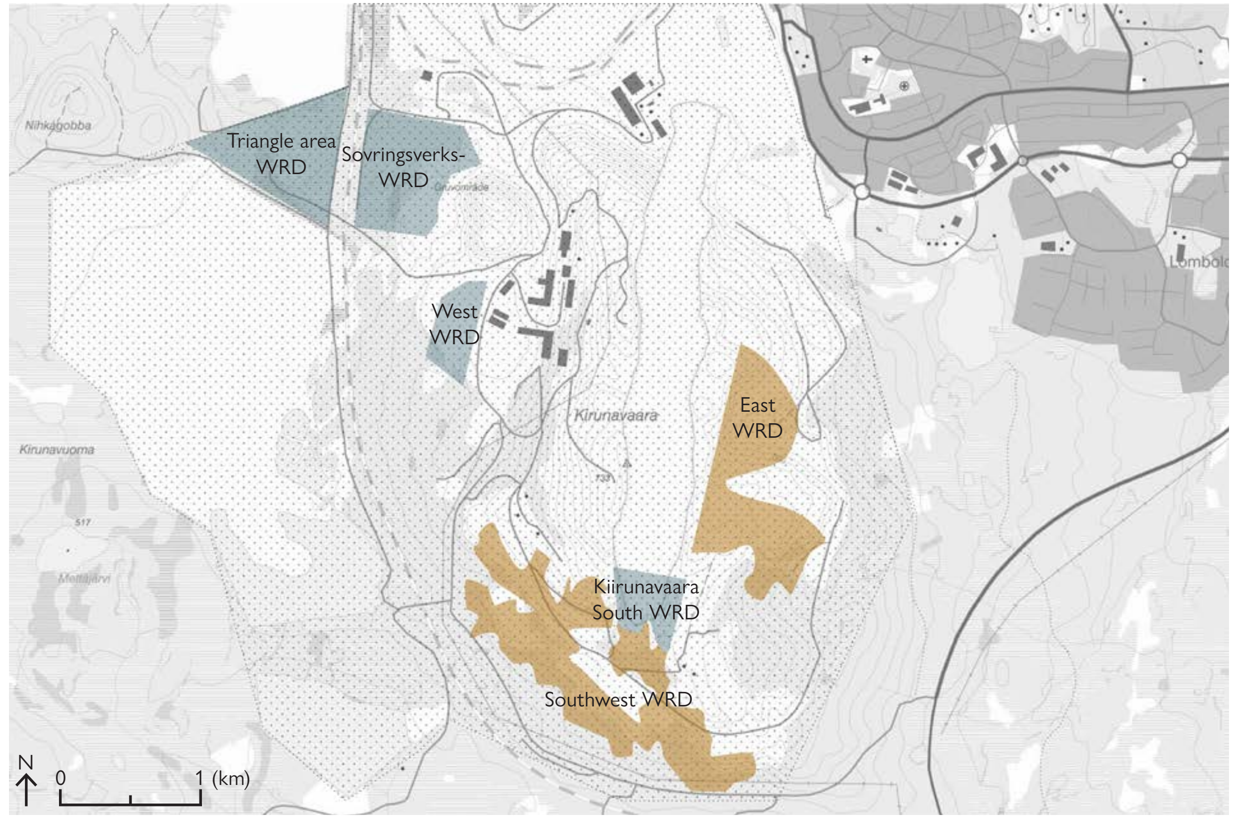


Figure 21. Mining lease area.

Mining lease area | Active WRD | Inactive WRD

Area B — LKAB Proposed Conventional WRD

Area B is located in the southern part of LKAB's ongoing operations in Kiruna on Kiirunavaara's southwest slope. The area includes waste rock previously deposited on the side of the mountain and older, historical dumps containing sludge and industrial waste. Within Area B, the existing landfill site is at a level of +590m. The natural land below the waste rock is approximately +550m and sits at about +530m at the southern end.

Construction

The permitted construction method for the proposed conventional WRD, as illustrated in Figure 22, is as follows:

1. Site preparation, including land clearance and removal and stockpiling of the underlying moraine (till) and topsoil.
2. Construction of benches (or lifts) using end-tipping according to the following parameters:
   - The first rise or bench is 15m high. Additional benches are 30m high with a 10m-wide drainage terrace between the benches. The maximum permitted height is 640m above sea level
   - A slope angle of 35°, which gives a slope ratio (V:H, H = Horizontal distance, V = Vertical distance) for a single bench of 1:1.5 (angle of repose) and for two benches of 1:1.65. If more benches are added, the overall slope ratio decreases further as more levels are introduced
   - The failure angle of the material is approximately 1:1, therefore the proposed slope angle provides a satisfactory safety factor

The approximate volume of the proposed conventionally designed dump is 72,000,000m^3 or 130Mt with a waste rock density of 1800kg/m^3.

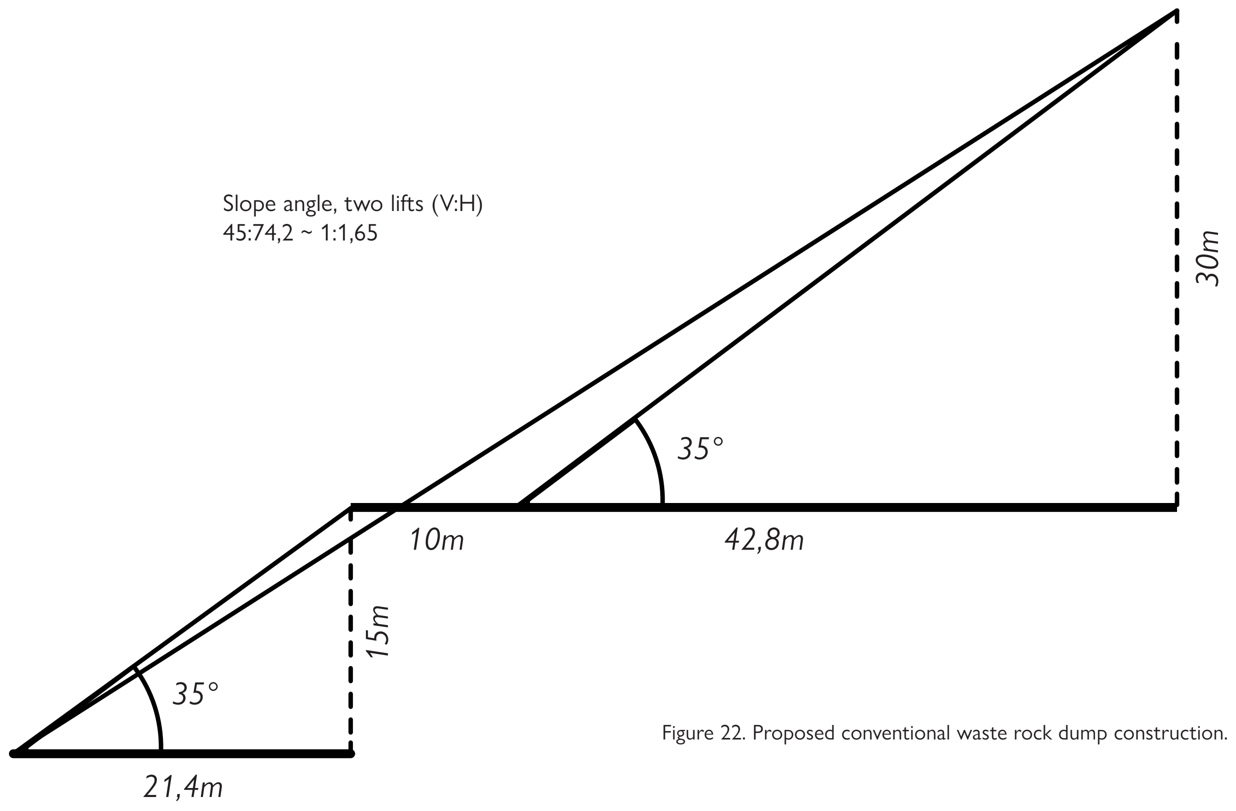


Figure 22. Proposed conventional waste rock dump construction.

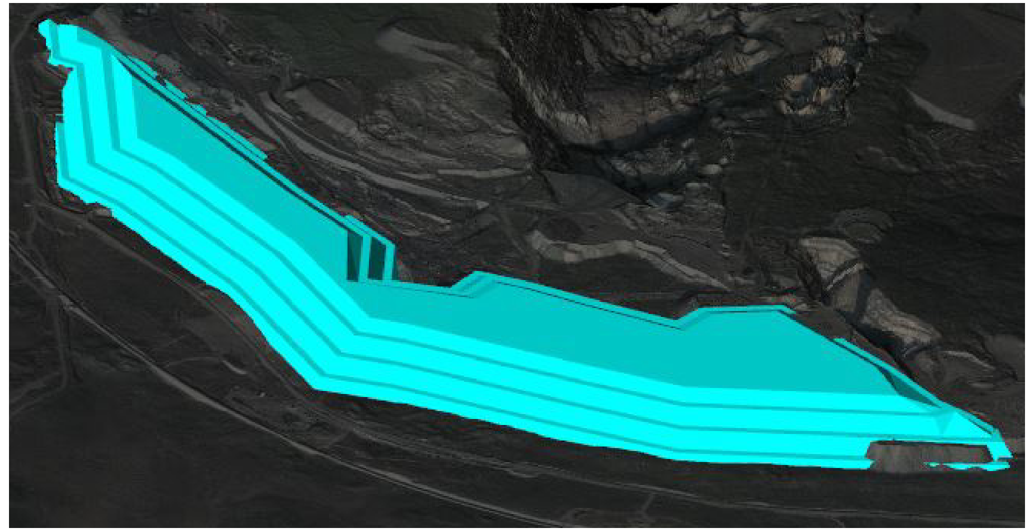


Figure 23. The proposed conventional waste rock dump at Area B.

Structure

Kiruna's waste rock consists of two grain size fractions: 0-30mm and 30-200mm. Density tests show a loose packed density of 2,100kg/m^3 for 0-30mm and 1,710 kg/m^3 for 30-200mm. Waste rock grain size has a direct bearing on the permeability of the waste rock.

The tipping of waste rock from haulage trucks distributes the material along a plane at the angle of repose. A significant degree of particle segregation takes place along each plane with the upper reaches of a level consisting of the finer grain material and the lower zones with the courser material, which extends across the entire footprint of the dump. The levels above and below will be exhibit similar characteristics. This creates a permeable zone that contrasts dramatically with the underlying natural ground surface resulting in preferential horizontal flow along the pre-existing land surface. In addition to this, a degree of horizontal compaction can be expected along the upper surfaces of terraces/benches as a result of vehicle movement. Surface compaction due to construction traffic can reduce the infiltration rate. The general path of water movement through the dump is thought to be close to the angle of repose in the upper portion of the dump where particles are significantly finer. As the water moves deeper the amount of fine material decreases and the water takes a more vertical path. Waste rock dump hydrology in combination with waste rock geochemistry determines seepage/runoff water quality. It is the baseflow component of the seepage discharge that is most likely to have poorer water quality and be of environmental concern, if not effectively managed.

The porous nature of the waste rock provides enhanced infiltration capacity. As a result, the waste rock has limited water holding capacity meaning there is a reduced risk of water pressure building up inside the dumps, which can lead to slope failures. Therefore, slope failure and erosion have been classified as low risk by LKAB.

Sulphide minerals occur primarily in the finer fractions of the waste rock; however, there is a low potential for acid generation as any acid produced by sulphide oxidation is neutralized by carbonates present in the waste rock.

Photo survey from Area B

Figure 24. View to the south from existing WRD on area B.

Figure 25. Surface flows from Area B.

Figure 26. Limited erosion on the WRD outslopes.

Figure 27. View to the northeast from the foot of the WRD of existing vegetation - naturally re-colonised mountain birch.

Figure 28. Aerial view from southwest of Area B.

Water

Mining Lease Area

The Kiruna mine site is divided by a watershed directing flows north towards the Luossajoki catchment and south towards the Rakkuri catchment. The operation affects three receiving systems: the Luossajoki system, the Rakkuri system and the Pahtajoki/Rauta river northwest of the site (Figure 29).

Groundwater flow is dependent on the soil infiltration properties and the underlying geohydrology, as well as on precipitation, climate and evaporation. Groundwater flows are greatest during the spring and at their lowest, or non-existent, during the winter. Groundwater flows at two levels – shallow and deep. Flows are greatest in the shallower layers and decrease with depth, partly as a result of a reduced flow gradient, but also as a result of different water carrying capacities in the deeper rock. Ground and surface flows fluctuate during the year with the climate with higher flows during snowmelt in April-May.

Figure 29. Watershed within the mine site.

Area B

Water flow in Area B is affected by old mine waste deposits and runs towards the wetlands south of the Kirunavaara mountain. The catchment area covers approximately 300ha. According to WSPs Area B Pre-Study report 2019, hydrological studies (Figure 30) indicated that the total drainage in the area is estimated at 1.31 million m^3. Of this, approximately 545,000m^3 drains off towards the mining lease area and can be treated in the mine's water management system and approximately 765,000m^3 drains towards Rakkurijoki.

WSP have identified eight sub-catchment areas along with five low drainage points (Figure 30). Area B is, predominantly, a local infiltration area, i.e. there is a downward flow of groundwater. The geology at the site gives rise to different groundwater reservoirs, partly in the soil layers and partly in the bedrock. Generally, the water moves in pores in the soil layers and in the cracks of the rock that exists in Area B. Field studies have also identified locations where surface flows occur.

Leachate that passes through the area's existing dumps is largely expected to exit the site via natural drainage until it is collected in ditches along the transport road to the south of the area. The water then flows along the ditches to low points where it flows under the road via culverts. The same process occurs further south at the railway line. The leachate eventually enters the wetland area south of the railway line that surrounds Lake Mettä Rakkurijärvi and the Rakkurijoki stream towards Kalix River.

Water draining from Area B will carry nitrate estimated at concentrations of 80-90mg of nitrate/L. If this is not collected and processed, it will flow directly into the receiving water body. Monitoring and testing have indicated that water entering the wetlands currently contains 1,200kg/year of nitrate and 120,000kg/year of sulphate. As a result of the proposed WRD, the area's pollutant loading is predicted to increase to 60,000kg/year of nitrate and 610,000kg/year of sulphate, which will be above the regulatory limits and the standards of the EU Water Directive.

Figure 30. Surface water flows from Area B.

Remediation

Mining Lease Area including Area B

Swedish law obligates a mining company to restore its mine site to a satisfactory condition with regard to protecting land, water quality, biodiversity and landscape aesthetics and with consideration given to future land-use. Accordingly, LKAB has developed rehabilitation goals for the Kiruna mine site which are outlined in their mining permit application.

LKAB have a strong focus on ecological restoration to increase the natural value of its sites governed by the principle of 'no net loss of biodiversity based on a baseline of the site's possible biodiversity'. Their approach aims to avoid and minimize disturbance followed by restoring disturbed land and creating environmental offsets when the other options do not suffice.

In 2015 LKAB developed guidelines requiring all WRDs remediation to be carried out with an ecological focus. LKAB's current mining permit states that their end-use goal for WRD rehabilitation is to return the land to a useable state for reindeer herding and recreation. Measures to achieve this will include the following:

- A 30cm cover of moraine (till) and 10cm of organic material.
- Establishing vegetation suitable for grazing by reindeer, which is the current intended end-use.
- Fertilizer application during an initial plant establishment period.
- A proposed overall slope gradient of approximately 1:3 (V:H), with a gradient on each bench of approximately 1:2.5 (V:H, H = Horizontal distance, V = Vertical distance) to enhance access for animals and people and improve safety in the future.
- Re-sculpting results in the extension of the toe of the WRD by approximately 30m from its design footprint and a corresponding indentation reduction of the dump's crest and a slight lowering in its height. The extension of the dump's toe can impact on site infrastructure, such as the railway, that dissects the site and several operational haul roads; therefore, early remediation to most of the waste rock dumps is not possible.
- The finishing work might include sculpting the lower parts of the dumps to improve wind protection and water availability by using moraine to construct valleys and ridges.
- To further enhance the landscape aesthetic and reduce the visual impact, the slope crown could be rounded off with only low-lying vegetation planted in the area so as not to accentuate height differences to the surrounding landscape.

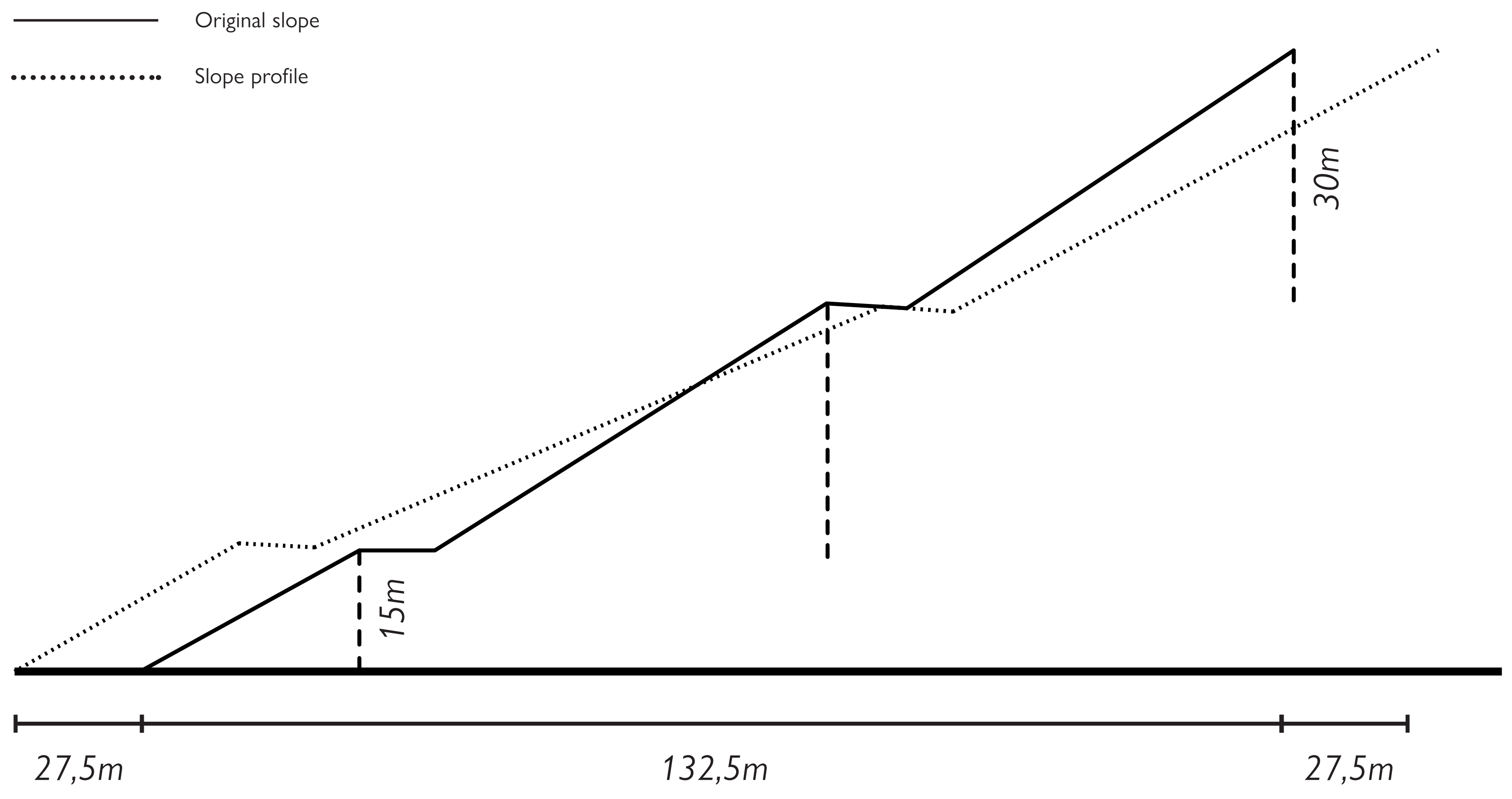


Figure 31. Principle sketch for regrading the proposed conventional WRD slopes for remediation.

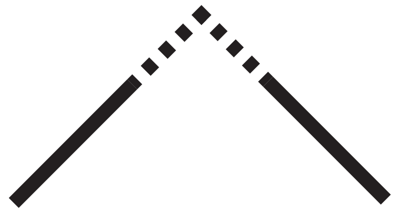
Area B - Alternative Remediation Plan

Ecological consultants EcoGain explain in their rehabilitation recommendations for the site that by introducing deep, fertile topsoil there is a risk of undesirable and competitive species being introduced, which will diminish the establishment success of the desired species, such as blueberry, lingonberry and reindeer lichen hindering the site to be used for reindeer herders in the future. The vegetation type above the tree-line elevation will be mountain heath and below the tree line will be mountain birch. Measures to achieve this will include:

- Creating complex topographies to encourage vegetation diversity. This includes hilly terrain with smaller hills, sinks, ravines and ledges.

Above the tree line

- Covering with 0-10cm of moraine and 1–5cm of nutrient-poor, organic matter
- Spreading lignin-rich material (bark chips or pieces of twigs) in a thin layer, about 1cm deep – preferably by-products from the local forest industry
- Spreading fragments of reindeer lichen over the surface.
- Plant lingonberry and blueberry in clusters over about 10% of the surface



Below the tree line

- Covering with 10-30cm of moraine
- Spreading 5-10cm of nutrient-poor organic matter
- Leaving 10% of the surface with exposed soil
- Applying an appropriate grass seed mix with target species; *Deschampsia flexuosa, Festuca ovina, Festuca rubra* and *Juncus trifidus*
- Planting trees in small groups covering about 20% of the surface

Figure 32. Local flora.

Existing NITREM System

Water monitoring and sampling across the LKAB site indicated nitrates leaching from the Triangle Area WRD (Figure 33). This led to the decision in 2018 to locate three bioreactors at the base of the dump in the north-east corner (Figure 34). The WRD is currently under construction, but nearing completion; 59Mt have been deposited in the area and another 13Mt are planned during 2020-2021.

The location of the bioreactors was based on the knowledge that the WRD was located on top of an existing stream bed and a former wetlands area, which assisted with an understanding of the groundwater flows in the area. Further field sampling and monitoring identified where the leachate from the WRD was flowing. However, today the system is experiencing a slower than predicted flow rate and lack of water in the collection reservoir. This indicates the groundwater studies undertaken prior to the bioreactor installations lacked adequate detail and knowledge to ensure the successful collection of leachate and its subsequent treatment.

When integrating the NITREM bioreactor technology with a WRD in a mining landscape it is critical to understand both the waste rock dump and site hydrology to ensure optimal functioning and efficiency of the bioreactors and that contaminated groundwater is intercepted before leaving the site.

This includes identification of the following features:

- An estimation of the annual surface runoff and groundwater recharge
- Surface water flow direction and discharge
- Catchment areas and their discharge points
- Leachate discharge point from the WRD
- Discharge area delineation and identification of area where a reservoir can be located
- Groundwater flows and depth
- Rainfall intensity
- WRD structure
- WRD composition
- Geochemical characterisation

Ideally, installing a bioreactor would be considered in the planning phase of new waste rock dumps, however, as is the case here this may not always be possible. The Kiruna NITREM system consists of three bioreactors and a collection reservoir. Leachate from the Triangle Area WRD is directed to the bioreactor system utilizing the sites natural topography for flows. The system captures surface water, groundwater and leachate via covered ditches, which is diverted to the collection reservoir. The water is first collected in the reservoir, allowing for year-round flows, before it is pumped into the operating bioreactors. The bioreactors are designed to process 0.5L/s, which was determined in previous laboratory experiments and pilot-scale bioreactor studies. Results have shown that during winter the flowrate into the bioreactors is around 0.1L/s showing that Kiruna's climate impacts the availability of water for treatment during the winter period. The approximate residence time is 7-10 days with these low flows, with results showing that this is sufficient time to remediate the water before it exists the system under gravity to the recipient, Luossajoki.

Monitoring data from 2018-2019 indicate a nitrate removal of >95% with initial concentrations of 70-110 mg/L nitrate-nitrogen. Higher flows would lead to a less efficient system with nitrates potentially leaving the system. The average temperature in the bioreactors is 3°C, such a high level of nitrate removal is very good for a biological process that is temperature-dependent. The discharge water from the bioreactor is also analysed for nitrogen bi-products such as nitrous oxide, ammonium and nitrite. Concentrations of these compounds are generally low but the operation of the bioreactor system is being optimized in order to minimize the release of bi-products. Monitoring of the bioreactors during 2018–2019 have provided valuable technical and landscape-related data such as the amount of water treated and the efficiency of water treated during its operation, which will inform the geomorphic landform design.

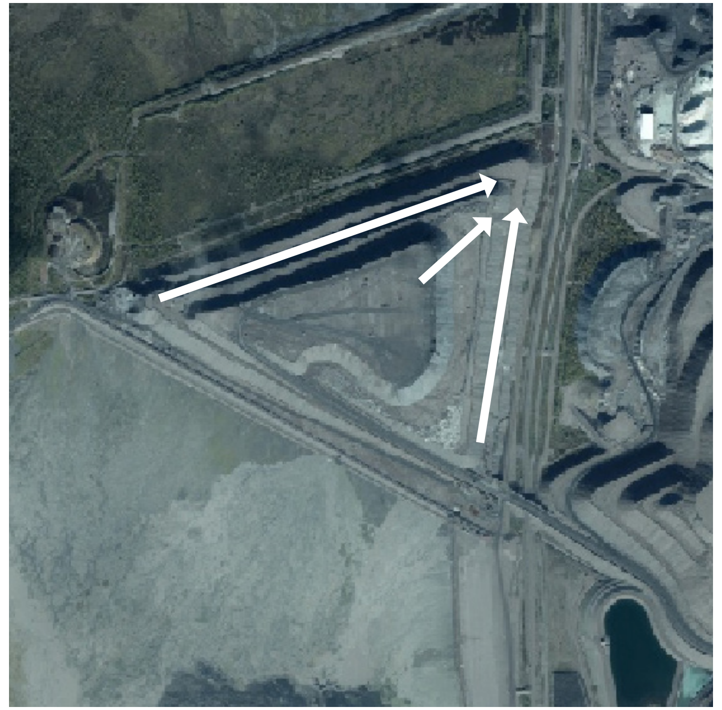


Figure 33. Identified leachate flows at the Triangle Area WRD.

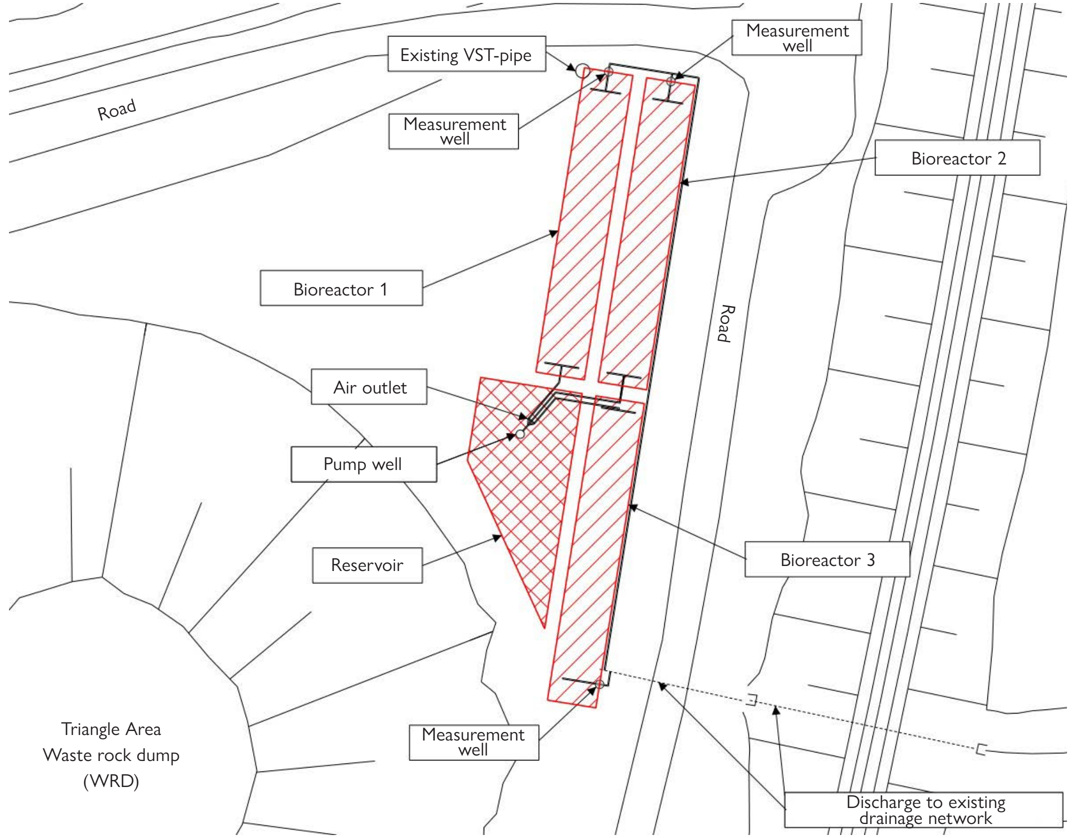


Figure 34. The Kiruna NITREM system consists of three bioreactors and a reservoir at the base of the Triangle Area WRD.

CHAPTER 3

Landscape Plan

This chapter considers the design and development of Kiruna's WRD landforms and incorporation of the NITREM bioreactors and is divided into the following sections:

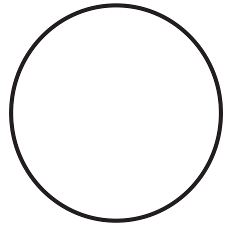
- Landscape performance goals and criteria
- Landscape model inputs
- Geomorphic design:
    - Pre-study
    - Revised design
- Bioreactor locations
- WRD ground water modelling

Landscape Performance Goals and Criteria

In order to construct sustainable landforms, consideration needs to be given to the purpose of the landform and, importantly, what can be measured to ensure delivery of this purpose. Landscape performance goals and criteria for the project have been established after internal stakeholder consultations and a review of LKABs Efterbehandling report and a review of good international industry practice. These specific goals include and expand on the goals identified in LKAB's Efterbehandling report. The development of goals and criteria is an important step in the project process to guide decision-making during the landform design process.

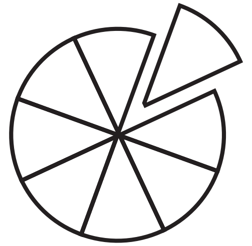
Landscape Performance Goals

The project's landscape performance goals are are explained on the following pages. The performance criteria will form the basis of an on-going monitoring plan to enable adaptive management of the new landform and ecological system, while enabling bioreactor function.



Landscape performance goals are defined as:

High-level statements of intent that set out proposed outcomes for the landscape in question.



Landscape performance criteria are defined as:

S*pecific, measurable parameters that enable monitoring of progress towards achieving the performance goals.*

Performance criteria are also important in highlighting shortcomings or problems with systems or processes, prompting adjustments as required.

Goal	Rationale	Criteria
Financial viability	Goals need to be financially achievable within the company's needs	• Progressing rehabilitation • Ongoing cost • Avoid double-handling of waste rock • Minimize haul distances
Ensure protection of workers and future landscape users	Health and safety	• Stable landform • Access – during construction and operation + afterwards for maintenance and public • Dust generation • Fencing requirements • Minimize risk for incidents/accidents
Socio-economic viability	Landscape needs to be socially acceptable and viable over the long-term – including after relinquishment	• Stakeholder consultation (early & ongoing) • Community participation • Systems & processes for post-closure management • Socio-economic monitoring & evaluation

Goal	Rationale	Criteria
Establish drainage density and water balance	Minimizing contaminated water exiting the site	• Optimise surface and groundwater flows • Reduce snow accumulation with landform design • Impermeable base • Evaluate flooding risk • Manage runoff to accommodate surrounding landscape surface water systems • Water balance
Optimize water treatment and bioreactor function	Treat leached water	• Efficiency of operation (residence time) • Efficiency of water collection (flow rate) • Access for maintenance/monitoring
Maintain surface and groundwaters	Meet environmental standards	• Environmental quality standards (MKN) • Ecological or human toxicological risk • Quality of recipient water system

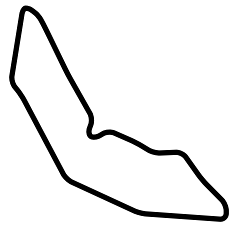
Goal	Rationale	Criteria
Create a physically stable, erosion-free landform that allows permeability for leaching the nitrate	Minimize ongoing economic cost	• Ensure geotechnical slope stability • Control of drainage • Design to account for any underground mining-related subsidence • Protect against surface erosion • Maintenance free • Target vegetation cover
Achieve appropriate WRD-cover/finishing	Helps functionality of geomorphic landform Improve success of vegetation re-establishment	• Substrate depth • Substrate porosity/ permeability • Substrate resistance to compaction • Substrate fertility • Erosion risk
Create an ecologically appropriate and, over time, sustainable vegetation cover	Enhance biodiversity and ecological function that supports the final end land-use Stabilize landform and prevent erosion	• Vegetation cover (% cover and density and canopy structure) • Species (cover abundance; presence/ absence; community type) • Resilience (vulnerability to disturbance; climate change; grazing) • Sediment reduction to surrounding environment • Vary topography, including at micro-level, and soil distribution to provide diverse ecological niches • Ecological connectivity with surrounding habitats • Ongoing maintenance cost
Ensure that the remediated site aesthetically blends into the surrounding landscape	Reduce visual impact Social acceptance	• Naturalized topography • Acceptance / visual impact (restoration of visual values) • Geomorphic compatibility with surrounding landscape • Access

Goal	Rationale	Criteria
Develop a post-mining land-use that meets socio-economic & environmental goals	Environmental legislation and social licence to operate	• Sami reindeer herding • Potential recreational use • Wildlife • Environmental & socio-economic monitoring & evaluation
Retain and enhance mining heritage	Preserve mining culture/heritage Enhance heritage remains	• Monitor historical buildings and artifacts
Implement a sustainable, post-mining land management system	Minimises mining company involvement after relinquishment Financially viable over the long-term Establish management body to take responsibility	• Land management body • Multi-stakeholder involvement • Local community participation • Appropriate financial support mechanism

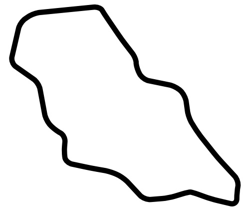
Geomorphic Design

The design work for a geomorphic design was undertaken in two stages. The first was a pre-study to investigate if the required volume of waste rock could fit into LKAB's permitted footprint for the Area B site and successfully achieve a geomorphic landform. The second stage looked at a revised geomorphic design based on the conclusions and recommendations of the pre-study.

The geomorphic design was completed in 2019 as a Phase 1 conceptual design. The landscape inputs used in the model were based on international experience and research allowing for a design which is considered accurate over a broad range of landscapes. Therefore, the design is theorictally stable. However, the model requires further refinement including site specific landscape input data (refer to Referencce Site section on page 64). Carlson software Natural Regrade's GeoFluv module was used to design the geomorphic WRDs.



STAGE 1 The Pre-Study



STAGE 2 Revised Geomorphic Design

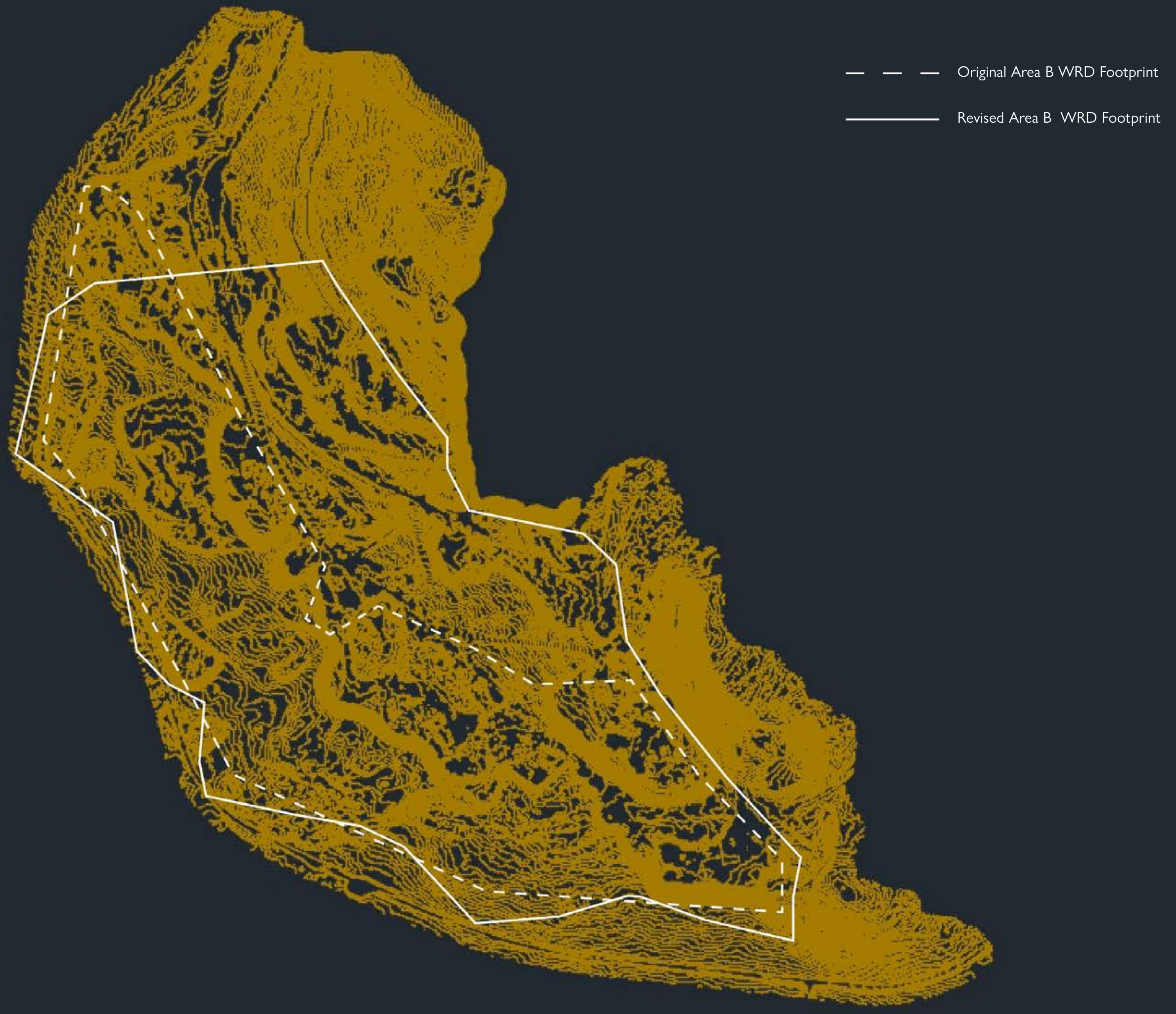


Figure 35. Footprint comparison.

Stage 1 - The Pre-study

The aim of this study was to determine if the required 72,000,000m^3 volume of the proposed conventional WRD could be maintained in a functional fluvial-geomorphic design WRD within the permitted boundary that would help convey runoff and infiltration waters to the proposed bioreactors. The reclamation landform would also have to meet criteria for reindeer habitat such as accessibility and the establishment and maintenance of grazing and shelter vegetation, while accommodating sunlit resting areas and shelter from the wind. The following describes the approach and discusses the findings and recommendations.

footprint

1,476,028m^2

(Or 207 football fields)

volume

72,000,000m^3

(Or 119 Ericson Globe-buildings)

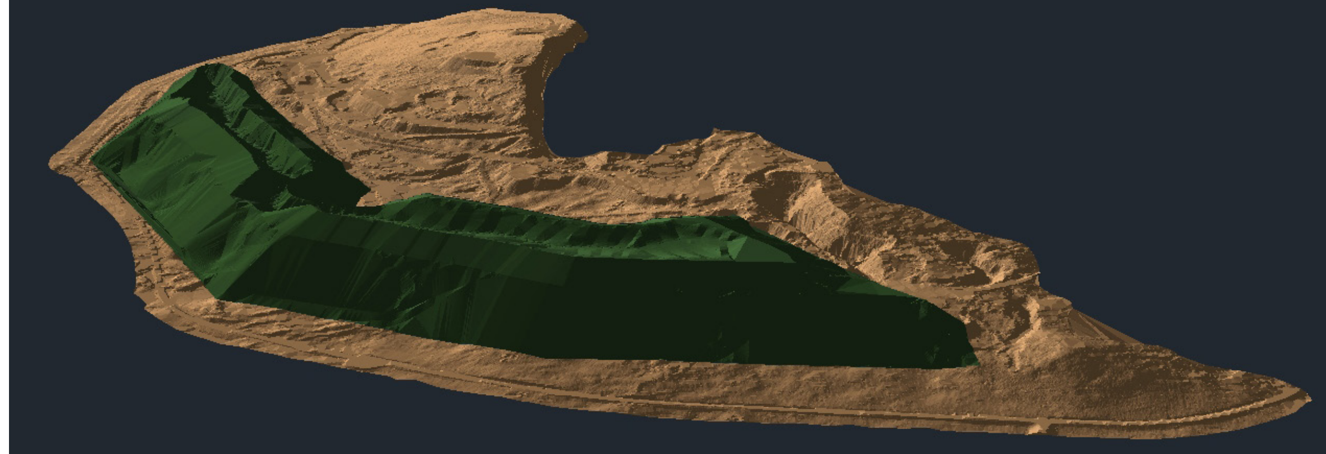


Figure 36. East to west 3D perspective view of geomorphic WRD.

Methods and Results

The existing drainage pattern in Area B was studied as it is assumed leachate percolating through the proposed WRD will flow over the underlying natural ground, including the existing WRDs, and follow the existing drainage pattern. A pre-mining, 3D topographic model of Area B was not available, so the natural drainage pattern under the existing WRD was not known. Using runoff tracking, the flow pathways of rainfall runoff were plotted on the surface of the 3D topography of the site. The results are shown in Figure 37.

The surface valleys are defined where the magenta runoff tracks collect and form a single preferred flow. The points where these valleys intersected the proposed WRD's downslope boundary line were marked with circles, representing the local base levels – the point to which each sub-watershed will drain. They identify the mouth of channels on the outslope of the geomorphic design. It is important to identify these points so that the reclamation channels optimize the collection of runoff and leachates for routing to the proposed bioreactors.

Figure 38, shows the boundary line of the proposed dump with the identified local base level circles on its downslope sides. A blue line shows the general trend of the valleys and channels needed on the WRD slopes to collect and convey water to the under-lying natural valleys. Gold lines between the blue valley lines indicate where the sub-watershed ridges separating adjacent valleys will trend.

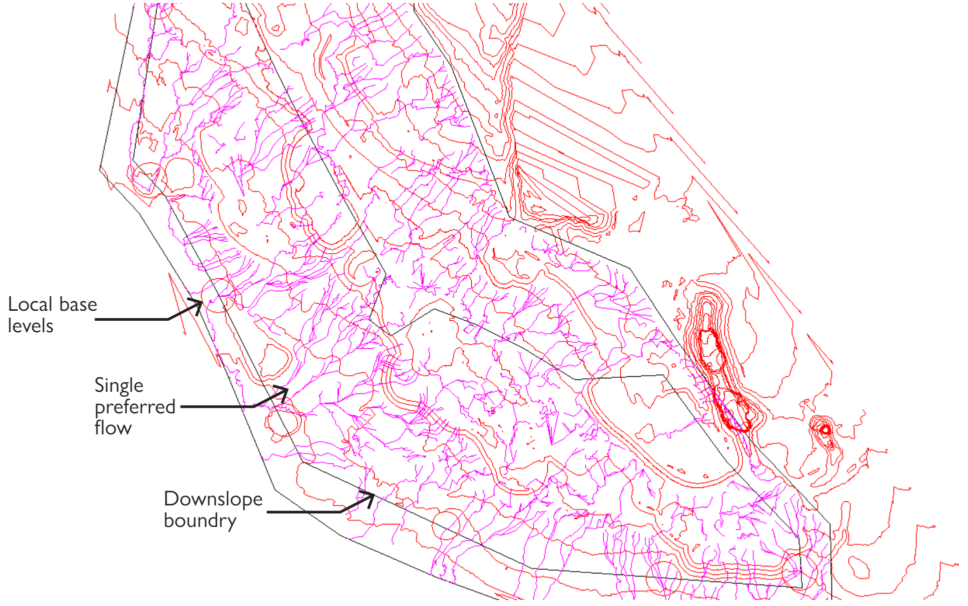


Figure 37. Runoff tracking used to identify overland flow paths and local base levels.

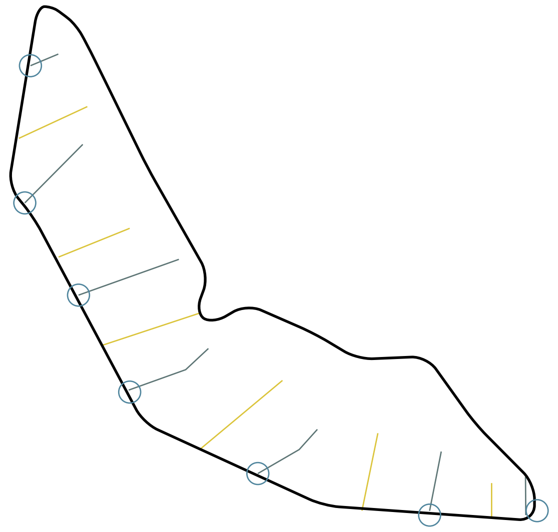


Figure 38. Identified low points, valleys and ridges.

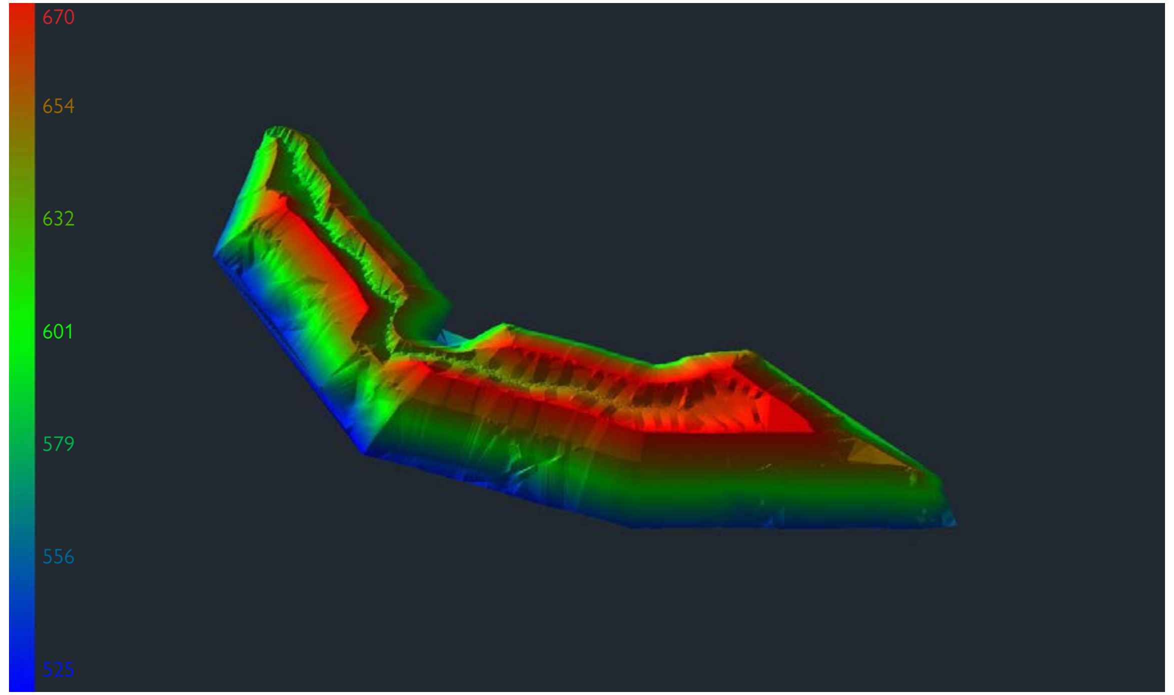


Figure 39. CAD elevation model of proposed dump with ridges of displaced valley cut material.

To determine if the proposed volume could fit within the site, a CAD model of the proposed dump using the permitted boundary line, the 1:1.5 slope and maximum 640m elevation as proposed in LKABs rehabilitation report, was modelled. The valleys required to design a functional fluvial geomorphic reclamation landform reduces the material volume of the conventional dump design. The estimated volume shortfall of 25% that the valleys would displace was added to the dump top as ridgelines that peaked at 670m. Figure 39, shows a 3D colour-by-elevation view of this revised dump model that would be the starting surface for a fluvial geomorphic design.

The required valleys and associated ridges and valley wall swales were then designed on the identified outslope positions and a long main channel on the dump top. The dump top channel has headwaters at the southeastern end and trends northwest following the dump access road.

The material volume held by the conceptual geomorphic design was calculated at approximately 82,000,000m³. This volume was greater than the minimum 72,000,000m³ WRD target volume, thus demonstrating that a fluvial geomorphic-based design can hold the required volume within the existing footprint.

Next the WRD slope angles were analyzed to assess their suitability for the designated post-mining reclamation land-use. Reclamation lands are generally designed at slopes less than 33% because the finer-grained growth material can be susceptible to erosion at steeper slopes and this is also typically the maximum operation angle for the agricultural equipment used to sculpt the geomorphic WRD. The slope analysis identified that approximately 70% of the designed slopes are steeper than the 33% maximum slope target for successful vegetation establishment on reclamation.

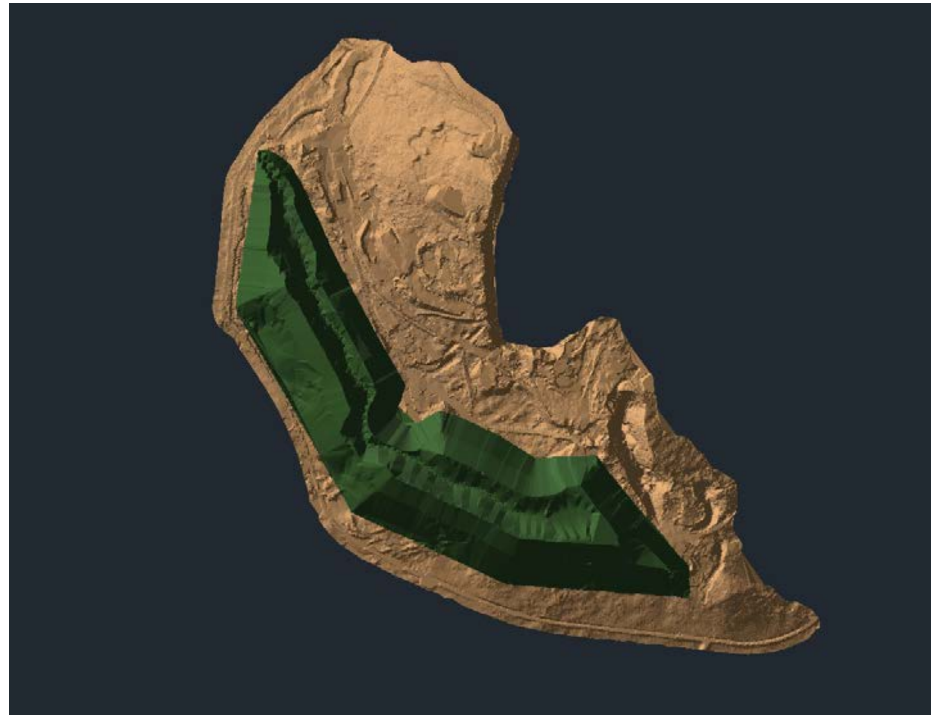


Figure 40. Planview.

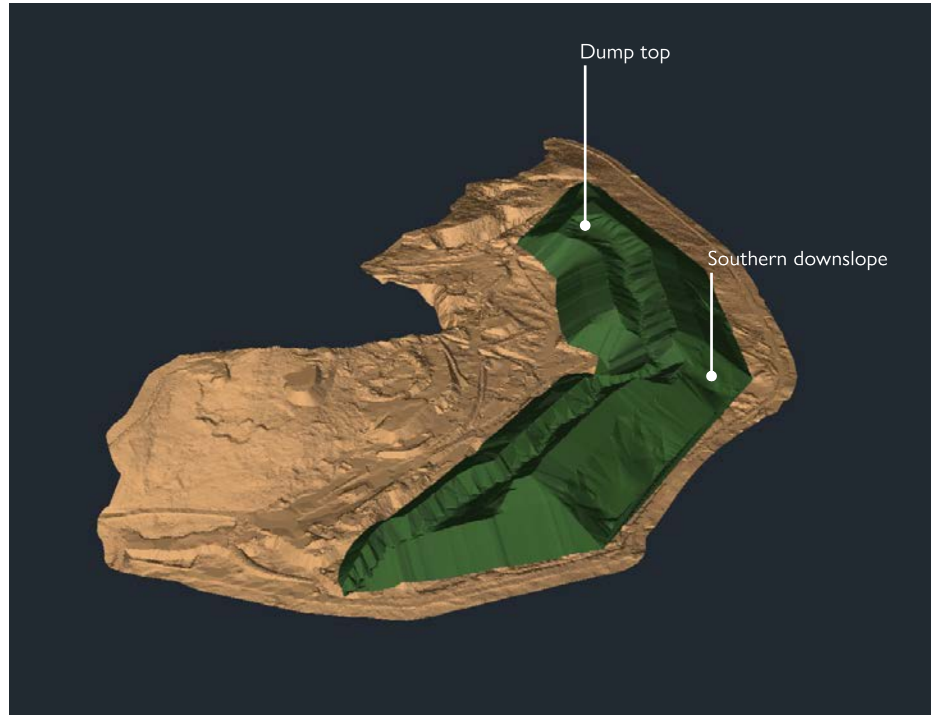


Figure 41. West to east 3D-view.

Conclusions

It is possible to make a fluvial, geomorphic-based landform within the designated footprint that will accommodate 72,000,000m³. It is assumed that, while its long-term stability has improved as a result of introducing a natural drainage network, such a landform does not achieve LKAB's desired remediation goal. Similar to the proposed conventional WRD, it also requires a significant portion of steep slopes in order to fit the necessary volume of waste rock. These slopes are too steep to apply a moraine/ soil cover due to the enhanced risk of erosion. As such, the landform is not expected to support vegetation desirable for the intended post-mining land-use.

The pre-study geomorphic design reflects a focus on a volume rather than aesthetics. Further design iterations may reduce the elevations and slopes within the existing footprint to improve the average slopes. However, when material is moved to reduce slopes in one area within a fixed footprint, the area that receives that material will increase in slope. Therefore, as a high proportion of the slopes within the designated footprint are over twice the desired gradient further design iterations were not undertaken.

Recommendations

The fixed volume and fixed WRD footprint constrain the design outcomes for a geomorphic design. It is recommended that further design investigations are undertaken that explore the reduction of volume or the extension of the footprint (size and shape) that would result in lower slopes that meet the target range for successful remediation.

Stage 2 - Revised Geomorphic Design

Based on the findings of the pre-study, a further design was explored that maintained the 640m maximum elevation but extended the footprint to create slope gradients that would better support the post-mining land-use. Thirty-five different alterations to the WRD footprint were explored until an alternative starting surface for the revised design, that could satisfy all the remediation criteria, was found.

footprint

2,227,500m²

(Or 312 football fields)

volume

83,000,000m³

(Or 137 Ericson Globe-buildings)

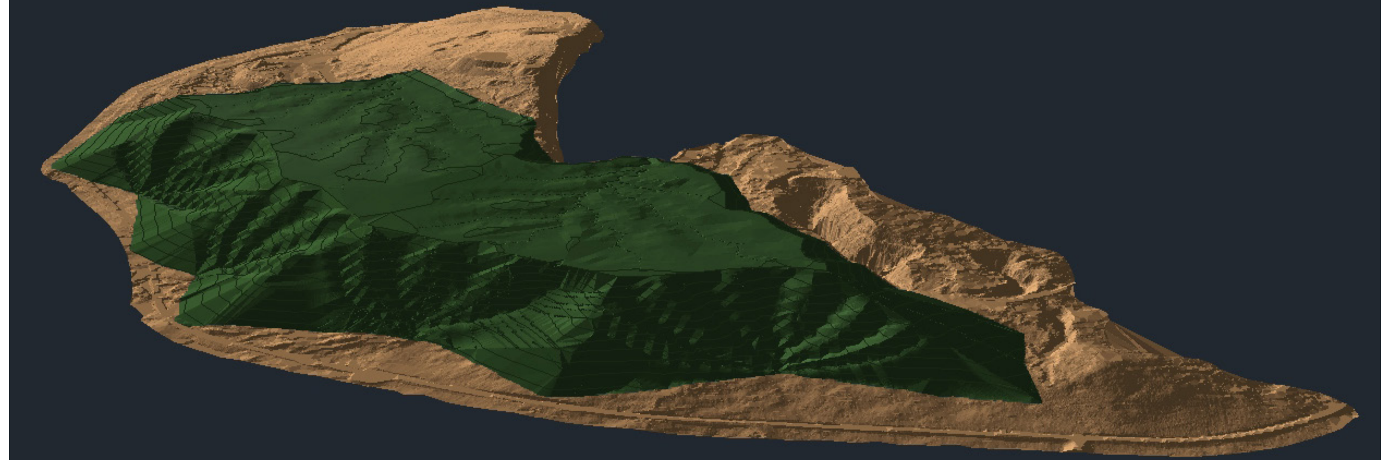


Figure 42. East to west 3D perspective view of revised geomorphic WRD with extended boundary line.

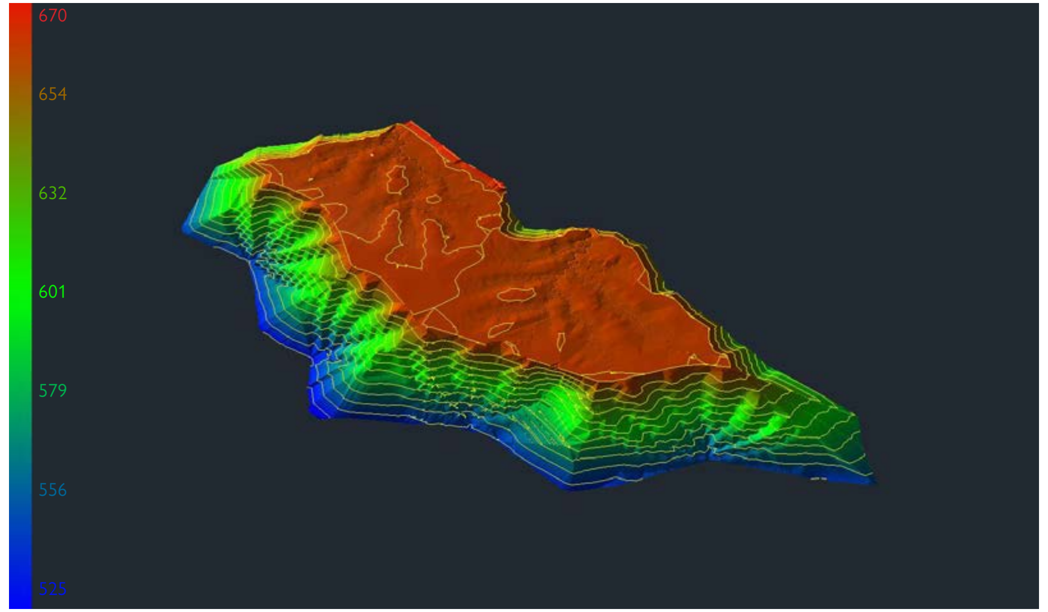


Figure 43. CAD elevation model of revised dump with ridges of displaced valley cut material.

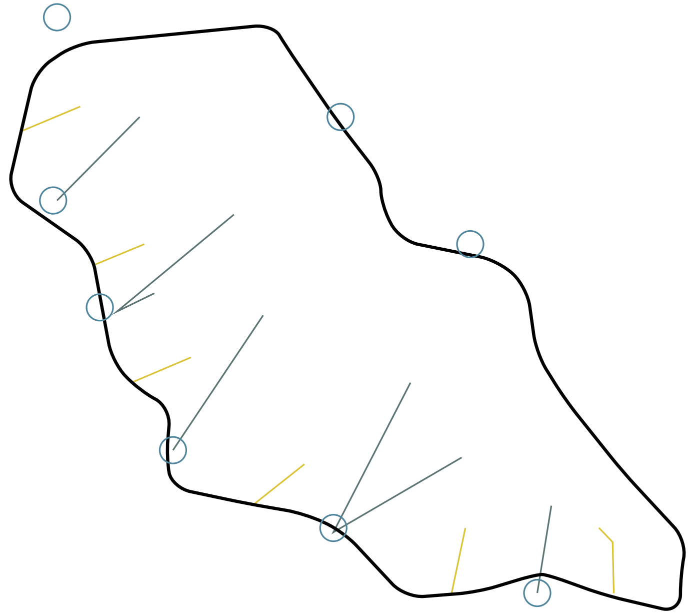


Figure 44. Identified low points, valleys and ridges.

Methods and Results

The entire WRD footprint was extended uniformly by 55m and then further extended along the northern boundary to the 640m contour elevation. Combined, this reduces the slopes to about 30%, provides for WRD top drainage without deep valleys and makes an overall landform that is similar to a kame terrace that blends into the topography rather than an isolated flat-topped hill with steep sides.

Figure 43 shows a 3D colour-by-elevation view of this revised dump model that would be the starting surface for a fluvial geomorphic design.

Resulting from the extended boundary line new local base levels were identified to ensure water flows from the design to the correct low points. Figure 44, shows the boundary line of the revised dump with the identified local base level circles on its downslope sides. Blue lines show the general trend of the valleys and channels needed on the WRD slopes to collect and convey water to the underlying natural valleys. Gold lines between the blue valley lines indicate where the sub-watershed ridges separating adjacent valleys will trend.

Figure 42 shows how such a landform would appear. The natural ground would intersect the WRD along the northern boundary at the 640m contour line and the transition between the WRD top and the outslopes is designed to be similar to that left by glaciers on the valley walls matching the geomorphology in the surrounding area.

The landform holds 83,160,016m³ of material. This is approximately 15.5% greater volume than the 72,000,000m³ target. A final geomorphic design can be honed down to the desired volume if required. The material volume and maximum elevation criteria are satisfied with this expanded boundary line geomorphic WRD.

The slope zone analysis for the revised design shows that approximately 77% of the slopes are less than 33% (Figure 45). The red colour indicates slopes less than 20% and the darkest blue indicates slopes greater than 40%. The revised design has a far greater area suitable for establishing vegetation, but also has more complex slope profiles including gradient and aspect that help to vary soil moisture retention and sunlight exposure. Such varied niches help to promote ecological diversity. The low-gradient top area is designed to be cleared of snow by prevailing NW winter winds and will also serve as reindeer grazing areas. The south-facing, steeper and more complex slopes could provide herd resting areas.

The WRD top has an integrated, dendritic drainage network of low-gradient channels to collect and convey runoff from the WRD top during rainfall or snow-melt events (Figure 46). Runoff from the east side of the WRD top is collected by the tributary channel network and conveyed northwards off the WRD top by the main receiving channel. From here the existing drainage network will convey the runoff eastward around the dump and south to the bioreactors. Similarly, surface runoff from the west side of the WRD top is collected by the drainage network and directed westwards off the WRD top where the natural drainage network will convey the runoff south around the WRD to the bioreactors. Any infiltration will be directed via the underlaying existing topography to the identified low points.

Figure 47 shows where the main valleys will be located on the downslope of the WRD. Aligning the designed valleys with the natural valleys and those created by the existing WRDs will promote leachate collection and discharge to the natural low discharge points at the southern boundary line of the WRD.

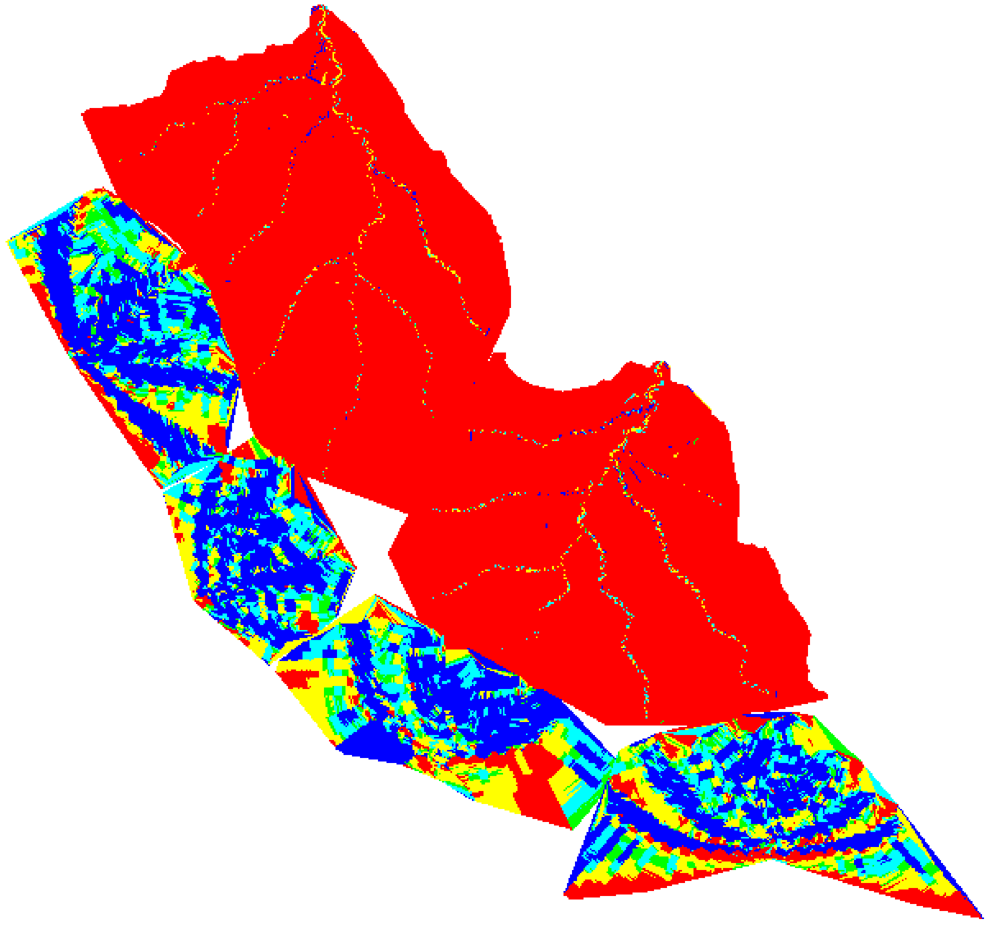


Figure 45. Coloured slope zones analysis showing drainage pattern.

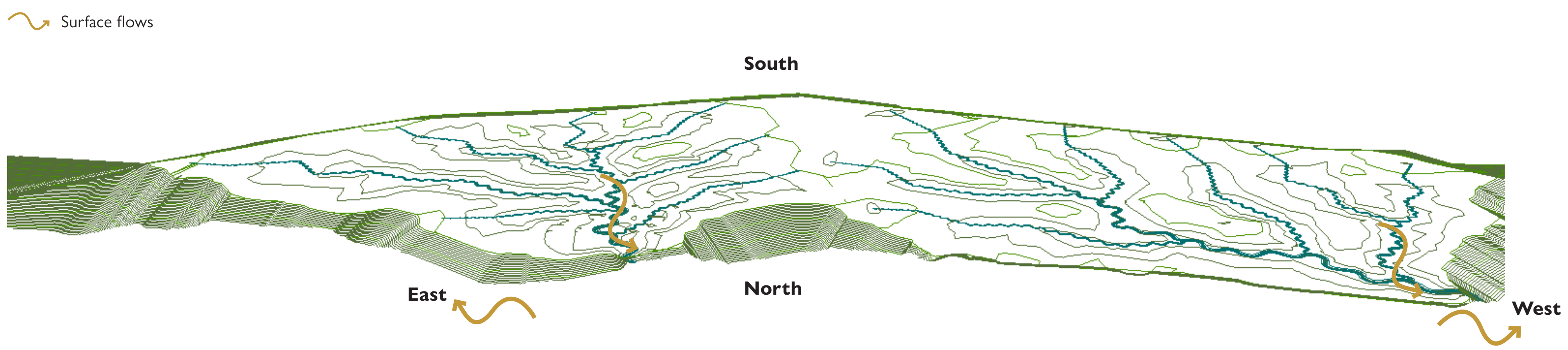


Figure 46. North to south 3D perspective contour view showing WRD top dendritic drainage network.

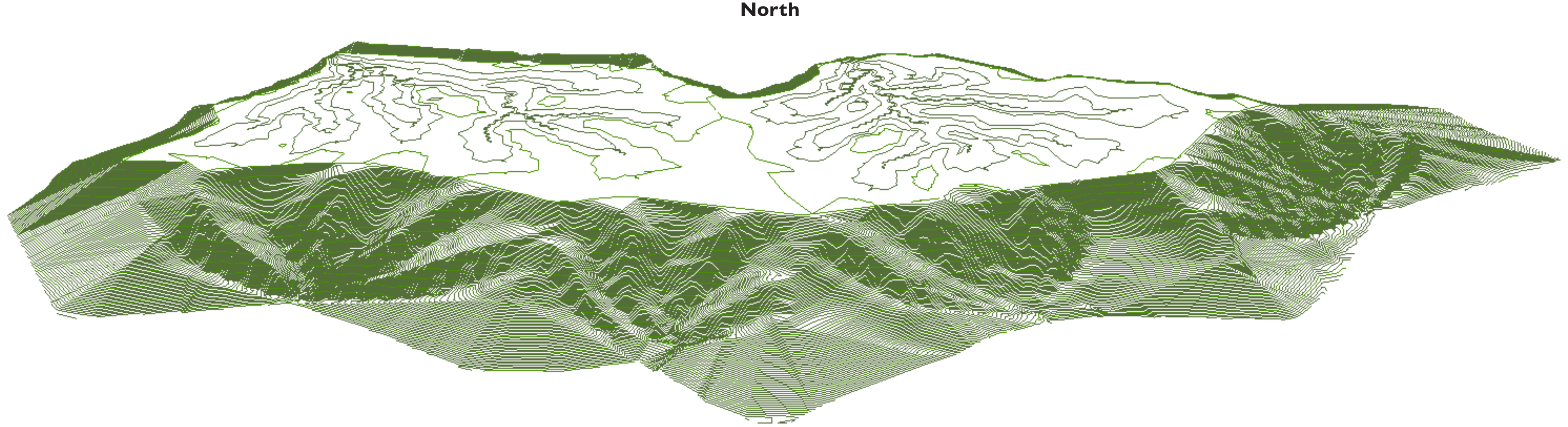


Figure 47. South to north 3D perspective contour view highlighting the main valleys.

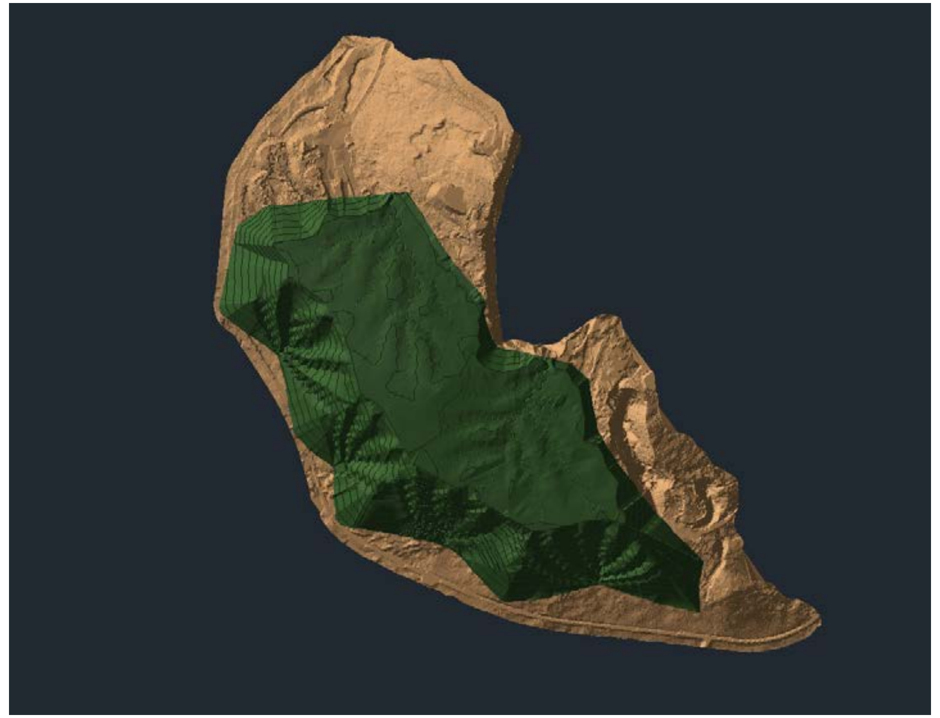


Figure 48. Planview.

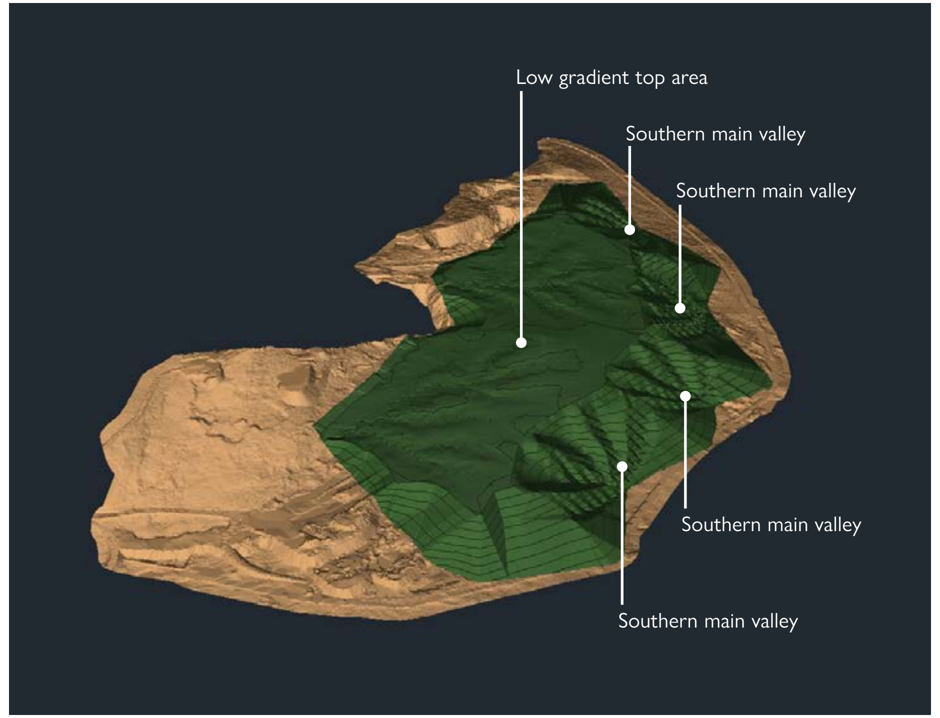


Figure 49. West to east 3D-view.

Conclusions

The revised design outcome is a conceptual phase 1 design with the resulting landform theoretically stable, but not necessarily constructible (Figure 48, 49, 50). Phases 2 and 3 of the design process, which includes evaluation of channel tractive forces, further refines the geomorphic design into a constructible WRD.

A WRD that has an extended footprint with a maximum elevation of 640m can hold an increased volume of approximately 83,000,000m^3 from the 72,000,000m^3 target volume. It can also incorporate fluvial geomorphic design elements effectively so that the majority of its surface will promote vegetation establishment to achieve LKABs remediation goals. The boundary line is extended over small sections of the transport road to the south, however, this is a recognised as a conceptual design and future adjustments can be made in a final design to resolve this. The purpose of this design was to show what could be achieved with an extension of the permitted WRD boundary line.

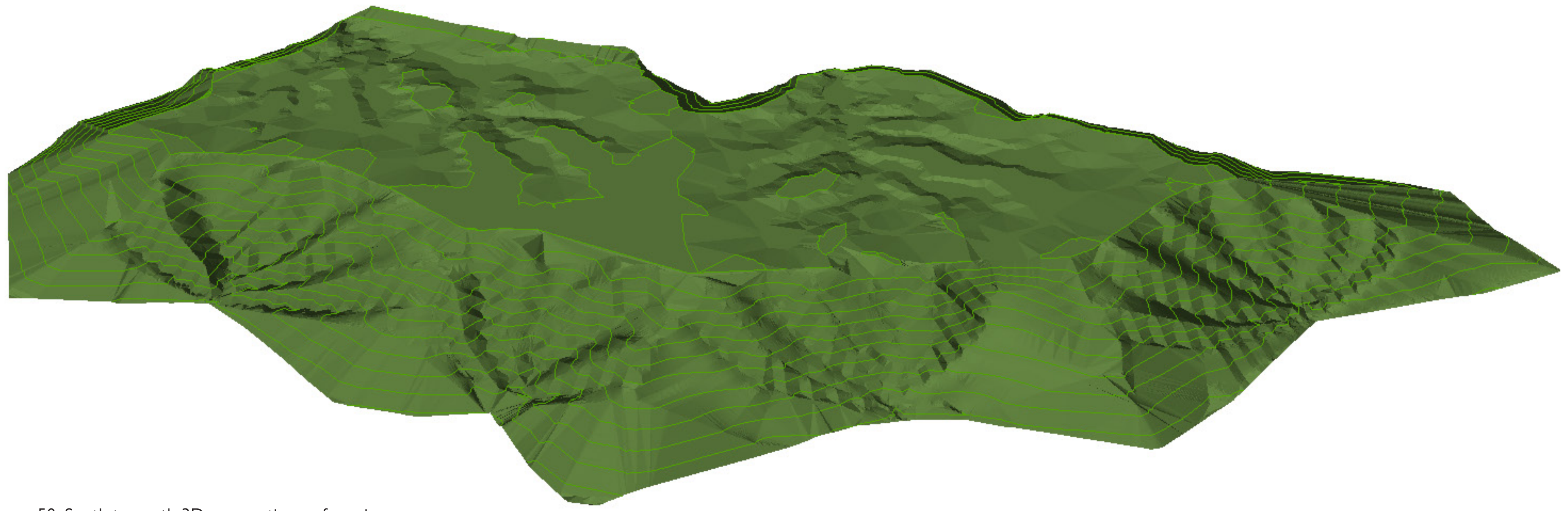


Figure 50. South to north 3D perspective surface view.

Recommendations

The revised geomorphic design has demonstrated that there are substantial benefits for site remediation to be derived from extending the WRD footprint. Further study and design iterations can vary the dump footprint and shape to enable further slope reduction, which would lower the channels' erosive energy during runoff-producing events, or to create more complex slopes to promote diversity, or to align the valleys and ridges and adjust their slope angles to influence snow accumulation in certain areas. Design alternatives can be revised to meet the different land-use objectives. The final land surface should also include accumulations of rocks, logs, etc. to provide more surface heterogeneity, which will enhance water retention, reduce the risk of erosion and provide more ecological niches. The 15.5% greater volume of the revised design gives confidence that adjustments to the boundary line and maximum elevation can be made and still accommodate the required volume.

If there was flexibility to the maximum 640m elevation, then the majority of the top WRD surface could be lowered and cut material from the valleys could be placed on ridges whose tops then might exceed the 640m elevation. This could provide an even more diverse topography and reduce the total volume of uphill material movement to save on transport cost.

There is considerable value in developing an understanding of WRD hydrology early in the WRD design and planning phase to provide greater insight into what impact the new landform might have on the surrounding environment and future land uses. Therefore, a conceptual hydrological model for the dump could be developed as part of the next design stage to allow for the timely identification of potentially detrimental environmental implications. Software such as SEEP/W, which analyses groundwater flow within porous materials could be used.

Reference Site

The basis of a GeoFluv design are site specific landscape parameters taken from a local reference site, which are used in the modelling process to ensure the geomorphic design functions and blends in with the surrounding landscape. This ensures a robust design based on the method using reference areas that have experienced historic, natural climate change over millennia.

The landscape around Kiruna is in an interglacial period with many landscape features having formed over the last 10,000 years. Therefore, a reclamation landform based on design input parameters from natural landscapes affected by widely varying climatic conditions over such a long period has built-in accommodation for the generally smaller predictions of change for the next century to come. Selecting the correct reference areas creates confidence in that the design is a landform that can respond to change over time.

Methodology

To identify suitable reference sites the following process was used:

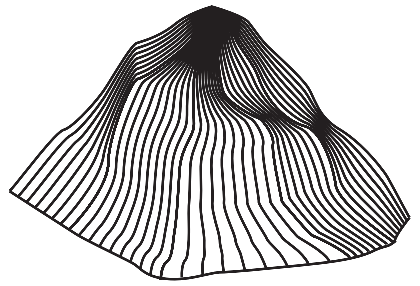
1. Literature review - Quaternary geomorphology research papers relating to the northern Sweden were reviewed and analysised.
2. Desktop analysis of aerial imagery and digital elevation model (DEM) data - the focus was to identify sites that aligned with unconsolidated land forms highlighted on geomorphology maps, drainage channels could be identified via the DEM data and were accessible by foot.
3. Ground-truthing/field data collection - visiting the identified sites to undertake site observations and measurements.
4. Review and analysis of data collected

Summary

During the GIS and field investigations of Kiruna's landscape it was problematic identifying a suitable reference site due to the difficulty in determining drainage networks in a post-glacial landscape, consisting largely of highly permeable material. A dense vegetation cover also contributed to the difficulty in identifying drainage networks. A key consideration in such a remote landscape is also accessibility.

During the successive visits in 2019 and 2020 a deeper understanding of the landscape was reached and the importance of site observations understood. Although difficult to identify – suitable reference sites do exist in the landscape. While the desktop analysis of aerial imagery and DEM data was valuable, exploring the landscape first hand with an experienced guide knowledgable of the local conditions proved the most successful in identifying reference sites.

The natural development of the fluvial networks in this landscape is different to the GeoFluv designs completed and constructed in other countries, with more fluvial erosion-dominated systems. Further field investigations and site specific landscape input measurements are required to better understand sub-arctic landscape morphology and dynamics in order to replicate them properly.

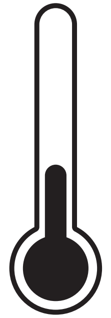


Stable 'mature' land form

- A 'mature' landform that is not actively eroding.
- Aiming to replicate a natural landform that is functioning, stable and none erosive.
- Undisturbed landforms.

Unconsolidated material

- The land form needs to be of unconsolidated material matching the characteristics of the mine waste (a once solid bedrock that has been broken apart to an unconsolidated material).
- It needs to be recognised that the reference site material will differ in some erosion properties compared to the waste rock.



Local climate

- A site that has been shaped by the same fluvial processes i.e. precipitation, so the model correctly represents the complexity, scale and size of the natural landforms.
- Creating something that belongs.

Landscape Model Inputs

Landscape model inputs, or parameters, are modelling inputs that determine the form and function of the geomorphic landform design. There are 12 key inputs for GeoFluv's global settings, which refers to the settings applying across the entire design. Such settings can be individually adjusted within specific areas of the design as required.

The parameters are measured and collected via spatial data i.e. digital elevation models and field data at suitable reference sites. Accurate data collection is critical to ensure true representation and replication of the reference site and creation of a successfully functioning landform that blends with the surrounding landscape.

During the WP5 team's site visit to Kiruna in 2020 several key landscape parameters were targeted for field collection. These included A-channel reach length and ridge to head of channel distance. Several other key parameters were also determined by GIS analysis. The following pages outlines the parameters and the reults.

It is recognised that the data collected is limited in sample numbers and therefore further data collection is required. The more accurate and representative the collected data, the greater will be the confidence in the final output designs.

Figure 51. Field data collection - Valley Hunting - Matt, Anders and José.

A-Channel Reach Lengths

Definition:

Based on Rosgen's stream classification types, A-channel reach lengths are relatively straight (in plan view) but steep channels, often characterised by a 'zig-zag' pattern with low sinuosity, on slopes ranging from 4-10% and above. A reach length is the length of each individual zig or zag.

A-channel reach lengths affect surrounding sub-watershed areas and by maintaining appropriately size sub-watershed areas, through careful A-channel reach design, we provide a balanced state where runoff ceases to degrade the slope due to excessive erosive energy, as observed in mature landforms.

Locations	Measurement (m)
Site 01	23.8
Site 02	26.5
Site 03	21,4, 33.6

Results:

Field data collection.

Comments:

- Appear to be broader than in lower latitudes (could be a result of snowmelt).

Figure 52. Frida, Anders and José.

Figure 53. Measuring location.

Figure 54. A-channel reach.

Ridge-to-head-of-channel

Definition:

The distance across the convex top of a ridge to the beginning of a downslope channel – the point of incision. The ridge to head of channel distance governs the level of built up water on convex ridge tops and controls erosive energy, or tractive force, of the water flowing downstream.

Locations	Measurement (m)
Site 02	36.5
Site 05	67

Results:

Field data collection.

Comments:

- Permeable ground and absorbent vegetation can possibly increase this distance – disperse flows and decrease velocity.

Figure 55. View of ridge to head of channel.

Figure 56. Measurement location.

57. Measuring ridge to head of channel.

Drainage Density

Definition:

A ratio of total straight-line valley length within a specified area (usually a defined catchment) divided by the total catchment or watershed area. In units of metres per hectare (m/ha), a specified drainage density for each domain design area must be applied in the design process. Inadequate drainage density or uneven distribution of channels can lead to new erosion as the landform attempts to balance itself through incision and formation of new rills and gullies, in accordance with local climatic conditions.

Results:

GIS analysis.

Comments:

- Average value of 18 m/ha
- Permeable ground material and absorbent vegetation i.e. ground cover and moss.

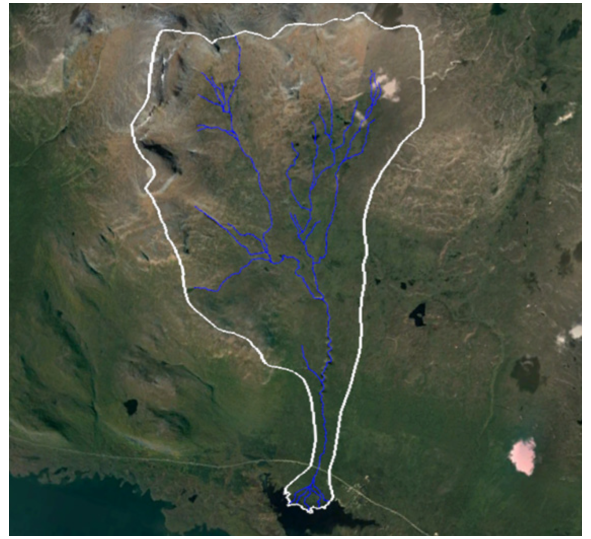


Figure 58. Drainage basin 1.

Drainage Basin 1: Nikkaluokta

Catchment Area: 2.468 ha
Total Channel Length: 41097 m
DD=TCL/Catchment Area = 16,65 m/ha

Figure 59. Drainage basin 2.

Drainage Basin 2: East of Kiruna

Catchment Area: 811 ha
Total Channel Length: 14608 m
DD=TCL/Catchment Area = 18,012 m/ha

Sinuosity

Definition:

The ratio of channel length divided by valley length, as viewed in plan view. It is an indication of the degree of meandering of a stream channel through a valley.
Resistance-dominated surfaces produce channels with higher sinuosity than those of slope-dominated surfaces because increased resistance impedes downslope flow.

Results:

DEM data analysis.

Comments:

- Permeable ground and absorbent vegetation can possibly increase this distance – disperse flows and decrease velocity.

Locations	Channel length / valley length	Sinuosity
C.1	468.24/392.23	1.19
C.2	290.38/242.39	1.2
C.3	470.81/414.55	1.14
C.4	811.29/681.65	1.19
	Average	1.18

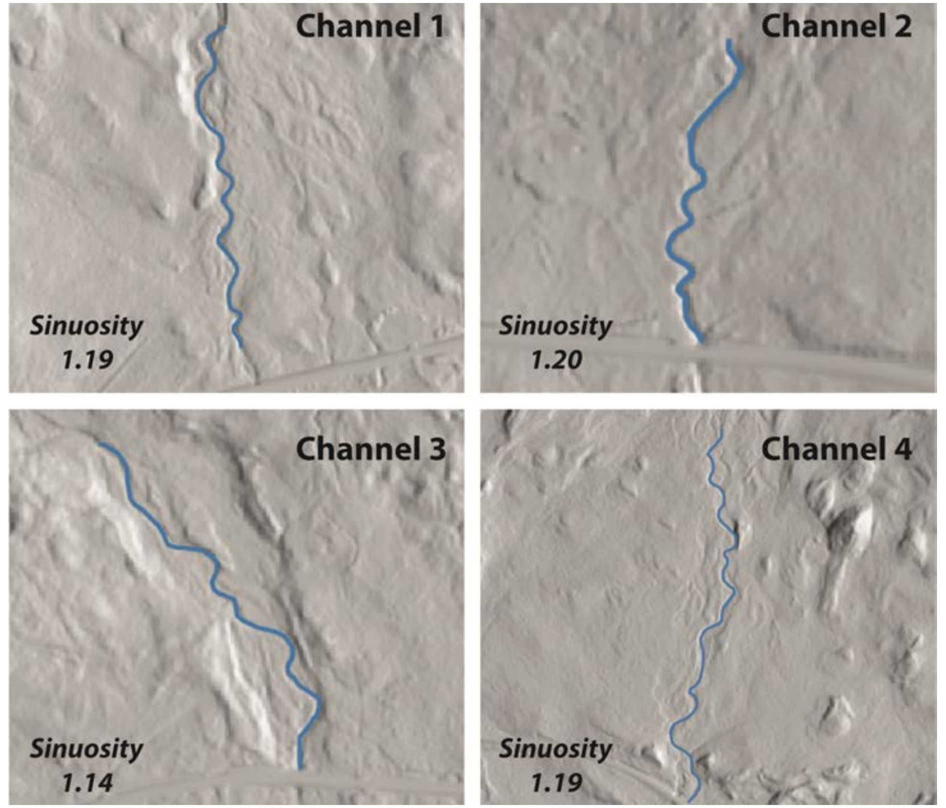


Figure 60. Sinuosity measurements on DEM-data.

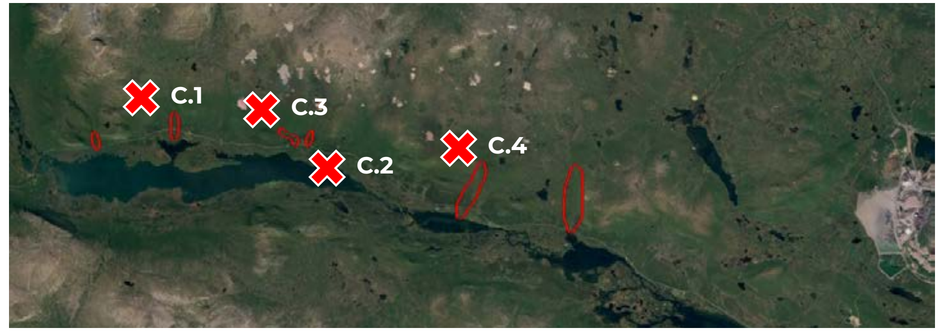


Figure 61. Measurement locations.

Precipitation

Definition:

Values of intensity, frequency and duration (IFD) in cm per hour. Provides upper and lower limits of expected or likely rain and flood events. Directly informs stream channel designs (bankfull and floodprone widths). Impacts on a streams capacity to adequately move sediment.

Hydrologists have determined that a stream's channel pattern is mathematically related to the water-surface width at the stream's bankfull and floodprone discharges. Therefore, the GeoFluv method uses a hydrologic basis to design its channel cross section profiles to convey water runoff during large and small rainfall events based on the following values:

- 2 year, 1-hour storm data – Bankfull discharge has been found to occur at about a 1.8-year recurrence interval.
- 50-year, 6-hour storm data – Flood-prone discharge has been found to occur to about a 50-year recurrence interval event.

Results:

Rainfall data and image from Swedish Meteorological and Hydrological Institute (SHMI).

N	15 min	30 min	45 min	1 tim	3 tim	6 tim	12 tim
2 år	9.3 ±0.3	10.8 ±0.3	12.1 ±0.3	13.3 ±0.4	19.3 ±0.5	24.0 ±0.7	30.6 ±0.8
5 år	11.8 ±0.5	13.5 ±0.6	14.9 ±0.6	16.3 ±0.7	22.9 ±1.0	28.0 ±1.2	35.0 ±1.5
10 år	14.2 ±0.8	16.0 ±0.9	17.5 ±1.0	19.0 ±1.1	26.1 ±1.5	31.6 ±1.9	39.0 ±2.3
20 år	17.1 ±1.4	19.0 ±1.6	20.6 ±1.7	22.3 ±1.8	30.0 ±2.5	35.8 ±2.9	43.7 ±3.6
50 år	21.8 ±2.7	23.9 ±3.0	25.7 ±3.2	27.6 ±3.5	36.3 ±4.6	42.6 ±5.4	51.1 ±6.4
100 år	26.3 ±4.6	28.5 ±5.0	30.5 ±5.3	32.6 ±5.7	42.1 ±7.3	48.9 ±8.5	58.0 ±10.1

Figure 62. SMHI Storm event data.

Comments:

People often ask why a 100-year event is not used. That is best answered by asking, "what is the hydrologic significance of the 100-year event?"

The answer is - "There is none."

It is just an arbitrary risk criterion that engineers started using.

The landscape of northern Sweden has formed over 10 000+ years and has experienced climate change during this time including the melting of an ice sheet 1km+ thick. The landscape has seen climate change and has been shaped by this. We select and take our GeoFluv inputs, including channel size inputs, from stable reference sites that show how the land has responded over great changes and widely varying climatic conditions over these 10,000+ years. This contrasts with typical weather records (approximately 100-130 years) that record a much shorter time than what the landscape has taken to form (millennia).

Therefore, using data from reference sites that are stable and have been formed over millennia, by storms far greater than 100-year recurrence and using a hydrologic basis for rainfall data the GeoFluv method is much more robust to create stable, reclamation landforms. A reclamation landform designed using the above-described approach has a built-in accommodation for climate changes and can handle 100-year events.

Figure 63. Matt and José, esker.

Bioreactor Locations

Water balance investigations by WSP divided the entire catchment area into five different groundwater sub-areas (A-E) to calculate the expected flows at future collection points for leachate management (Figure 64). Part of the total leachate volume does not drain towards the Rakkuri system, but remains in the mining lease area and will be directed to the tailings dam. From here it enters the mine water system and will eventually exit the site after remediation in the clearing ponds. However, much of the leachate will require treatment via bioreactors.

Trenches will be constructed of sufficient depth to collect both surface water and groundwater from Area B and direct the leachate to bioreactors. The exact number of bioreactors to be installed depends on the expected leachate flow from Area B, but a rule of thumb is that a bioreactor can purify a flow of up to 1 L/s.

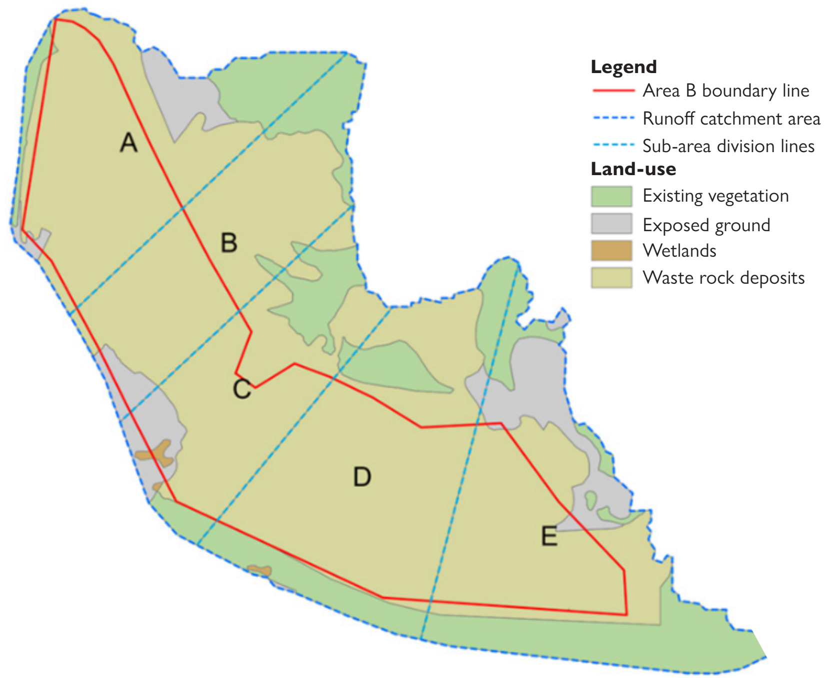


Figure 64. Area B land uses and subdivisions for calculating future water balance.

Leachate Flow

As noted in chapter 2, large fluctuations in leachate flow rates are expected during the year and in the same way the leachate flow to the bioreactors will also vary. It is expected that snow melt runoff in April and May will largely pass through the bioreactors without treatment. During this period the nitrate dilution rates should be relatively high, therefore the potential pollution issues should, in principle, be negligible. Thus, it is recommended that the system be adapted to average flows rather than maximum flows. Conversely, for the function of the bioreactors it is important that the flow through them is kept constant in order to ensure leachate remediation. Collection reservoirs upstream of the bioreactors are proposed to help achieve this.

The expected leachate flow rate from Area B (when all waste rock dumping has been completed) is 690,000m³/year or 26L/s. The flow rates for the drainage areas (A-E) range from 4L/s to 8L/s (Table 1).

	Current flow of leachate from Area B		Expected flow of leachate when the WRD is completed	
Area	**m³/year**	**L/s**	**m³/year**	**L/s**
A	280,000	9	230,000	7
B	230,000	7	150,000	5
C	210,000	7	140,000	4
D	320,000	10	160,000	5
E	330,000	11	120,000	4
Total	1,370,000	44	800,000	25

Table 1. Predicted future water balance of the Area B WRD.

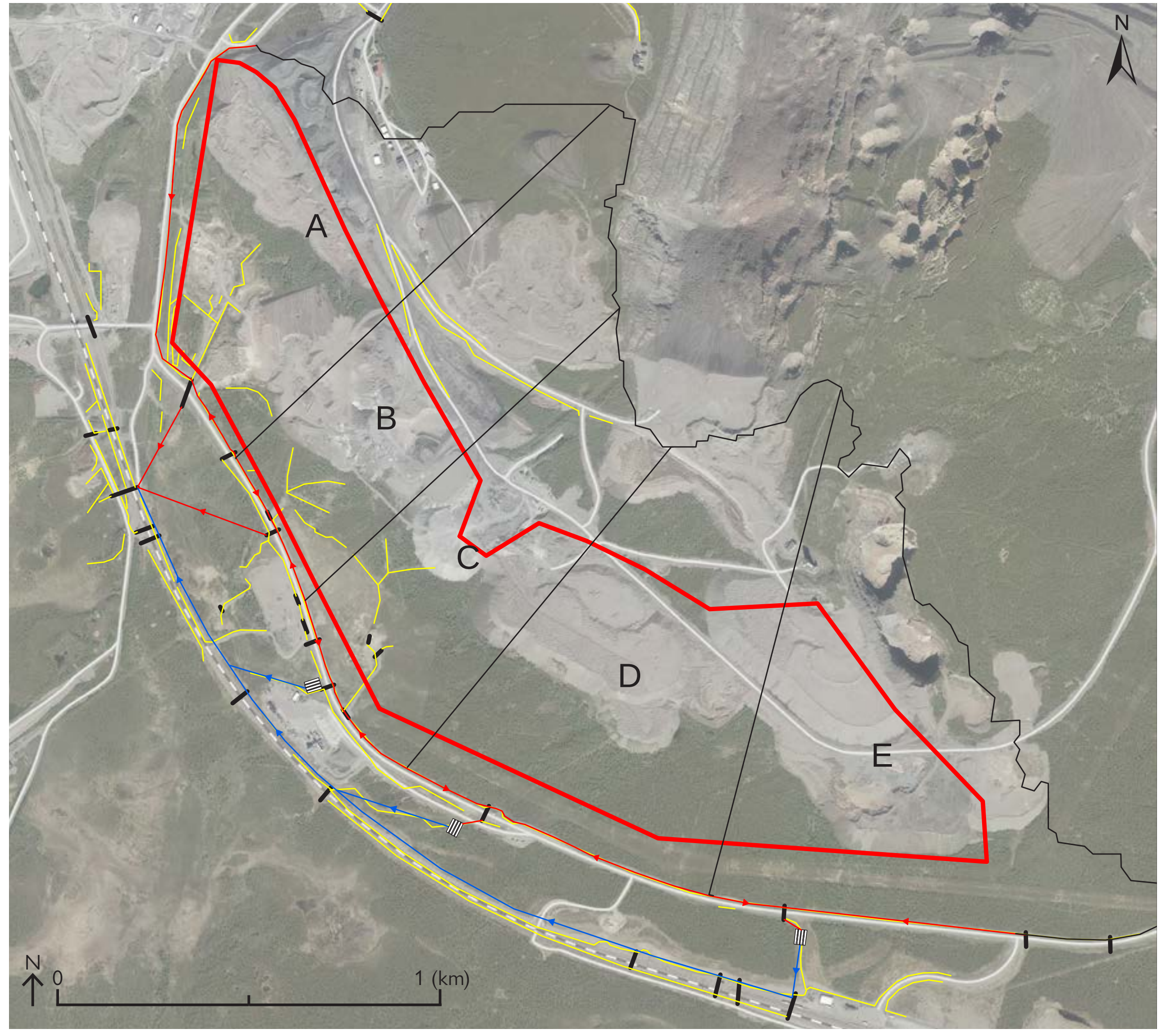
Figure 65. Bioreactors, Kiruna.

Bioreactor Locations

The original purpose of WP5 was not to determine the exact locations of the bioreactors, however, in collaboration with WSP and based on the flow calculations, a total of 13 bioreactors are suggested south and west of Area B. It is proposed that the leachate from two of the smaller drainage areas, A and B, is directed to the clearing ponds, while leachate from areas C (4 bioreactors), D (5 bioreactors), and E (4 bioreactors) will be treated in the bioreactors before being directed to the wetlands area or, alternatively, to the clearing ponds for secondary treatment.

The amount of leachate that can be collected for treatment varies with the choice of bioreactor location. More leachate is likely to be collected the farther south from Area B. If the bioreactors are built south of the railway line, it is predicted that 10-20% of the leachate will pass untreated; but if they are built between the railway line and the road, this figure becomes 15-25% and, if built north of the transport road, the untreated fraction could be approximately 30%.

It is recommended that the bioreactors are placed south of the transport road but north of the railway line (Figure 66). This is because the land is already affected by ongoing mining operations, is far enough south to allow for a higher percentage of leachate to be collected and treated and maintenance will be possible via the existing road. It is proposed that the bioreactor-treated leachate will then be discharged through culverts under the railway line into the wetland system.



Bioreactor recommended locations

Area B

Catchment area

Current surface water flows

Proposed trenches leading water to the bioreactors

Directiction water from bioreactor to clarification pond

Figure 66. Recommended bioreactor locations.

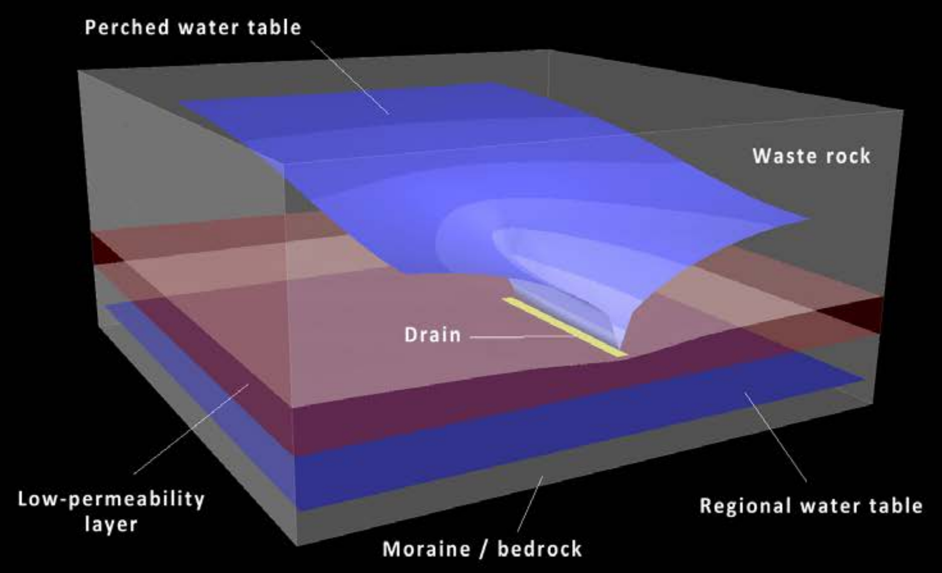


Figure 67. Schematic overview of the proposed solution.

Waste rock dump Ground Water Modelling

Geomorphic restoration presents many advantages on the surface, but what happens underneath? Research shows that infiltration into waste rock dumps is reduced as a result of a geomorphic design and increase over land flows so how could we handle the water that leaches through? With these two questions in mind the WP5 team in collaboration with Professor Pedro Martinez Santos from the Complutense University of Madrid the WP5 developed a ground watering model to investigate leachate through the 2019 proposed GeoFluv design and how to best direct it to the bioreactors.

The idea was not to present a final solution but rather present initial thinking and investigations to help gain a clearer picture and guide future decision making.

Objectives

A geomorphic design by its nature will increase runoff by approximately 25-35%. Sharma et al. (1983) found that infiltration into a flat fill surface ranges from 75-95% of the accumulated rainfall, whereas Ziemkiewicz (2011) and Meek and O'Dell (2012) stated that the percentage of precipitation on the slope of a WRD that infiltrates the surface was 52%-58%. Toegther with the proposed post-mining reclamation cover materials - moraine till, 300mm, and organic material, 100mm is predicted that surface run-off will increase reducing infiltration and thus leachate as a result. As such, it is considered important to explore a potential solution for how nitrogen rich leachate can be captured and directed to the bioreactors.

Groundwater modelling provides a compllment to the geomorphic restoration concept. The idea of developing a groundwater model is to provide a solution to capture the nitrate-loaded water that percolates through the waste rock, and to direct it towards the bioreactors for treatment by means of underground drains. This would contribute to alleviate two major problems, namely, the inflow of contaminants into the regional moraine aquifer and the need to maintain a constant flow rate into the bioreactors.

The proposed solution consists laying out a low-permeability surface between the waste rock and the existing topography (Figure 67), with the objective of creating a perched water table within the waste rock. Because the low-permeability surface can be designed as a surface water catchment, infiltration water would not only be collected, but could also be directed towards suitable outlets.

The main aim of the groundwater model is to examine the feasibility of this solution. More specifically, the model aims to estimate the thickness of the low-permeability layer, as well as the permeability contrast between the waste rock and the compacted material layer that would need to be achieved.

The model runs under steady-state conditions. This represents an average equilibrium state for the part of the year where groundwater remains liquid. While transient-state modelling would be needed to better understand flow dynamics, the steady-state assumption is considered representative because the water table currently remains approximately stable. Field records show it to oscillate by about one meter throughout the year.

Model Development

The model was developed with Processing Modflow 8.047, a conceptualization of the classic Modflow code whose reliability and robustness has been tested in a wide variety of conditions.

The conceptual groundwater model of the site is presented in Figure 68. The bottom of the groundwater system consists of fractured bedrock. This is overlain by different materials, including moraine till, colluvium and the existing waste rock.

The main recharge mechanism of the groundwater system is precipitation. Recharge estimates have been computed for natural soil, waste rock, naked soil and wetlands (WSP 2020). Water percolates through these materials and eventually discharges through evapotranspiration, as well as into springs and wetlands located towards the south of the restoration site. A share of recharge also flows into the mine.

Modelling is carried out in two steps. A steady-state model depicting the current site conditions is developed and calibrated first. The goal is to ensure that the model replicates the behaviour of the system prior to building the new waste rock mound. This also allows for adjusting those hydrodynamic parameters subject to uncertainty (vertical and horizontal hydraulic conductivity). Once the model is calibrated, it is used to simulate a series of scenarios to determine the thickness and hydraulic conductivity of the compacted material layer.

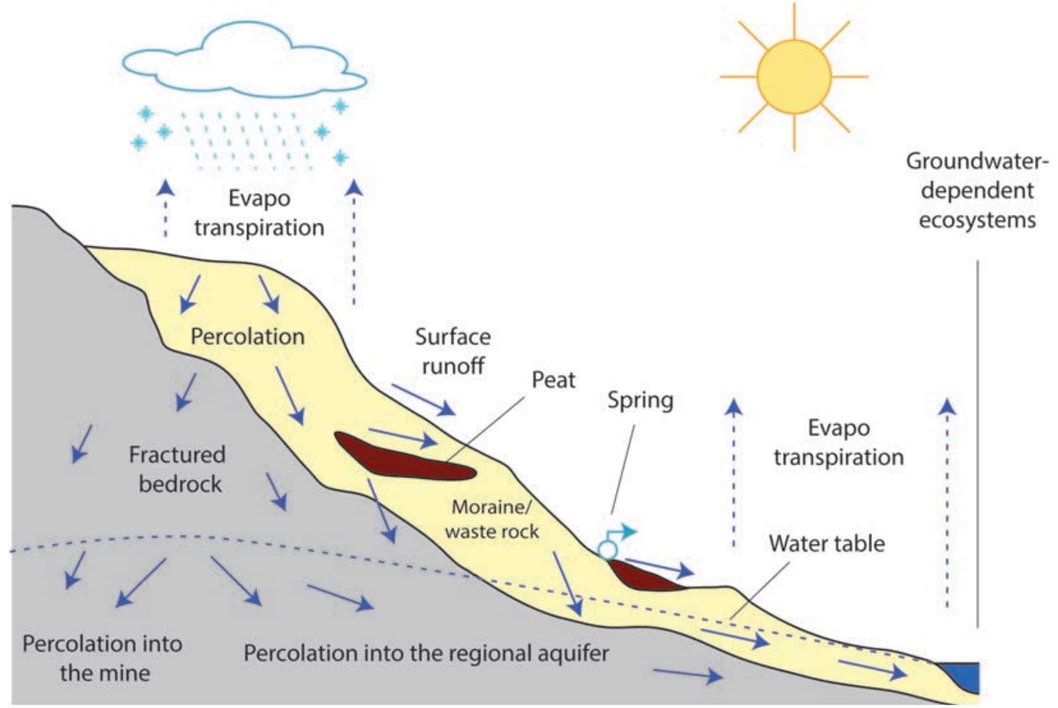


Figure 68. Conceptual groundwater model of the site (diagram modified from WSP 2020).

The model spans a surface of 4x4 km, with a uniform cell size of 10x10 m. Model geometry is structured in four layers. Layers do not represent a specific material, but adapt to the geometry of the system. From top to bottom, and from north to south, layers represent the following materials (Figure 69):

- Layer 1. Projected waste rock
- Layer 2. Compacted layer
- Layer 3. Fractured bedrock / current waste rock / moraine / lake
- Layer 4. Fractured bedrock /moraine

Layers 1 and 2 are inactive during the calibration runs, and activated for the simulations.

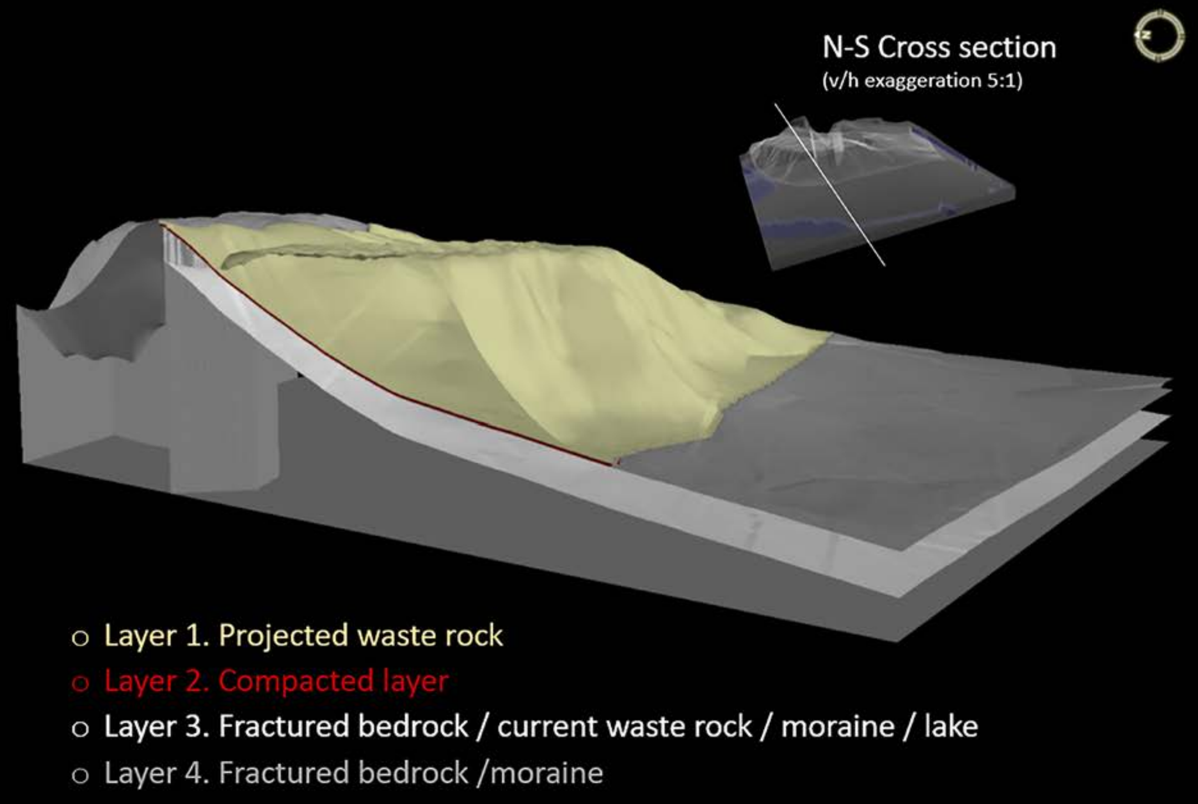


Figure 69. North-south cross-section of the model. Layers 1 and 2 are only active during the simulations.

Material	K_h (m/s)	K_v (m/s)
Waste rock	10^{-6}	10^{-8}
Moraine	10^{-6} to 10^{-7}	10^{-8} to 10^{-9}
Fractured bedrock	10^{-6} to 10^{-9}	10^{-8} to 10^{-9}
Compacted layer (*)	10^{-6} to 10^{-8}	10^{-8} to 10^{-11}

Table 2. Range of horizontal and vertical hydraulic conductivity values (m/s) for each material on site.

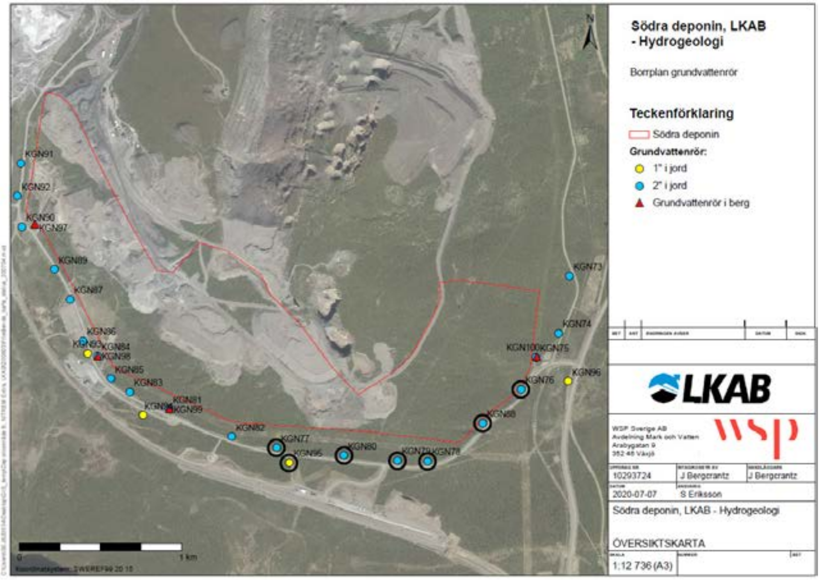


Figure 71. Borehole locations for model calibration. Map made available by WSP.

Figure 70 shows the boundary conditions of the model. The northern part of the site is represented by no-flow boundaries except for the mine, which is modelled as a series of drains. Most of the eastern border is modelled as a constant-head boundary to represent the decantation/clarification ponds, as well as Pieni Rakkurijarvi. The southern end of the model includes part of this lake, as well as the stream that communicates it with the wetlands located towards the southeast. All these water bodies are also considered constant-head boundaries. Finally, the western part has been modelled based on the inferred hydraulic head in the moraine aquifer. No flow borders are prescribed at all remaining locations.

Additional drain cells are used during the simulation runs to model the effect of drains within the projected waste rock mound.

Because the model runs under steady-state conditions, the resulting spatial distribution of groundwater levels comes down to the ratio between recharge (assumed known) and hydraulic conductivity. Starting hydraulic conductivity values were obtained by the groundwater model of the northern side of the site developed by Interra (2018). These were adjusted manually at first, and then by automated parameter fitting until an acceptable agreement was obtained between the modelled and observed water table levels. Table 2 presents the range of horizontal and vertical hydraulic conductivity used during the final calibration run.

Model calibration is based on the groundwater logs made available by WSP. Measurements were taken twice in each of the 28 boreholes, with one measurement in July and another one in October 2020. All boreholes are located along the southern road of the site (Figure 71).

The calibration run rendered an average discrepancy between observed and modelled groundwater elevations of less than 0.80 meters, with a maximum of 1.23 meters and a minimum of 0.11 meters. The R2 coefficient is 0.98. This was deemed sufficient for practical purposes in view of the known oscillation of the water table.

A second calibration element is the water balance. According to WSP (2020), about 45% of the recharge flows into the mine, while the calibration run of the model renders an estimate of 43%. Again, this was considered sufficiently consistent for the purpose of the model.

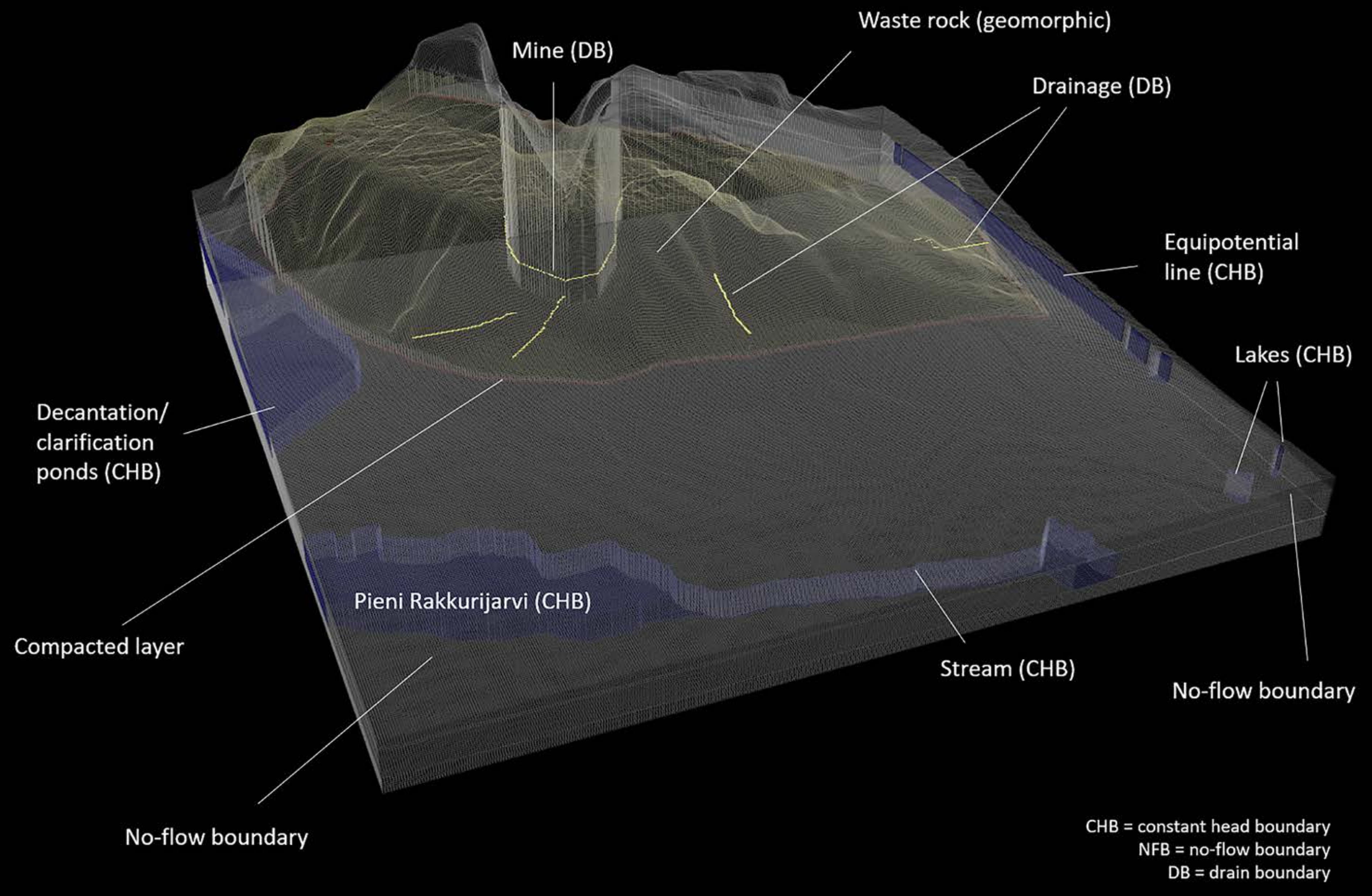


Figure 70. Model overview with boundary conditions. Layers 1 and 2 are only active during the simulations.

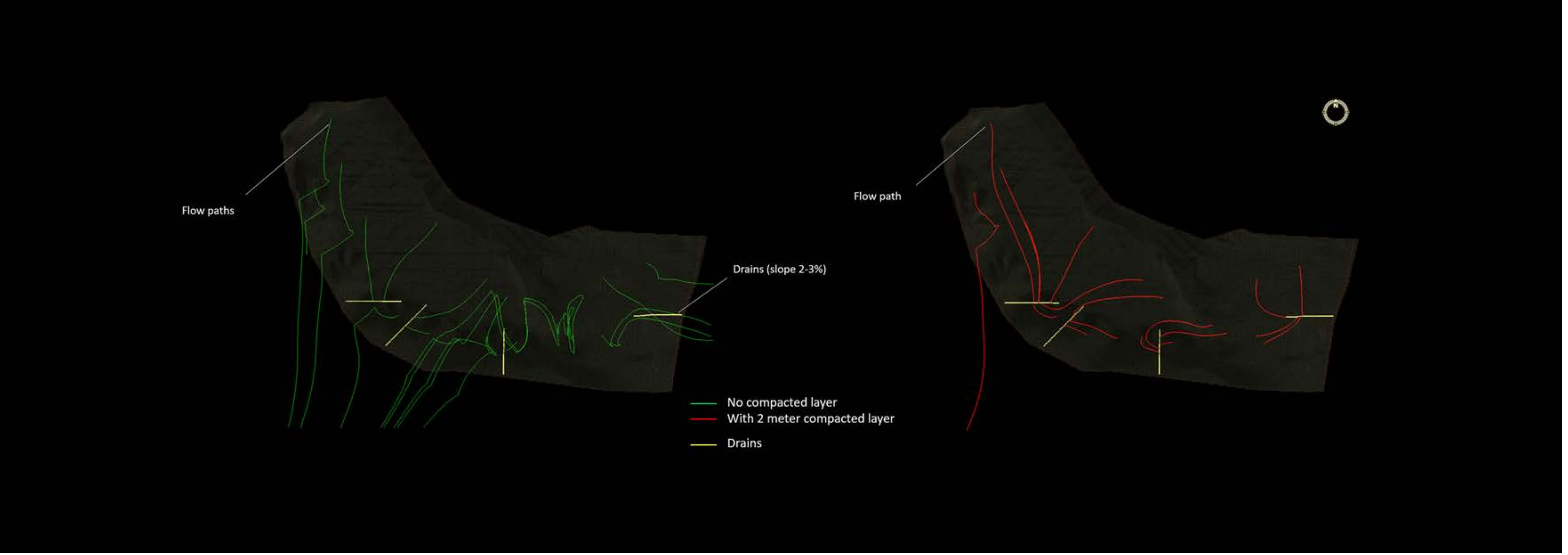


Figure 72. Captured recharge versus compacted material thickness under several possible permeability ratios.

Simulations

Sixteen simulations were carried out. The first one assumes that no compacted material is laid out between the projected waste rock mound and the underlying material. The remaining simulations are a combination of different compacted material thicknesses (0.5, 1, 2, 3 and 5 meters) and permeability ratio between the vertical hydraulic conductivity of the waste rock and that of the compacted layer (10, 100 and 1000).

All simulations include four drains, each leading into the nearest bioreactor. Drain length ranges between 300 and 400 meters, while drain slopes range between 2 and 3%. The hydraulic conductance of drains is obtained by multiplying the length of the drain in each cell by the calibrated hydraulic conductivity of the cell itself.

Figure 72 shows the main model results. These suggest that approximately 70% of percolation could be captured by the drains alone (that is, without laying out the compacted material layer to isolate the waste rock from the underlying material). This would imply an average flow of about 22 l/s into the bioreactors during the months in which groundwater remains in liquid state. In contrast, 95% of percolation would be captured with a 2 meter thick compacted material layer with a vertical hydraulic conductivity two orders of magnitude lower than the waste rock. This would represent an average flow of 30 l/s. Figure 72 also suggests that the 95% threshold could also be reached with a thickness of one meter and a permeability contrast of three orders of magnitude.

An immediate practical implication of this is that between 3·106 m3 and 6·106 m3 of compacted material would be needed below the new waste rock dump, assuming that it spans approximately 300 hectares.

Figure 73 presents the distribution of groundwater flow paths in plan view. Green lines represent flow paths without the compacted material layer. Percolation follows complex trajectories, bouncing back and forth between the second and the first model layers until it eventually finds a way into the moraine aquifer. If a compacted material layer is applied, the majority of flow paths (in red) are observed to flow in an orderly manner into the drains.

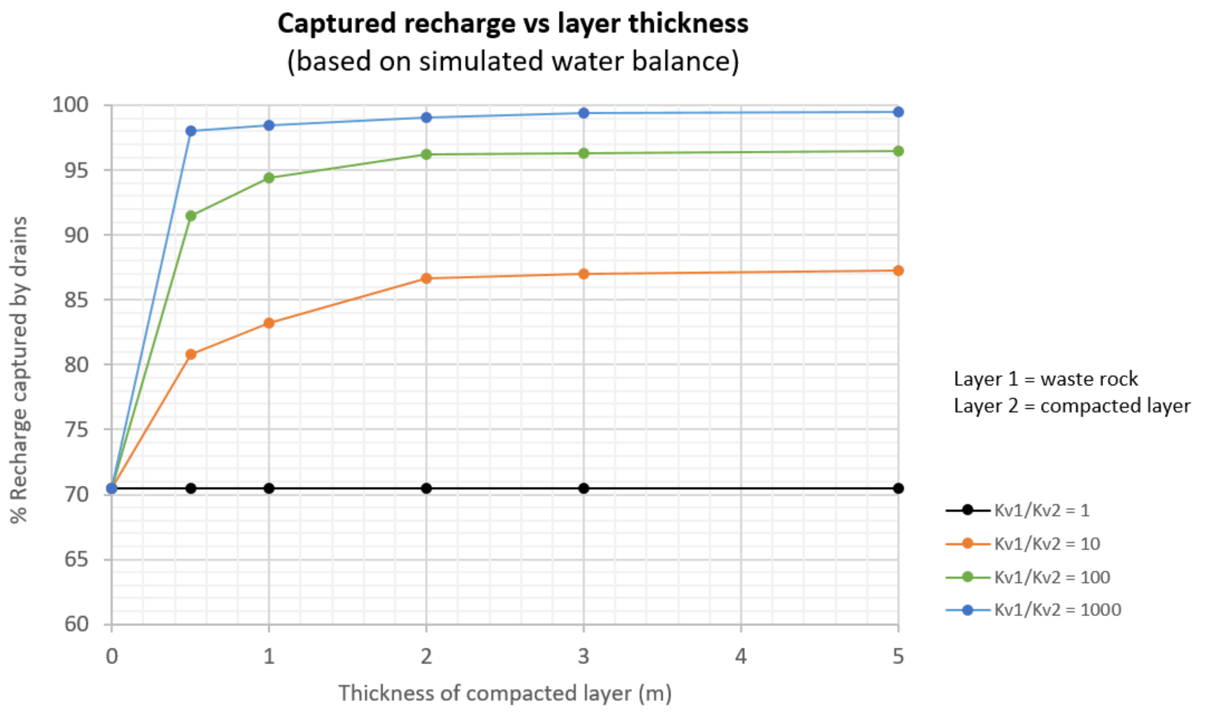


Figure 73. Plan view of groundwater flow paths without a compacted material layer (left) and with a 2 meter thick compacted material layer of a permeability two orders of magnitude lower than the waste rock (right).

Sensitivity analysis and future work

A sensitivity analysis of the model reveals it to be highly sensitive to changes in horizontal and vertical conductivity. This implies that these two parameters need to be further characterized in the field. Porosity also needs to be better quantified, both for the natural materials present on site and for the waste rock, while it would be important to characterize bedrock geometry. It is recommended to drill additional boreholes further away from the southern road in order to enhance the groundwater network, and to continue with periodic water table monitoring. Furthermore, it is recommended to carry out infiltration tests to evaluate whether it is possible to achieve the required permeability contrast under field conditions.

Should the proposed solution be adopted, it would also be necessary to evaluate the availability of material for compaction, as well as the potential environmental and administrative implications of obtaining this material. This could become an issue due to the sheer size of the site.

This model is considered a first approximation to the problem. The potential geotechnical, hydrodynamic and geochemical implications of the proposed solution should be further assessed as the geomorphic restoration project moves forward.

Conclusions

A groundwater model was developed to test a constructive solution to prevent undesired percolation of waste rock constituents, such as nitrate, into the underlying moraine aquifer. This solution consists in building a compacted layer between the projected waste rock pile and the underlying material. The goal of the model is two-fold. In the first place, it attempts to establish the characteristics of the compacted layer, namely its thickness and its hydraulic conductivity. Secondly, it evaluates the optimal location of groundwater drains in order to redirect subsurface runoff into the projected bioreactor locations.

Model results suggest that a compacted material layer laid out between the projected waste rock pile and the existing topography could prevent undesired leachate into the regional aquifer. A thickness between one and two meters and a hydraulic conductivity of at least two orders of magnitude lower than the overlying waste rock would be enough to capture about 95% of percolation. Drains leading into low points should be constructed in order to facilitate the collection of groundwater and its redirection into the projected bioreactors.

Groundwater investigation on the southern side of the mine is an ongoing process. Uncertainties exist as to infiltration rates, as well as to the hydrodynamic parameters of natural and waste rock materials. Furthermore, longer piezometric logs are needed to calibrate the model under transient-state conditions. In this context, the results of the model need to be interpreted as a preliminary approximation, subject to reevaluation and recalibration as new field data becomes available.

Figure 74. Natural stream at the Kiruna mine site.

CHAPTER 4

Design Methodology

It is recognized that the Kiruna site is different to other sites across Europe where the bioreactor technology could be potentially utilized. Site specificity is a key challenge to developing a successful landform design methodology that is applicable to other sites. It requires a process that is generic and transferable, but which can be tailored to the different conditions and contexts of other sites. The following chapter outlines the design methodology developed through the NITREM project for use in future projects.

Landscape Design Methodology

The WP5 working process outlined in chapter 1 has been the foundation for the development of the design methodology. The methodology is applicable to different sites during different phases of waste rock dump development, including the feasibility, planning, design and construction phases. Users can work through the methodology as necessary depending on their requirements and level of readiness and site knowledge. It focuses on optimizing bioreactor function from a technical perspective, maximizing the volume of WRD leachate water treated and ensuring that closure goals, such as biodiversity and post-mining land-use, can be achieved.

The design methodology flow diagram has been designed to fit with a variety of mining projects regardless of their stage in the mining lifecycle (Figure 75). It is recognised that the stakeholders, engineering requirements, environmental and socio-economic contexts, etc., will differ when considering mines or WRDs in the planning/ design, construction, operations or closure phases, hence the terminology and key stages used in the flow diagram accommodate potential variations.

It is the nature of a flow diagram to provide a simplified track to what are often cross-cutting processes and cycles. It has been kept simple and the key stages have been identified along with the work elements, outputs and deliverables for each stage. Also, a work element in one silo may simultaneously inform and support a work element in a different silo; this cross-cutting is not shown in the diagram.

Reporting processes should be determined according to a client's requirements. 'Reporting', as opposed to 'reports' are identified in the various outputs as a contingency to be finalised according to project specifics. In some situations, clients may not require a formal written report as an output, but may expect reporting back in a different format, such as presentations or discussions.

Design Methodology

Conceptual planning

Project initiation

- Carry out site visit
- Identify project site & ownership
- Identify WRD functional requirements
- Identify post-project WRD/bioreactor landscape management requirements
- Identify landscape restrictions/opportunities
- Research social & environmental context
- Identify bioreactor functional requirements
- Review and understand existing company plans/targets/goals/permits such as rehabilitation & after use goals

Project development*

- Identify key stakeholders
- Define project goals
- Identify resources, staffing, permits
- Identify outline costs
- Identify funding sources
- Identify project restrictions/opportunities

Output

Conceptual project plan report & terms of reference for project

Preliminary tasks

- Build team
- Develop project schedule
- Prepare budget
- Develop project objectives
- Begin stakeholder engagement
- Install infrastructure/services i.e. access & utilities
- Train personnel

Output

Project start-up reporting

Detailed site analysis

Analysis

Desktop analysis:
- Surrounding/local context (history, climate, landscape, hydrology, cultural values, etc.)
- Existing site conditions (hydrological, geotechnical, ecological, topographical)
- Geomorphic identification - GIS review of surrounding landform types & patterns

Consider:
- Mining and processing methods
- Mine waste mineralogy & environmental geochemistry
- Environmental management & monitoring systems

Site selection

- Select potential WRD & bioreactor sites
- Determine suitable reference site to measure landscape parameters

Project development

- Review & update project goals & objectives (if needed)
- Develop landscape perfomance goals & criteria

Output

Site analysis summary - links to design reporting

Landform design

Modelling phase 1 conceptual design

- Determine landscape parameters - GIS analysis of reference site
- Digital Elevation Model (Tin-file)
- CAD-modelling
- Prepare 3D-visualizations

Modelling phase 2 design verification

- Landscape parameters fieldwork inputs
- Design review & checks
- GeoFluv-modelling
- Prepare 3D-visualizations
- Quantity surveying & cost viability/analysis

Landform preparation

- Prepare construction method
- Prepare preliminary construction schedule
- Plan ecological restoration & social/post-mining land-use

Output

Landform design report

Implementation planning

- Prepare detailed work schedules
- Prepare WRD performance standards
- Prepare monitoring protocols
- Carry out procurement
- Develop training plan for post-handover operations
- Finalise budget for implementation

Output

Method statements
Monitoring protocols
Finalised schedule
Finalised budget
Training plan

Implementation

- Construction mobilisation
- Manage engineering/construction
- Construction oversight & monitoring
- Implement site security
- Carry out ecological restoration & post-mining land-use plan
- Commissioning
- Carry out training for post-hand-over operations
- Prepare cost-implementation management plan & procedures
- Handover

Output

Completed WRD with reliably functioning bioreactor

Post-implementation

- Monitoring & evaluating
- WRD maintenance
- Bioreactor maintenance
- Carry out adaptive management
- Reporting (monthly/quarterly/annual)
- Publicise - online, social media, industry press, academic media, etc.

Output

Monthy/quarterly/annual reports

*Highlights similiar key stages and/or tasks required in each methodology. Communication and coordination of these across departments will save cost and time and produce better projct outcomes.

Figure 75. Design methodology.

Key Stages

Conceptual Planning

The first stage in project development is defining a concept that addresses the challenges in question. This is the critical foundation to the project and must be informed by a range of information sources, including: site visits, stakeholders, relevant literature, technical/functional requirements, etc. A process of iteration and feedback between this stage and subsequent stages and the project working group will be necessary before the project goals can be finalised and an appropriate, informed concept is developed. The key output of this phase will be a conceptual project plan, which will contain a terms of reference for the subsequent stages of the project.

Preliminary Tasks

Once a concept has been agreed, the next stage of delivery is the project set-up. Preliminary project tasks including preparing and agreeing a budget, building the delivery team, creating a delivery schedule, engaging with stakeholders (which also feeds back into developing the concept in the previous stage), identifying and providing any necessary training requirements and creating appropriate project administrative, technical and logistical support.

Detailed Site Analysis

An appropriate site needs to be selected to install the bioreactor/ WRD, so a detailed analysis of the site(s) selected in the first stage (Conceptual Planning) is essential to determining a detailed technical response to the social and environmental challenges in question. A review of existing environmental monitoring and management at the mine site will indicate the key environmental challenges and the main locations of any exceedances and seasonal variations, permitting requirements, etc. A major aspect of the project's context is the mining and processing methodology employed by the mine and its waste rock mineralogy and chemistry, which may indicate the extent in space and time of any contamination issues. A thorough understanding of the hydrological systems and topography of the site and its surroundings are also critical at this stage.

Given an increased level of knowledge of the site parameters, it should now be possible to refine and then agree the overall project goals and objectives, as well as performance goals and measurable criteria for the final landform. Once this is achieved the team will then able to estimate a provisional cost for delivering the concept according to the site requirements. A potential output for this stage could be a GIS model of the site in question, informed by the information unearthed during the detailed site analysis.

Landform Design

A landscape design response to the site context and environmental and social challenges, within the project's limitations, is the next step in the methodology. This stage will define the landform type required that will address the landscape performance goals and criteria to ultimately produce a conceptual landform design for the WRD/ bioreactor. The design will then be modelled to illustrate the concept to stakeholders. A detailed model will enable checks on the design's technical feasibility and subsequent cost estimations. Once the design of the physical structure has been finalised, its ecological restoration – informed by the intended after-use – can also be planned, as can the construction method and schedule. Outputs from this stage might include a statement on the landscape goals and criteria, a computer- and 3D-model of the proposed WRD landform and bioreactor placement and a design report.

Implementation Planning

Once the design has been finalised, the detailed methodologies and schedules can be developed and agreed. Suppliers will need to be identified and construction procurement started along with the finalization of the budget for the construction phase. The implementation planning stage is also the appropriate time for developing a training plan for the post-handover operations of the WRD/ bioreactor and the performance standards and monitoring protocols for the final landform. Outputs for this stage might include construction method statements, WRD/ bioreactor monitoring protocols and a finalised schedule and budget.

Implementation

The penultimate stage is implementation, i.e. construction of the WRD/ bioreactor. This will involve mobilisation of the constructor and the preparation of lay-down areas and construction of site access, etc. During the implementation, appropriate oversight of technical, health and safety and environmental management is required and the site will need to be kept secure. Training for operating the site post-handover should also be carried out. Once WRD construction is completed, the ecological restoration project should begin, though ideally this should happen in a progressive manner during construction, which should save costs overall. A post-implementation phase WRD/ bioreactor management plan and associated procedures will also be prepared. The final step before handover is commissioning, the timeframe for which will be dependent upon the project specifics. This is an important step to ensure that the WRD/ bioreactor function properly and that project contingencies are in-place and reliable.

Outputs from the implementation phase will include a completed WRD with a reliably functioning bioreactor, finalising environmental measures for ecological restoration, management plans and procedures and staff trained to manage the site post-construction.

Post-Implementation

Once the site has been commissioned and handed over to the new team responsible for WRD/ bioreactor function and monitoring, a programme of ongoing monitoring and maintenance will begin. This will mark the start of an adaptive management regime to ensure continual improvement of the management of the WRD/ bioreactor and its ecology.

Key outputs are likely to include some form of regular reporting, such as monthly, quarterly and/or annual reports, depending on the project's obligations. Ideally these should fit with existing environmental monitoring and reporting regimes on the site. This might also fit with a public awareness-raising campaign too.

NITREM Solutions

This chapter has outlined the design methodology developed for the project at the Kiruna mine site. This transferable methodology is intended for use during the planning and implementation of future projects that incorporate the NITREM bioreactors and geomorphic waste rock dump design. Depending on the NITREM solution purchased by the client, the client can either works through the methodology independently or with the assistance of the NITREM team.

As part of the NITREM project the knowledge gained has been developed into a service available for purchase and implementation by other companies with nitrate issues. The service is offered in two solutions, NITREM Essential and NITREM Extended. The solutions are explained here:

NITREM Essential

NITREM Essential reduces the amount of nitrate in leachate from mining and quarrying operations in a sustainable, economical and flexible way such that the solution requires very little maintenance.

NITREM Extended

NITREM Extended delivers a unique and almost maintenance-free solution for nitrate reduction in leachate combined with a sustainable landscape design for rock piles. NITREM Extended reduces the amount of nitrate in rock pile leachate combined with landscape design that enhances the local ecology and provides an opportunity to return to the traditional land-use after the end of operations.

Visit the NITREM-website at https://www.nitrem.eu/


Figure 76. Kiruna mine WRD.

CHAPTER 5

Social Transition Methodology

As discussed in the introduction chapter for a landscape design to be considered 'sustainable' not only are environmental factors fundamental but socio-economic considerations also require analysis, understanding and a proactive approach to accommodate them. Similar to the design methodology this methodology focuses on a general approach that can be tailored to different sites and communities. The social transition methodology takes a holistic view, rather than just focusing on the immediate landscape elements outlined in chapter 3. This means that the wider community and economic aspects are considered in developing the methodology beyond the immediate mine site itself.

Social Transition Methodology

The purpose of the following chapter is to augment the NITREM WP5 sustainable landscape design process with a methodology for developing a vision for the socio-economic aspects of mine closure. The term 'social transition' is used instead of the more familiar, but less accurate, 'social closure', as the former better describes the process of what happens to a society when its mine closes.

In order to be considered successful, social transitioning projects must deliver significant enduring positive impacts on the ground. To increase the probability of success they need to fit with the broader sustainable development objectives of the relevant authorities involved and the smaller-scale community-led projects on the ground.

A social transition model for mining is provided in ICMM's recent mine closure toolkit. This has been adapted and includes further information based on the experience of the WP5 team in mine closure planning and delivery to present the process outlined herein.

The methodology shown is not exhaustive; its purpose is to outline a generic process for developing an agreed vision for social transition in relation to mine closure and prepare the way for collaborative approaches to implementation.

The methodology is an iterative, multi-disciplinary and collaborative process that should occur through the whole of the mine lifecycle.

Several tasks under the key stages in the design and social transition methodologies overlap so with the right coordination and communication between departments the sharing of data, information and knowledge can save a company time and cost and produce better project outcomes.

It should be recognised that the purpose is not to develop a vision for social transition for Kiruna per se but offer a generic process for how such a vision can be developed.

Social Transition Planning Methodology

01. UNDERSTANDING

- Collate information from internal knowledge base
- Collate information from external sources
- Stakeholder mapping
- Research & analysis

OUTCOMES

- Current knowledge base
- Preliminary formulation of vision & goals
- Current risk assessment
- Understanding of social investment requirements

02. PARTICIPATION

- Involve appropriate stakeholders
- Develop a social transition communication plan
- Contribute to and validate the approach
- Develop a shared vision and goals
- Align social investment plans with shared vision

OUTCOMES

- Improved mutual understanding among partners/ stakeholders
- Refined & agreed vision for social transition
- Agreed priorities for social investment
- Sustainable partnership approaches

03. PLANNING*

- Build a team to deliver social transition
- Agree priorities & goals for social investment
- Develop plans for implementing on each priority
- Plan the necessary resources to enable delivery
- Determine the implementing bodies

OUTCOMES

- Social transition team established
- Agreed social investment priorities & goals
- Implementation plans available
- Resources for implementation made available
- Implementing bodies identified

04. IMPLEMENTATION

- Secure funding
- Sign contracts with implementing bodies/ stakeholders
- Develop processes for transfer of assets
- Mobilise for delivery
- Run trials (if necessary)
- Prepare & disseminate communications

OUTCOMES

- Funding made available
- Contracts signed
- Asset transfer processes in place
- Trials underway
- Communications delivered

05. ASSESSMENT

- Implement monitoring & evaluation processes
- Use key performance indicators to determine performance against agreed goals
- Track socio-economic changes after closure
- Transparent reporting of results (including, if appropriate, wider communication)

OUTCOMES

- Assessment processes established
- Monitoring & evaluation implemented
- Understanding of effects of closure
- Findings reported back

06. REVISION

- Review assessment findings
- Make & implement recommendations for improvement

OUCOMES

- Recommendations for improving the social transition project/programme

* Highlights similiar key stages and/or tasks required in each methodology. Communication and coordination of these across departments will save cost and time and produce better project outcomes.

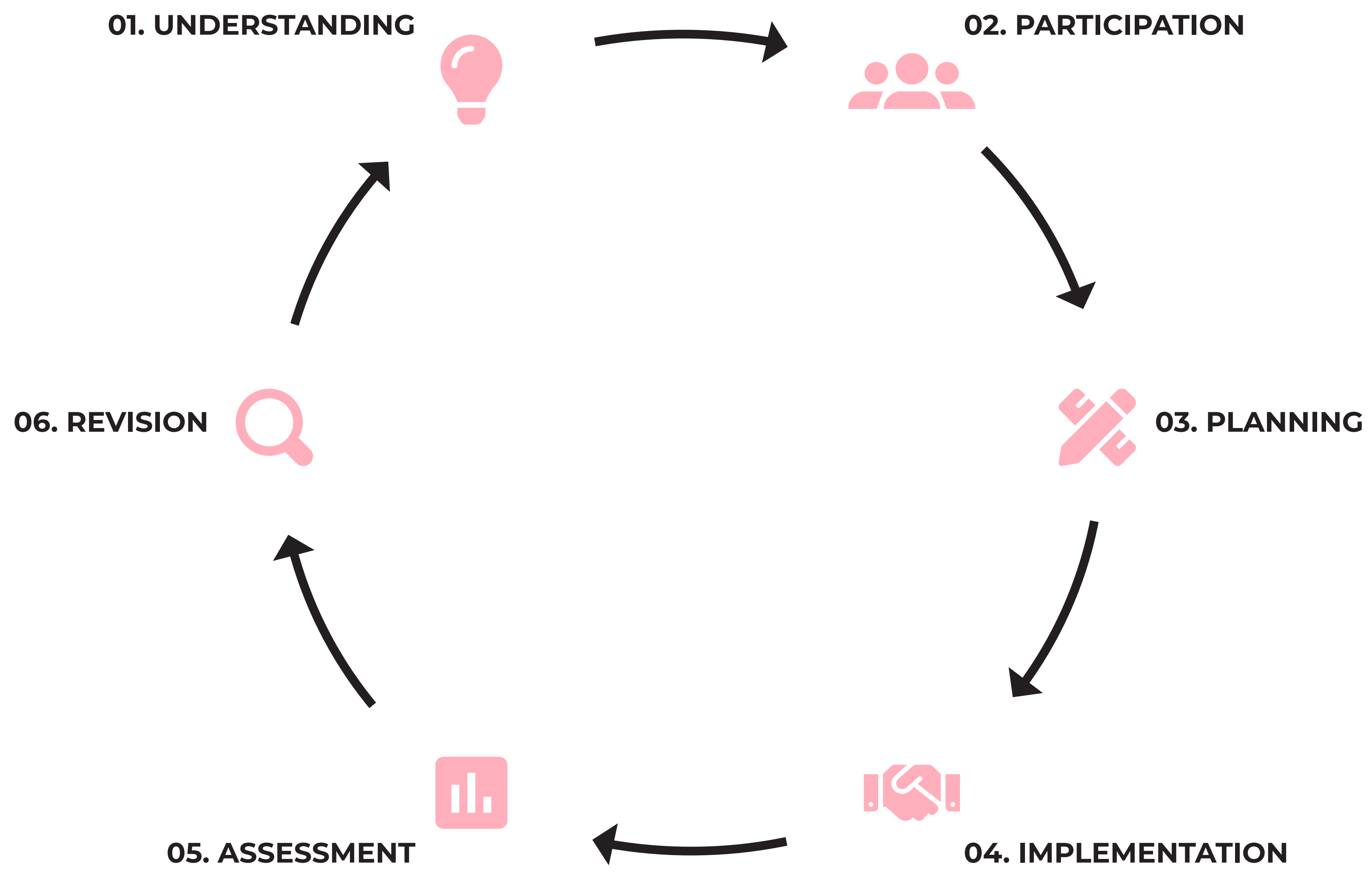


Figure 77. Social Transition Planning Methodology.

Key Stages

Understanding

Every mine will have its own knowledge base of environmental and socio-economic/ community/ sustainable development information. The knowledge base provides the basis for understanding the degree of socio-economic dependence that has developed, or that could develop. No knowledge base is perfect and the legal, environmental, social and mining contexts will change often during the mine lifecycle. Up-to-date and complete information is, therefore, critical for informing good decisions on social participation and investments going forward. The following activities are essential in understanding and responding to the current and future socio-economic context of the mine.

- Collating information from existing internal sources such as: the ESIA, other environmental/ social/ community/ sustainability assessments, mine closure plan, socio-economic management plans and monitoring data, procurement and supply chain information, local recruitment and sourcing programmes, workforce training programmes, social investment initiatives and any risk assessments focussing on the socio-economic aspects of mine closure. Information should also be collated from external sources such as: socio-economic/ sustainable development plans, climate change forecasts, additional funding schemes, academic studies, etc.
- Stakeholder mapping enables the mine (and other stakeholders) to understand who the main actors are who can influence the mine or be influenced by it. Such knowledge will enable appropriate engagement, consultation and participation opportunities with and by these actors in the planning and implementation of social transition. Also, beyond the formally elected leaders of communities and other stakeholders, it is usually worthwhile engaging with 'unusual suspects' (see Participation).
- Research and analysis of the knowledge base is required regularly to determine its relevance to the current context and any information gaps that need to be addressed. This is necessary to inform decision-making and to determine the adequacy of planning and associated financing. Some key aspects that will need to be assessed include: the extent of the zone of influence, assessment of socio-economic impacts and opportunities, closure goals and success criteria, the closure timeframe, commitments to community groups and stakeholders, closure funding amounts and commitments and the relevance of the socio-economic baseline, community capacities and needs and opportunities for economic diversification. It is important to also consider climate change predictions and to understand how these could affect social transition planning and activities in the future. Key analytical tools to be used as routine procedures in the ongoing planning process throughout the mine lifecycle include gap analysis and risk assessment. Any gaps, obsolete information or unexpected or high risks that are identified need to be addressed by the commissioning of appropriate research.
- The main outcomes from this process will be an up-to-date knowledge base appropriate for the current context, a current risk assessment and a better understanding of the social investment requirements. It should also be possible to develop an early formulation of a vision and goals for social transition to be subsequently offered to stakeholders for development.

Participation

Stakeholder participation is critical to developing successful social transitioning outcomes. In reality the aim is to build a partnership of stakeholders where each participates fully and mutual understanding is enhanced. The term 'participation' is preferred to 'engagement' or 'consultation' because it conveys the expectation that active involvement is required of stakeholders over the long-term to develop a shared vision and partnership approaches to implementation. This step builds on the existing stakeholder engagement plans and mechanisms that already exist within the company; however, specific messaging around closure/ social transitioning needs to be integral to such engagements from an early stage and be ongoing. It may be necessary to involve some new stakeholders, for example the 'unusual suspects', with a specific focus on closure/ social transitioning.

The goal of stakeholder participation is to develop a common, shared vision of social transition for the area pre- and post- mine closure. An iterative approach over time is required, with regular review and updating with new information from the knowledge base, as required.

A specific communication plan with key social transitioning messages will be necessary. Messaging should be aimed at internal as well as external stakeholders and will need to be strategically adapted to different phases of the mine lifecycle.

Ultimately, investments by the mining company and, possibly, other stakeholders are necessary to enable social transition. Appropriate stakeholder participation will enable alignment of these social investments with the vision and goals to maximise the chances of success.

Planning

Delivering successful social transition is a substantial amount of high priority work over a prolonged period. A dedicated social transition delivery team should be established. This team should be multi-disciplinary and should consist of relevant stakeholder representatives. Membership of the team may flux according to the issues and expertise available. Reflecting the iterative planning process, there will be frequent and ongoing interaction with stakeholders to agree robust implementation plans.

How social investments will be targeted to achieve the agreed vision requires coordinated and multidisciplinary planning. This should focus on determining agreed priorities and goals for social investment – and these priorities will change according to the changing socio-economic context of the mine and the phase of the mine lifecycle. Implementation plans for each priority should include considerations for resourcing sufficient budgets, time and personnel, monitoring and evaluation plans and appropriate progress reporting mechanisms.

Planning should focus on building community resilience over the long-term, starting early, integrating social investment with other closure activities and stakeholder initiatives and developing strategic and resourced partnership approaches.

Key Stages (cont.)

Implementation

The social transition delivery team will be responsible for overseeing implementation of the plans. This requires the securing of sufficient funding, competent groups to initiate and manage projects on the ground, processes for transferring ownership of mining company assets and land and managing trials or programmes over the long-term.

Social transitioning costs should be clearly linked to the other components of the overall closure cost estimate to gain an accurate closure costing; however, unlike other aspects of closure cost estimation, social transition costs do not typically have readily available, experience-based unit costs or easily measurable quantities and, inevitably, there is considerable variability between sites with respect to socioeconomic, environmental and political settings, stakeholder expectations, community capacity, etc.

Messaging and communication around implementation will be critical to keep stakeholders (both internal and external) and the wider public informed and supportive. There should also be opportunities for the lodging of grievances and a process for handling and responding to them.

Social transitioning programmes should be sustainable post-closure and implemented as early as possible during the mine lifecycle. Typical programmes include:

- social investment projects,
- the preferential employment of local people,
- employee (and stakeholder?) training programmes to build transferable skills and capacities for greater and different responsibilities post-closure and to improve their employability,
- building capacity in and using local supply chains for goods and services during the mine lifecycle,
- realising socio-economic opportunities derived from landscape restoration and management for new, sustainable livelihoods,
- progressive retrenchment planning that staggers the reduction in the size of the workforce and assigning post-closure responsibilities where possible, and
- processes for transferring responsibility and control from the mining company to other stakeholders such that, after closure, the non-mining company representatives are in control.

Assessment

Project/ programme performance needs to be assessed to ensure maximum benefit and value for money and to highlight any issues that can be addressed in the future through a process of adaptive management. The key steps are to carry out an agreed process of monitoring and evaluation which compares the results of the project to the goals established for its implementation. It is also important to track the socio-economic impacts of mine closure to improve understanding and assist in determining appropriate, early, targeted responses.

A series of appropriate performance indicators, developed during the planning phase, are used in the monitoring and evaluation work. The findings of the assessment process are then fed back through transparent reporting.

Revision

Revision is an important, integral part of this iterative social transition methodology. It allows for continual improvement in the system/ programme/ project over the long term to enhance outcomes. Findings from the assessment step will inform recommendations for improving the knowledge base, participation, planning, implementation or assessment parts of the methodology – an adaptive management approach.

Figure 78. A house being re-located during the relocation of the Kiruna town centre resulting from the encroaching (and planned) subsidence from the mine.

Some challenges and good practice principles for social transition.

Developing a successful social transition for a local community at the end of mining is not a straight-forward or easy process. There are several recognised challenges to delivering a successful post-mining society that the social transition planning process must address. These include:

- Socio-economic dependency,
- Planning too late in the mine lifecycle,
- Institutional barriers and silo thinking,
- Defining the boundaries of responsibility,
- Maintaining a social licence to operate,
- Identifying and engaging stakeholders,
- Agreeing a post-closure vision, and
- Inadequate funding.

In response to these challenges, there are some good practice principles to developing and implementing social transition, which include:

1. Starting planning early; planning should begin in the exploration or design phase, which allows for greater understanding of the risks and potential liabilities around closure, thus enabling a longer timeframe for planning and actions to address them in advance. This leads to reduced end closure costs and reputational benefits.
2. Ongoing, proactive planning and management for closure/ social transition should occur throughout the mine lifecycle, not just a few years before closure. By then it will probably be too late to implement social transition actions that will have a significant sustainable impact.
3. Planning for temporary or sudden closure. Mines close – this is an inescapable truth; but predicting precisely when is difficult. They sometimes close temporarily or unexpectedly, but understanding the consequences of this can help reduce the impacts, if appropriately planned for.
4. Learn from others. There are few socio-economic challenges around mine closure that are unique; it is likely that successful responses to specific problems have already been found in other locations and circumstances. The challenge is to find these examples and extract the transferable lessons, thus saving time and money in developing bespoke solutions from first principles again. In other words, avoid re-inventing the wheel!
5. Integrating social transition planning into broader mine closure planning, which should also be part of the mine's short, medium and long-term business planning.
6. Taking a multi-disciplinary approach – social transition planning (as for closure planning in general) is a multi-disciplinary process that requires expertise from a number of disciplines, not all of which will be available within the mining company, but may be through the community or wider stakeholder group.
7. Early identification of stakeholders and initiation of multi-stakeholder approaches. Stakeholders will typically include communities affected directly by mine closure, Indigenous Peoples/ traditional owners, (national, regional and local) government and regulators and associated agencies, industry peers, other industries in the area, civil society, academia and media.
8. Encouraging diverse community participation throughout the mine lifecycle to build trust and the social licence to operate and promote shared ownership of the planning process. Communities themselves consist of a diverse range of groups that could be included, such as: women's groups, community associations, youth groups, vulnerable groups and under-represented minorities. It is important to facilitate robust consultation that does not only reflect the perspective of the majority.
9. Empowering leadership: sometimes there exist in communities people acting informally as leaders beyond those formally elected as such. If these people are empowered to participate in the planning process, they could strengthen local community involvement.
10. Transparency. Effective closure planning is underpinned by consistent and transparent engagement with stakeholders and communities and is essential in building trust
11. Enhancing available funding and efficient spending. When social transitioning initiatives are implemented during the mine lifecycle, the costs will be considered as operational expenditure and will be spread over a longer period than if delayed till the advent of closure when the mine is producing much less revenue, if any. With progressive stakeholder relationships, it may be possible to match and augment funds for social transitioning with those from non-mining sources to create a greater positive impact.
12. Encouraging innovation and creativity. A mining company and the stakeholders conventionally associated with it may not necessarily have answers to some of the vexing challenges around mine closure/ social transition. Delivering innovation requires creative and lateral thinking, which often lie outside conventional company – stakeholder relationships. There are many successful and innovative social transition projects that have engaged 'unusual suspects'. These are people and groups from beyond the usual mining circles, who are engaged with novel, creative approaches and may have broader shared interests around mine closure and social transition and may include artists, anthropologists, landscape designers, architects, historians, educators, etc.
13. Realising opportunities for social transition before closure. If the principles described briefly above are followed, opportunities to develop projects for social transition will arise early and should be implemented sooner rather than later. This approach is akin to progressive restoration in environmental terms, such that the end costs and risks and liabilities at the point of closure become substantially reduced.
14. The importance of climate change. It is highly relevant to accommodate predictions of climate change impacts in social transition planning – particularly for medium- to long-term projects and programmes. This could have a significant impact on the success of an initiative.

CHAPTER 6

Project Summary

The following pages outline the key decisions, conclusions and a general discussion that have been drawn from the report.

Summary Introduction

The project decisions and conclusions are shown graphically on the following pages through a project journey map. The journey map helps to visualize the story of the project and explain how the WP5 team made decisions and how project conclusions where reached.

The key conclusions for each of the WP5 projects objectives are highlighted and a general discussion is offered that can help guide the continuation of the project.

Project Journey Map

NITREM
Nitrgen removal from waste rock drainage.

The source of the problem is residue from explosive chemicals, namely ammonium nitrate (NH4NO3) that contaminates waste rock from the mining operation. At the surface where the waste rock is stored in extensive waste rock dumps (WRDs), the highly soluble nitrate (NO3) is readily leached from the waste rock by percolating water from rain and melting snow.

Environmental issues

NITREM

A research and development project to upscale a bioreactor treatment technique for reducing the nitrate loading of waters leaching from the Kiruna iron ore mine site. The project consisted of different Work Package Teams to bring the research and knowledge together to develop the project to reach a commerical application for the bioreactor Technology.

The Work Packages included:

WP0 - Feasibility Study

WP1 - Project Management

WP2 - Bioreactor Construction

WP3 - Operations, monitoring and elvaluation

WP4 - Knowledge transfer

The focus of this report was,

WP5 Sustainable landscape design:

For a landscape design to be considered `sustainable', not only are environmental factors fundamental but socio-economic considerations are critical and need to be accommodated within, and allowed to influence, the plans and designs.

WP5 Objective 1:
Develop landscape performance goals and criteria

In order to construct sustainable landforms, consideration needs to be given to the purpose of the landform and, importantly, what can be measured to ensure delivery of this purpose.

Chapter 3 outlines the landscape performance goals and criteria that were developed for the project. They were established after internal stakeholder consultations and a review of LKABs Rehabilitation report and a review of good international industry practice.

WP5 Objective 2:
Design a WRD that incorporates the NITREM bioreactor technology

The focus of WP5 was to design a WRD that considers WRD hydrology, aesthetics, post-mining land-use, landform function, biodiversity and ecosystem services in combination with NITREM bioreactors. This includes the identification of a suitable WRD design method to achieve successful bioreactor function and mine rehabilitation goals.

See pages 100-101

WP5 Objective 3:
Develop a design methodology to guide the successful planning and implementation of future NITREM projects

It is recognized that the Kiruna site is different to other sites across Europe where the bioreactor technology could be potentially utilized. Site specificity is a key challenge to developing a successful landform design methodology that is applicable to other sites. It requires a process that is generic and transferable, but which can be tailored to the different conditions and contexts of other sites.

The design methodology outlined in Chapter 4 is applicable to different sites during different phases of waste rock dump development, including the feasibility, planning, design and construction phases. Users can work through the methodology as necessary depending on their requirements and level of readiness and site knowledge. It focuses on optimizing bioreactor function from a technical perspective, maximizing the volume of WRD leachate water treated and ensuring that closure goals, such as biodiversity and post-mining land-use, can be achieved.

WP5 Objective 4:
Prepare a social transition methodology to guide development of a vision for addressing the socio-economic aspects of mine closure

For a landscape design to be considered 'sustainable' not only are environmental factors fundamental but socio-economic considerations also require analysis, understanding and a proactive approach to accommodate them.

The Social Transition Methodology, Chapter 5, is a general approach that can be tailored to different sites and communities. It takes a holistic view, rather than just focusing on the immediate landscape elements. This means that the wider community and economic aspects are considered in developing the methodology beyond the immediate mine site itself.

WP5 Objective 2:
Design a WRD that incorporates the NITREM bioreactor technology

Geomorphic WRD approach:

Creating landforms that mimic the function and aesthetics of more natural environments. The basis of a geomorphic design is to create a landform that does not require ongoing treatment to prevent erosion, is hydrologically stable, minimizes soil erosion, is visually appealing and promotes a self-sustaining ecosystem.

Best Available Technique (BAT, European Union)

Prevent leachate

A geomorphic design by its nature (via the introduction of a surface drainage network) will increase runoff by approximately 25-35%, which will reduce infiltration and thus leachate as a result.

Reduced infiltration will increase the time taken for the nitrogen to be washed from the dump via percolating water and therefore the overall time to remediated the leachate via the bioreactors.

It is considered important to explore a potential solution for how nitrogen rich leachate can be captured and directed to the bioreactors.

Can a geomorphic design help direct leachate to the bioreactors?

It was assumed that a geomorphic design would assist the flow of leach water towards the bioreactors helping to capture the maximum volume.

Geomorphic designs introduce a drainage network to the dump surface helping convey run-off water from the site (run-off is increased and infiltration is decreased).

However, infiltration still occurs. Bioreactors need to treat the leachate not the surface water, hence controlling the surface flows has little direct benefit to the bioreactors.

Underground water modelling:

Undertaken to provide a solution to capture the nitrate-loaded water that percolates through the waste rock, and to direct it towards the bioreactors for treatment by means of underground drains.

This would contribute to alleviate two major problems:

- the inflow of contaminants into the regional moraine aquifer
- the need to maintain a constant flow rate into the bioreactors.

The proposed solution:

- An "impervious" layer between the waste rock and the underlying aquifer could:
- Create a perched water table within the waste rock
- Collect most (all) ground water and redirect it into the bioreactors by means of drains
- Prevent deep percolation to a large extent (and hence, contamination)

Goals of the model:

- How thick would that layer need to be?
- How permeable would that layer need to be?

Model results:

With the introduction of drains under the dump, 70% of leachate could be directed to the bioreactors without an impervious layer between the waste rock and the underlying aquifer.

With the introduction of drains and a 2m thick compacted layer with a permeability two orders of magnitude lower than the bedrock, over 95% of leachate could be directed to the bioreactors.

The purpose of the modelling was to offer a first approach to a problem. There are still many implementation and model issues that need resolution if this solution was to be taken forward.

Suitable in an subarctic climate?

The basis of a GeoFluv design are site specific landscape parameters taken from a local reference site, which are used in the modelling process to ensure the geomorphic design functions as the landscape. This ensures a robust design based on the method of using reference areas that have experienced historic, natural climate change over millennia.

Accurate data collection is critical to ensure true representation and replication of the reference site and creation of a successfully functioning landform that blends with the surrounding landscape.

The landscape inputs collect during the project, outlined in chapter 3, were sufficient for the project, however, further data would be required if the project was to continue.

A geomorphic design approach is suitable in an subarctic climate.

LKAB remediation goals.

International research and studies on geomorphic design have shown how such an approach does help companies achieve their remediation goals such as minimizing erosion and increasing in biodiversity.

Volume target

See page 102

Bioreactor locations

See page 102

Conventional WRD method:

Conventional WRD designs are limiting in several ways – even if this approach is considered as good international industry practice, the practice is not progressive. The nature of the design can restrict development of an ecologically sustainable and natural-looking vegetation cover and landscape, with knock-on effects for post-mining land-use options, water quality standards and social acceptance. This may eventually become manifested in permitting problems.

Doesn't lead to a sustaiable landscape design due to the high possibility of ongoing erosion issues, ongoing maintenance issues and its limited possibility for a post-mining land use.

Volume target

In order to design a stable geomorphic landform that meets LKABs target volume, 72,000,000m3, an extension to the boundary was required from the original. The boundary extension allowed a landform that adhered to LKABs permit elevation of 640m a.s.l. and help the company achieve their stated remediation goals including minimizing erosion, a stable WRD that promotes biodiversity and blends in with the surrounding landscape both functionally and aesthetically.

Design adjustments:
Further study and design iterations can vary the dump footprint and shape to enable further slope reduction, which would lower the channels' erosive energy during run off-producing events, or to create more complex slopes to promote diversity, and to align the valleys and ridges and adjust their slope angles to influence snow accumulation in certain areas.

If there was flexibility to the maximum 640m elevation, then the majority of the top WRD surface could be lowered and cut material from the valleys could be placed on ridges whose tops then might exceed the 640m elevation. This could provide an even more diverse topography and reduce the total volume of uphill material movement to save on transport cost.

The geomorphic design, with extend boundary, can hold 83,000,000m3, which is approximately 15% more volume than LKABs target volume.

Bioreactor locations

In a separate project, a team of hydrologist determined the best location and number of bioreactors required for the watershed area and volume of waste. It was recommended 13 bioreactors to be placed south of the deposit.

The optimal location was determined from groundwater studies, which simplified can be explained as 'not being too far away from the WRD making it difficult to collect all the leach water before it flows from different points into the wider landscape' and 'not too close to the WRD where the leachate could be missed for capture in the bioreactors'. The selected location also aligned with existing road infrastructure to help collect and direct water to the bioreactors. The location along a road also makes maintenance easy.

The placement of the bioreactors is more based on groundwater flows to ensure the capture and remediation of the maximum volume of leachate rather than trying to incorporate the bioreactors into the geomorphic design of the WRD. As such, the geomorphically design WRD and placement of bioreactors are independent from each other.

General Discussion

It could be argued that a conventional WRD is as, or more, beneficial to the function of the bioreactors as a geomorphic WRD. In the sense that a conventional dump has a higher infiltration rate due to the flat surfaces and is therefore assumed to be able to eliminate the problem quicker i.e. more precipitation percolates the waste material washing out the ammonium nitrate. However, this could take 50-100 plus years.

On the other hand, a geomorphic WRD will have less water leaching through the waste material so therefore could be considered as a preventative approach to the nitrogen issue. However, leachate containing higher than acceptable levels of nitrogen is produced regardless of the dump construction method. While with one method it is assumed will result in a longer period of nitrogen-rich leachate occurring the problem is considered long-term with either method. It is not been known how long the before the leach water will continue to be nitrate loaded. In monitoring undertaking in an existing LKAB dump it was determined that nitrogen still exist, causing an issue 50-60 years after the construction first began on the dump.

Controlling surface flows and groundwater flows are two different things. For a geomorphic design approach the aim is to convey, as quickly as possible, run-off water off the dumps surface via the designed drainage network in order to minimize erosion and create stability. Whereas, for the bioreactors, the aim needs to focus on being able to control the leachate to achieve maximum remediation of the water. This requires a different solution below the dump.

While the connection between the WRD and bioreactors seems obvious i.e. the problem stems from the waste rock and therefore are considered as one system, the connection and relationship between the two is more difficult to define. They are dependent on each other and both aim to reduce contamination of the surrouding landscape yet at the same time have different needs and solutions for their success.

The big issue regarding optimizing bioreactor function and maximizing the capture of groudwater volume for both WRD approaches is collecting leachate at the bottom of the dump and directing it to the bioreactors and therefore preventing contamination of the ground water. The idea behind the water modelling undertaken by the WP5 team was not to present a final solution but rather present initial thinking and investigations to help gain a clearer picture and guide future decision making. The key questions for the proposed solution that require further investigation if the project is to move forward include:

- What is the permeability of the waste rock? And, would it be feasible to achieve a permeability two orders of magnitude lower by compacting till?
- How much till is available i.e. is there enough to cover the dumps to meet the requirements of LKAB's rehabilitation plan and also have a layer beneath them?
- What happens where deposits already exist?
- Is it a financially viable solution?

Also importantly, as determined by the water modelling results, with the introduction of drains under the dump 70% of leachate could be directed to the bioreactors without an impervious layer between the waste rock and the underlying aquifer, is this acceptable?

With this said, a conventional WRD with its limitations does not allow a company to create a landform that can be considered sustainable and therefore was not the chosen approach for this project and WP5 investigations. The geomorphic design process introduces a paradigm shift in that it does not generate pollution i.e. erosion and sediment and then try to contain it onsite, but instead creates stable landforms that don't pollute and discharge at levels comparable to stable surrounding natural land. The approach can be a challenge for mining engineers and regulators is to consider and accept a new way of rehabilitating mined lands and that a new approach, as proposed here, can be designed and built (for new sites) or re-graded (for existing sites) while satisfying rehabilitation criteria.

Appendix

Figure References

Front page. Nikkaloukta, Pete Whitbread-Abrutat 2019.
Back page. Geomorphological map 28 H SAREK
- Description and assessment of areas of geomorphological importance, by Olle Melander.

Chapter 1

Figure 01. The Kiruna mine site highlighting Area B.
© Lantmäteriet.
Figure 02. Bioreactor construction at the Kiruna mine Triangle Area deposition.
Figure 03. Bioreactor system.
Figure 04. Bioreactor design.
Figure 05. Generalized degradation of a WRD landform.
N Slingerland, N Beier & G Wilson, 2017.
Figure 06. Conventional waste rock dump design.
Figure 07. Geomorphic waste rock dump design.
Figure 08. WP5 Project process.

Chapter 2

Figure 09. Pulsas.
Figure 10. Bedrock nob
Figure 11. Esker
Figure 11. Esker
Figure 12. Subglacial gorge
Figure 13. Thermo cirque
Figure 14. Talus deposit
Figure 15. The team exploring Tundra
polygons (patterned ground) east of Nikkaluokta.
Figure 16. Hummocky topography on fluvioglacial deposits.
Figure 17. Fluvioglacial deposits common for the area.
Figure 18. Nature values surrounding the Kiruna mine site.
© Lantmäteriet.
Figure 19. Nature values by the Kiruna mine site.
Figure 20. The mine offices and subsidence zone,
photo taken from north of the mine site facing south. Ecogain 2019.
Figure 21. Mining lease area. © Lantmäteriet.
Figure 22. Conventional waste rock dump construction, based on illustration from Golders, Efterbehandlingsplan, Kiruna, 2018.
Figure 23. Proposed conventional waste rock dump, LKAB, Volymberäkning, 2019.
Figure 24. View from existing WRD on area B.
Figure 25. Surface flows from Area B towards ditch along existing road.
Figure 26. Limited erosion on the WRD outslopes.
Figure 27. Existing vegetation - mountain birch
Figure 28. Aerial view of Area B, EcoGain 2019.
Figure 29. Watershed within mine site. © Lantmäteriet.
Figure 30. Surface water flows from Area B to recipient.
© Lantmäteriet.
Figure 31. Principle sketch for regrading the proposed conventional WRD slopes for remediation, Golders, Efterbehandlingsplan, Kiruna, 2018.
Figure 32. Local flora.
Figure 33. Identified leachate flows at the Triangle Area WRD. © Lantmäteriet.
Figure 34. The Kiruna NITREM system consist of three bioreactors and a reservoir at the base of the Triangle Area WRD.

Chapter 3

Figure 35. Footprint stage 1 and 2.
Figure 36. East to west 3D perspective view of geomorphic WRD.
Figure 37. Runoff tracking used to identify overland flow paths and local base levels
Figure 38. Identified low points, valleys and ridges.
Figure 39. CAD elevation model of proposed dump with ridges of displaced valley cut material.
Figure 40. Planview.
Figure 41. West to east 3D-view.
Figure 42. East to west 3D perspective view of revised geomorphic WRD with extended boundary line.
Figure 43. CAD elevation model of revised dump with ridges of displaced valley cut material.
Figure 44. Identified low points, valleys and ridges.
Figure 45. Coloured slope zones analysis showing drainage pattern.
Figure 46. North to south 3D perspective contour view showing WRD top dendritic drainage network.
Figure 47. South to north 3D perspective contour view highlighting the main valleys.
Figure 48. Planview.
Figure 49. West to east 3D-view.
Figure 50. South to north 3D perspective surface view.
Figure 51. Field data collection - Valley Hunting - Matt, Anders and José.
Figure 52. Frida, Anders and José.
Figure 53. Measuring location. © Lantmäteriet.
Figure 54. A-channel reach.
Figure 55. View of ridge to head of channel.
Figure 56. Measurement location. © Lantmäteriet.
Figure 57. Measuring ridge to head of channel.
Figure 58. Drainage basin 1. © Lantmäteriet.
Figure 59. Drainage basin 2. © Lantmäteriet.
Figure 60. Sinuosity measurements on DEM-data.
Figure 61. Measurement locations. © Lantmäteriet.
Figure 62. SMHI Storm event data. Extremregn i nuvarande och framtida klimat, SMHI, KLIMATOLOGI Nr 47, 2017.
Figure 63. Matt and José, esker.
Figure 64. Area B land-uses and subdivision for calculating future water balance, WSP, Deponiområde B , 2019.
Figure 65. Bioreactors, Kiruna.
Figure 66. Recommended bioreactor locations, WSP, Deponiområde B , 2019.
Figure 67. Schematic overview of the proposed solution.
Figure 68. Conceptual groundwater model of the site (diagram modified from WSP 2020).
Figure 69. North-south cross-section of the model. Layers 1 and 2 are only active during the simulations.
Figure 70. Model overview with boundary conditions. Layers 1 and 2 are only active during the simulations.
Figure 71. Borehole locations for model calibration. Map made available by WSP.
Figure 72. Captured recharge versus compacted material thickness under several possible permeability ratios.
Figure 73. Plan view of groundwater flow paths without a compacted material layer (left) and with a 2 meter thick compacted material layer of a permeability two orders of magnitude lower than the waste rock (right).
Figure 74. Natural stream at the Kiruna mine site.

Chapter 4

Figure 75. Design methodology.
Figure 76. Kiruna mine WRD.
Chapter 5
Figure 77. Social Transition Planning Methodology.
Figure 78. Relocating the town.

Table References

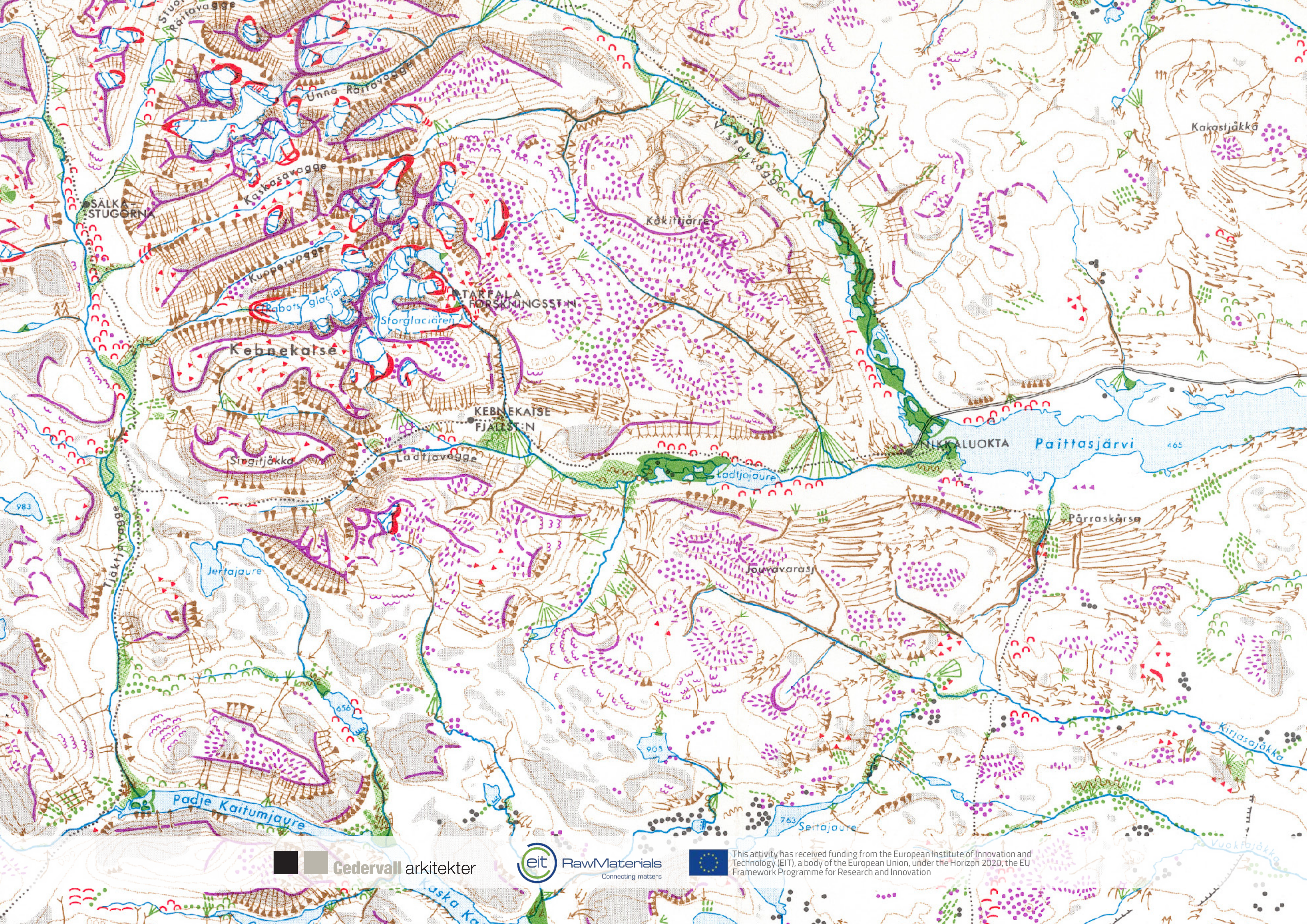
- Table 1. Future water balance (with completed WRD), WSP, Deponiområde B , 2019.
- Table 2. Range of horizontal and vertical hydraulic conductivity values (m/s) for each material on site.

Report References

- Optimerad design av sidobergsdeponier i Kirunagruvan, Tyrens, 2017
- Beskrivning av LKAB:s vattensystem i Kiruna – en genomgång av nuvarande och framtida vattenbalans och vattenkemi, LKAB, 2018
- Deponiplan, LKAB Kiruna, WSP, 2016
- Golders, Efterbehandlingsplan, Kiruna (2018)
- Avfallshanteringsplan för LKAB:s verksamhet i Kiruna, LKAB, 2018
- Inventering och bedömning av naturvärde, Gruvverksamhet i Kiruna kommun, Enetjärn, 2017.
- Olle Melander, Geomorphical map, 29 J Kiruna – Description and assessment of areas of gemorphological important, Statens Naturvårdsverk 1976
- Inventering och bedömning av naturvärde, Gruvverksamhet i Kiruna kommun, Enetjärn (EcoGain), 2017
- Ekologisk Efterbehandling (Utkast), EcoGain, 2019
- Annual and Sustainability Report, LKAB, 2017
- Climate change in Norrbotten County, County Administrative board in Norrbotten County, consequences and adaptation, 2016
- Diffust läckage utan nya mätvärden, Sweco, 2019
- Melander O, Geomorphological map 29 j kiruna- description and assessment of areas of geomorphological importance
- Deponiområde B – Deponering av gråberg och hantering av kväverikt lakvatten, WSP, 2019
- Interra (2018). Site-wide Hydrogeological Investigation at LKAB Kiruna Iron Mine Page. Update to the Site-wide Surface Water-Groundwater Model. Technical report. 65p.
- WSP (2020). Deponiområde B. Deponering av sidoberg och hantering av kvävertikt lakvatten. Technical report. 44p.

Literature Review References

- Broda S, A et al Improving control of contamination from waste rock piles, Journal of Environmental Geotechnics · December 2014
- Coppin N. A framework for success criteria for mine closure, reclamation and post-mining regeneration, Mine Closure 2013, Cornwall UK.
- E. J. Howard*, R. J. Loch and C. A. Vacher, Evolution of landform design concepts, Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology, June 2011
- Eckels, R and Bugosh N, Natural Approach to Mined Land Rehabilitation, FIG Congress 2010, Facing the Challenges – Building the Capacity
- G.R. Hancock, J.B.C. Lowry, T.J. Coulthard , Long-term landscape trajectory — Can we make predictions about landscape form and function for post-mining landforms?, Geomorphology 266 (2016) 121–132
- G. R. Hancock, r. J. Loch, and g. R. Willgoose, the design of post-mining landscapes using geomorphic principles, www.interscience.wiley.com, DOI: 10.1002/esp.518
- Hollingsworth D & Odeh I, Simulation and assessment of mine landscape reconstruction using analogue landform and environmental design criteria, conference paper
- Linklater C, Bennett J and Edwards N, 2006, modelling of a waste rock dump design to control acid rock drainage at the Svartliden gold mine, northern Sweden
- Meek, A., O'Dell, K. 2012. Selenium Treatment ArchEastern, Birch Mine. Proc., West Virginia Mine Drainage Task Force Symposium. Morgantown, WV.
- N. Slingerland, N. beier, and G. wilson, 2017, enhanced geomorphic design for rural waste-scapes, Sixteenth International Waste Management and Landfill Symposium
- Nordström A & Herbert R., Determination of major biogeochemical processes in a denitrifying woodchip bioreactor for treating mine drainage, Uppsala University, Department of Earth Sciences, Villavägen 16, SE-752 36, Uppsala, Sweden
- R Barritt, P Scott, I Taylor, Managing the waste rock storage design — can we build a waste rock dump that works?, Mine Closure 2016, Perth Australia.
- Sharma, K.D., Singh, HP. 86 Pareek, P. 1983. Rainwater infiltration into a bare loamy sand. Hydrological Science Journal vol. 28, (1983), pp.417-424.
- Stefan Bergman, Geology of the Northern Norrbotten ore province, northern Sweden, Geological Survey of Sweden, 2018
- Swaffield S, A framework for landscape assessment, landscape review i999:5(i) pages 45-5i
- Terrence J. Toy & Willow R. Chuse, 2004, Topographic reconstruction: a geomorphic approach, Ecological Engineering 24 (2005) 29–35
- Wright A 2006, Understanding Waste Rock Dump Hydrology is Essential for Effective Closure Plan-ningand ARD Management, Mine Closure - Australian Centre for Geomechanics
- Zapico I, Martín Duque J, Bugosh N, Laronne B, A et al 2018, Geomorphic reclamation for re-establishment of landform stability at a watershed scale in mined sites: The Alto Tajo Natural Park, Spain, Ecological Engineering 111 (2018) 100–116
- Ziemkiewicz, P.F., O'Neal, M., and Lovett, R.J. 2011. Selenium leaching kinetics and in situ control. Mine Water Environment. 30(1): 141-150.
- Integrated Mine Closure - Good Practice Guide, ICMM 2019, 2nd Edition



Cedervall arkitekter

eit RawMaterials
Connecting matters

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation