Simulation and assessment of mine landscape reconstruction using analogue landform and environmental design criteria

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Abstract— **Environmental disruption from mining activity has increased markedly in the 21st century leading to increased emphasis on reconstructing natural environmental processes in post-mining landscapes. We present simulation and assessment approach to designing post-mining landforms at Ranger Uranium Mine in Northern Australia. A mine landform design was developed from mine planning estimates of waste rock and pit volumes. Landform design parameters were developed from analogous natural landscapes using digital terrain analysis. Evaluation of erosion, water balance and visual impact identified areas of localized erosion and links between soil reconstruction and the viability of native woodland ecosystems. The simulation and assessment approach identified where further refinement of the ecosystem reconstruction strategy was needed. In addition, it provides the basis for communication of plans to a wide audience, including traditional land owners.**

Keywords- mine-landscape recontruction; landform design; environmental evaluation; analogue landforms; ecological survey

I. INTRODUCTION

Global mining and quarrying involved movement of over 57 billion tons of rock and earth per year, a figure that rivals natural material displacement and geomorphic processes [1]. Surface mining damages 6 times more land than underground mining [2], leading to extensive areas of disturbed landscape in the vicinity of the mine site. Typically, post-mining landforms comprise open pits and above grade waste rock landforms that have been engineered and constructed to a particular failure risk profile based on hydraulic design parameters. However, in the US and increasingly in many countries that rely on mineral exploitation such as Australia, mine restoration legislation provide for the reconstruction of the original topography [6]. In this case the main purpose of topographic reconstruction is to restore hydraulic and erosional stability to the mined landscapes. Instead of environmentally engineered slope designs that incorporate berms, benches and engineered flumes for safe hydraulic management of water movement, the legislation prescribes that natural slope and catchment conformations be incorporated into the mined landscape with the aim of creating a sustainable landform. Furthermore, in Europe while topographic reconstruction is also favored, there is an emphasis on erosion modeling and the need for simulated landscape evolution modeling to validate landform designs [11]. However, where the closure objective is to restore the native ecosystems in the post-mining landscape, the link between the reconstructed topographies with analogue topography, soil conditions and vegetation, to achieve ecologically stable outcomes is not well defined. The analogue natural ecosystems need to be described in sufficient detail to support ecological modeling capable of predicting the design outcomes.

An alternative approach is the one that focuses on ecological objectives of mine rehabilitation which is conceptually different from the basin relief approach to topographic reconstruction [6]. The latter is directed more to the protection of the off-site receiving environment. Reference or analogue sites are used routinely to set closure criteria for opencast mine rehabilitation using the basin relief approach [13]. However, ecological landform design methodologies [11] that would ensure successful restoration of natural biodiversity levels have not been explored [8, 9]. The aims of this paper were to: (i) develop a landform design at Ranger uranium mine in the Northern Territory of Australia; (ii) describe the ecological context for the waste rock landform in detail; and (iii) evaluate the long-term environmental performance of the design.

II. METHODS AND MATERIALS

A. *The Study Area, Experimental and Data Analysis*

The study site is the Ranger Mine, located in the central part of the Northern Territory of Australia. An oblique air photo of the mine site in 1974 before mining began shows the site to be located on a peneplanated surface, bounded by streams and backed by high relief sandstone plateau (Figure 1a). Another aerial oblique photo of the site taken in 2001 and looking north (Figure 1b) shows land use associated with the operating mine including waste rock stockpiles, open pits, ponds, tailings storage facility and industrial facilities. This gives an indication of the extent of the rehabilitation task. The landscape rehabilitation design and evaluation process for Ranger uranium mine, as reported here, is represented schematically in Figure 2.

B. *Experimental and Data Analysis*

Landform design criteria at Ranger mine were derived from the central tendency and dispersion measures of terrain

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attributes derived from a digital elevation model (DEM) in the *Georgetown* analogue area, adjacent to the mine site. The design criteria were applied in VULCAN program to draft a post-mining landform. The geomorphic similarity of the designed landform to the natural landscape, as gauged by digital terrain analysis, was then evaluated. Following this, landscape evolution modeling (using SIBERIA) and hydro-ecological modeling (based on WEC-C, a deterministic catchment-modeling tool) were applied to simulate and assess whether the landform design exhibited similar erosion and water balance processes to the natural analogue. Then a detailed environmental survey of the *Georgetown* analogue area was used to describe vegetation communities and patterns, in addition to describing and analyzing soil properties. The overall purpose was to enable ecological modeling and landform trial activities, and thus environmental monitoring at the Ranger site, in the context of ecological objectives.

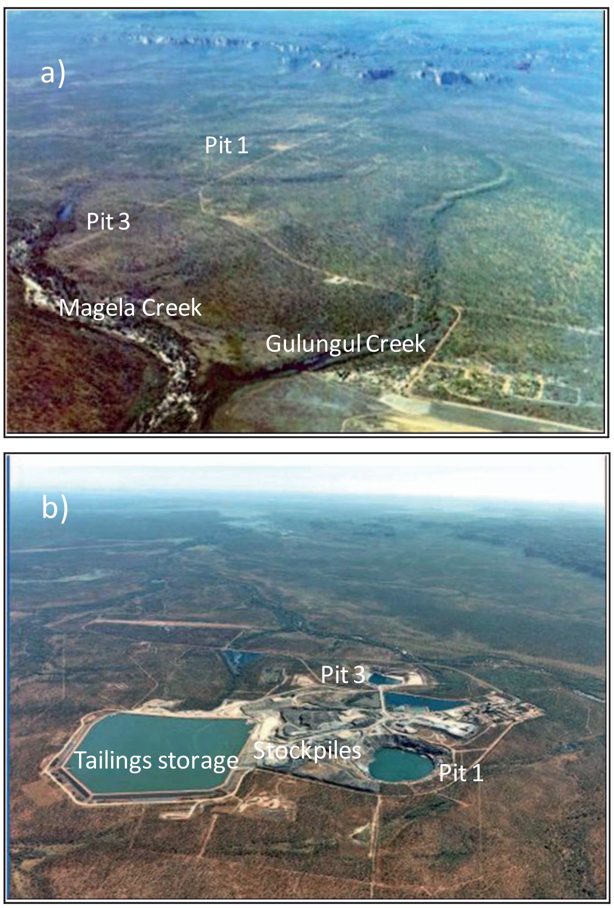

Figure 1 a) 1974 oblique air photo of Ranger site prior to mining, looking south; b) Oblique air photo of Ranger mine in 2001, looking north.

III. RESULTS AND DISCUSSION

The landform design method provides a clear ecological context in the natural landscape, which facilitates communication of design issues to a range of stakeholders (traditional landowners, the mining industry, government agencies and the public- see Figure 2). The method also extends the topographic reconstruction approach [6] to include ecological objectives. The outcomes of the detailed environmental survey of soils, vegetation and terrain properties in a selected natural analogue are an important addition to knowledge resulting from this work.

A. Environmental surveys

The structure of natural plant communities is patchy in this environment and this patchiness increased in areas that were poorly or imperfectly drained. The number of species also declined as drainage was impaired from hillslope to valley flat. Consequently, revegetation objectives that do not account for the patchiness, which is induced by hillslope environmental variation, are unlikely to be achievable and terrain factors that affect drainage could be expected to influence revegetation outcomes.

This work has broadened the scope of existing analogue studies for Ranger mine [3], which documented well drained woodland sites across the region. The analogue design methods support a range of revegetation outcomes that are integrated with hillslope topography and soil pattern to support ecosystem reconstruction in the mine landscape [11]. This development has practical implications that could improve the success of mine rehabilitation using natural analogues. For instance at Nabarlek mine site, some distance to the northeast of Ranger mine in Arnhemland, the topographically reconstructed mine landscape failed to meet the objective to establish uniform eucalypt woodland [14] because the effects of hillslope hydrology on environmental pattern in the rehabilitated landscape were not explicitly defined and incorporated.

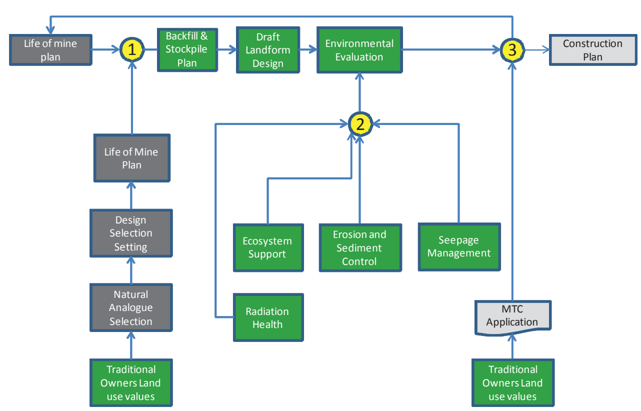

Figure 2 Landform design process - numbered circles indicate consultation points

The soils in the natural analogue area at Ranger are rocky, moderately deep and gradational in texture profile. These properties are similar to the waste rock cover materials at the mine site. However, whereas organic matter associated with enhanced levels of macro and micronutrients has accumulated near the land surface in the native soils, this could take time to develop in the revegetated mine soils. This pattern has been observed elsewhere in tropical and temperate deep weathered landscapes [5, 12]. Soil organic matter accumulation is a key component in assessing functional integrity of ecosystems in general [10] and rehabilitated mine soils in particular [7]. One solution to this slow accumulation of organic matter is carefully conserving and using natural topsoil in rehabilitation to enhance the process [12, 13]. At Ranger mine, where topsoil was not conserved because of long timeframe before rehabilitation could commence, different measures will be needed to restore soil fertility and ensure successful revegetation and rapid development of surface organic carbon content.

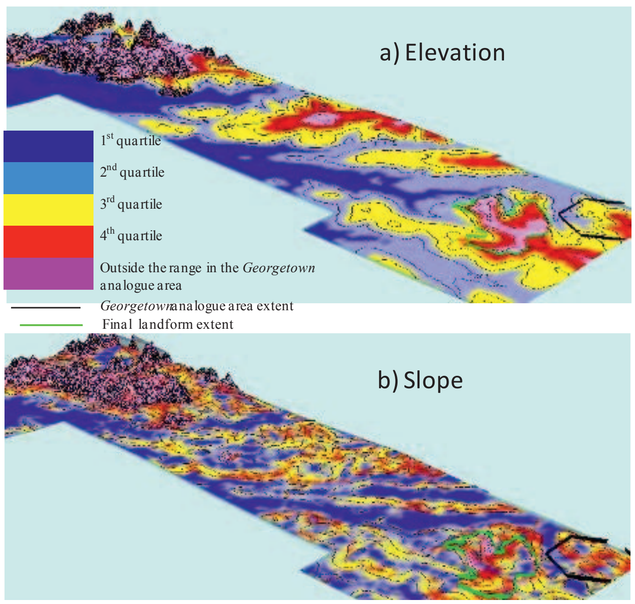

Figure 3 Three-dimensional perspective views of two terrain properties highlighting their range of values in the analogue area

B. *Environmental evaluation*

A reconstructed landform has slopes and catchment properties within the ranges and at similar frequencies to those of the analogue area. Potential failure areas for gully erosion, plant available water store and recharge were identified from landscape evolution and hydro-ecological modeling.

The landform evolution simulation indicated the difference between the initial and final elevation of the reconstructed landscape (Figure 3). Gullies that were three to five meters deep was predicted in steeply sloping areas abutting the creek lines for natural (a) and worst case (b) modeling scenarios, while three to four meter deep gullies were also predicted in the natural analogue area over the same period. The reconstructed terrain appeared to be similar in oblique aerial view to the pre-mining landscape (Figure 4). Viewing a computer rendered image of the landscape design with the 2001 mine landscape confirmed the backfilling of the pits, reshaping of residual waste stockpiles and tailings storage facility, and the removal of mine water ponds.

The hydro-ecological simulations indicated recharge rates to be dependent on the density of vegetation cover; and that, the vegetation density depended on the soil profile or landform cover, particularly the rooting depth, water retention and the downward flux of water. This soil-moisture storage was found to be readily available for plant transpiration during the dry season. Due to variations in rainfall, both recharge and transpiration ratio was episodic with low rainfall periods having no significant recharge and high rainfall periods averaging 17% rainfall recharge. Consequently a simulation approach, with support from monitored natural and reconstructed catchments, will be needed to assess the hydrological performance of the mine rehabilitation.

The landform evolution and hydro-ecological modeling methods need further development before reliable quantitative assessments can be made. Parameterisation of the landform evolution model was not flexible enough to allow variation in cover properties that affect runoff. While a number of enhancements to the model that address some of these issues have been made [15] a different modeling approach that accurately represents soil forming processes apart from erosion and deposition may be necessary.

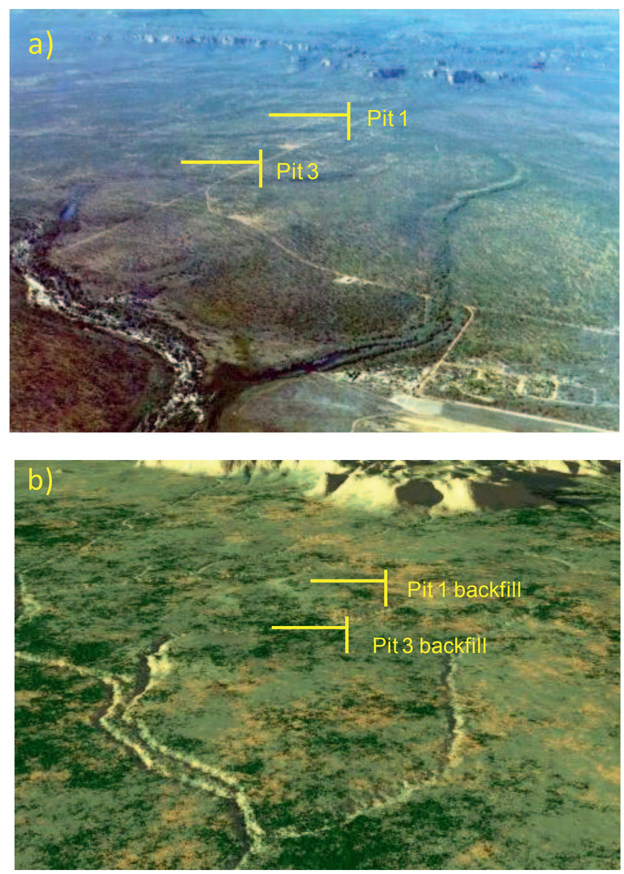

Figure 4 a) 1974 oblique air photo of Ranger site in 2001, looking to the south; b) Computer-generated 2.5D perspective of the same site.

The mechanics of the processes controlling water balance components evapotranspiration (ET), stream flow generation and groundwater recharge, determines whether the mine rehabilitation would be restore the pre-mine water balance in the upper layers, or whether it will move towards a state with a different total ET and thereby different rates of stream flow and groundwater recharge to that of the natural landscape.

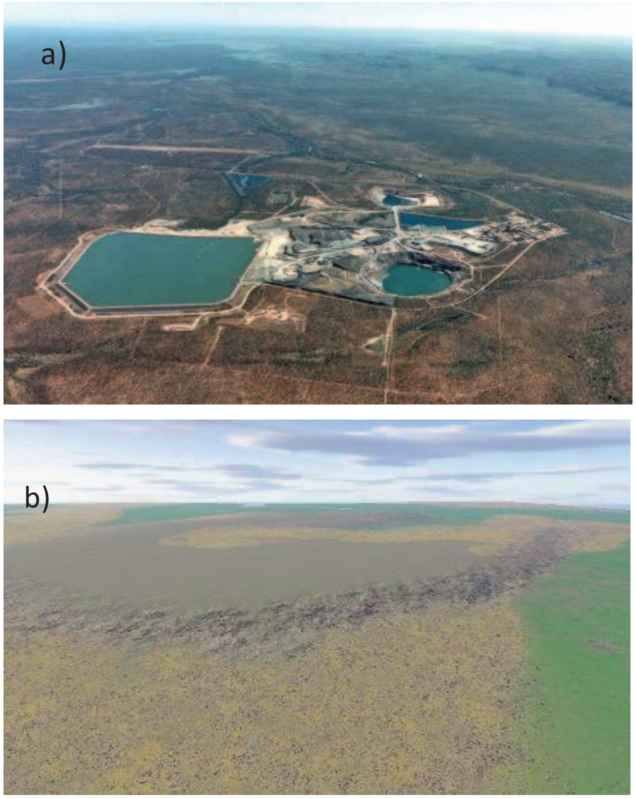

Figure 5 a) Oblique air photo of the Ranger mine in 2001, looking to the north, compared to b) reconstructed landscape visualization

Water balance simulation implied the long-term average recharge for the rehabilitated mine area will be something like 8 to 9% of rainfall for the areas overlaying a subsoil and 10% of rainfall for the areas overlaying the pits. In the natural situation, excess water vents from the system via stream flow, which accounts for more than 20% of the water budget (compared with 34% for Howard River) while estimated ET was 1,240 mm yr^{-1} for Corridor Creek (compared with 1,110 mm yr^{-1} for Howard River) [4]. This assumes that the revegetation reaches a density similar to that of the surrounding native areas.

Runoff generation processes in areas with waste rock cover material behave differently from those with vegetation cover. The covered areas are capable of generating runoff during intense rainfall events via an infiltration excess process, while the uncovered areas may be subject to a combination of excess saturation and interflow processes. In addition, there appears to be no interflow from the covered areas at the cover–soil interface. Therefore the groundwater system should be capable of absorbing a net recharge rate of around 9.4% of rainfall to prevent groundwater rise, although this remains to be determined.

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