Surface water control in the bauxite mines of Porto Trombetas (Pará, Brazil)

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Abstract MRN exploits large bauxite deposits by strip mining of plateaus in the Amazon rainforest. One important challenge is the control of water runoff, to minimize the entrainment of suspended solid material, and to avoid instability in the slopes at the plateau edge. These objectives have been achieved successfully after implementation and testing of micro-reservoirs installed across the mining areas. An important part of the micro-reservoir concept is that water infiltrates into a deep aquifer, reducing the amount of water that reaches the edges of the mining areas. Another advantage obtained with this methodology is the settling of suspended solids and colloids contained in the waters coming from mined areas.

Keywords Bauxite stripping mine, Amazon rainforest, suspended solid minimization, colloid removal, water infiltration, micro-reservoirs.

Geological context

The bauxite deposits of Porto Trombetas (State of Pará, Brazil) are sub-horizontal stratiform bodies of large regional extent, located at the top of the Upper Cretaceous Alter-do-Chão Formation, consisting of continental sediments deposited in a fluvial and lacustrine environment. These sediments are arranged in plane-parallel layers, with frequent interbedded clays. The thick sedimentary series overlies the Paleozoic rocks of the Amazon Basin, as shown in Fig. 1 (Mendes *et al.* 2012).

In detail, the Alter-do-Chão Formation comprises siltstone with interbedded sandstones, overlain by a sequence of more than 100 m thickness of indurate sediments, characterized by layered sandstone and conglomerates intercalated with mudstones, siltstones, sandstones, sandy clays and clayey sands (Cunha *et al.* 1993). The bauxite mineralization occurs as a result of weathering processes, where the tropical climate, with high levels of precipitation, humidity and drainage, were key factors in the hydrolysis and modification of layered primary ferruginous alumino-silicate minerals on top of the entire sedimentary body.

The intense erosion upstream caused a characteristic morphology of valleys and

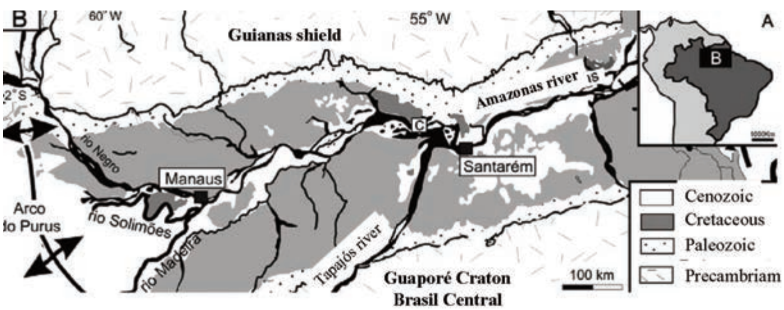

Fig. 1 *Exposure of the Alter-do-Chão Formation along the Amazon River.*

plateaus, which stand out in relief, and are jagged, indicating an immature geomorphological, non-stabilized stage (Fig. 2).

The bauxite deposits exist today as eroded remnants in these plateaus or “tablas” at the top of the Alter-do-Chão Formation, intersected by a dense network of surface drainages with dendritic patterns (Fig. 3).

The bauxite is in general restricted to the residual sub-horizontal plateaus, surfacing within or below the surficial topsoil and yellow clay. The higher hardness and erosion resistance of the bauxite causes it to form the edge of the plateau, as a morphological highlight (Fig. 4). On the slopes of the plateaus the overlying sedimentary materials outcrop over a significant length resulting from the depth of erosion achieved by the creeks. The hillsides have average slopes of less than 20 %, although locally they can be much steeper.

Hydroclimatic context

The average annual rainfall at the minesite is 2,189 mm, with annual maximums in excess of 3,000 mm. The site has an especially high rainfall period from December to May, with an average of 1,654 mm of rain. This represents a major water contribution to the runoff drainage basins, and creates great potential for soil erosion in deforested areas, or those areas with insufficient vegetative cover for its protection, providing significant amounts of suspended solids in runoff. Between June and November, the average rainfall is 532 mm, which is far from negligible. The maximum monthly rainfall occurred in March, 2005, with 637 mm. These rainfall rates have large spatial variability resulting from local convective-type storms. Monitoring of the precipitation has required installation of 24 rain gauges, 3 A-Class evaporation pans, and dozens of Piché-type evaporation gauges.

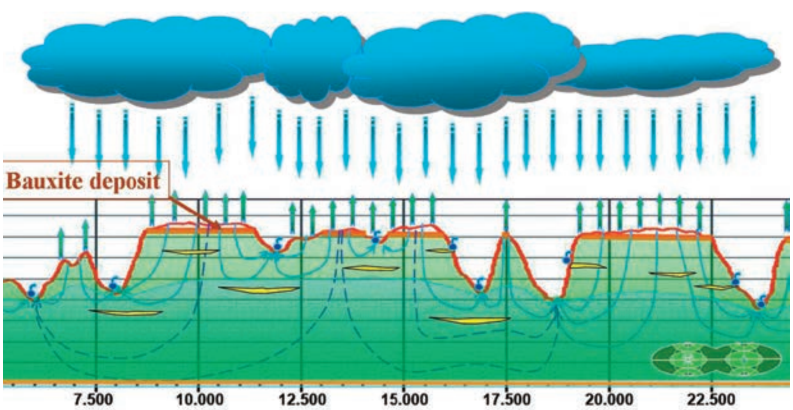

Fig. 2 *General morphology of the bauxite deposits and conceptual hydrologic model of Porto Trombetas.*

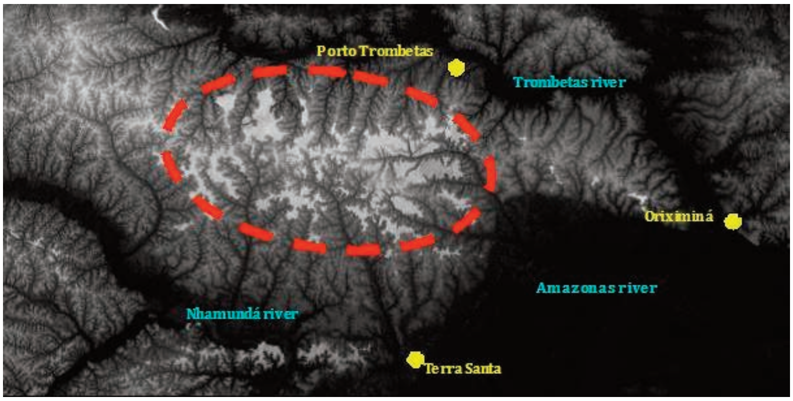

Fig. 3 *Tabular arrangement of the Porto Trombetas bauxites (satellite image).*

Hydrogeological context

A conceptual hydrogeological model has been developed for the project, with the support of a large number of shallow and deep piezometers. The model comprises three hydrostratigraphic units: isolated shallow aquifers; local suspended aquifers, and a regional deep aquifer (Fig. 5).

The sequence of lateritic and bauxitic horizons on top of the plateaus have reduced but not negligible permeability, causing most of the rainfall that is not evaporated to seep out into the plateaus under natural conditions. The infiltrated water can flow sub-horizontally to the periphery of the plateaus, giving rise to small temporal springs scattered around the edges of the plateau. Another important part of the hydrological system is that rainfall infiltrates vertically through the underlying clay and silt aquitard to the underlying local aquifers, and through them to the deep regional aquifer, which feeds the surface hydrological system by springs in incised streambeds.

Mining operation

The mining sequence in the plateaus consists of the following sequence:

1. Clearing the dense rainforest, which is supported by a thin layer of topsoil (usually less than 1 m thick).
2. Removal of topsoil, which is stockpiled for use in reforestation.
3. Mining of the silt and clay cover above the bauxite, with deposition into the mined-out adjacent strip, which is typically 30 m wide.

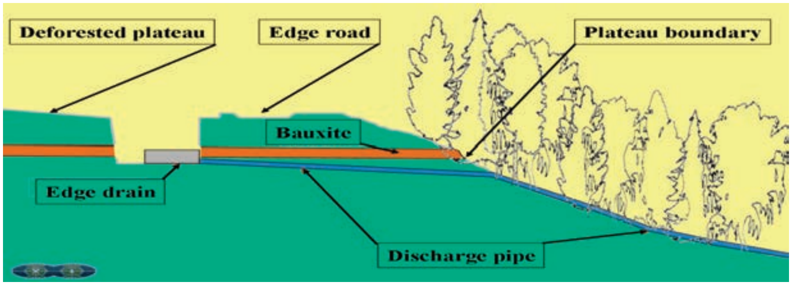

Fig. 4 *Plateau edge morphology with drainage water system.*

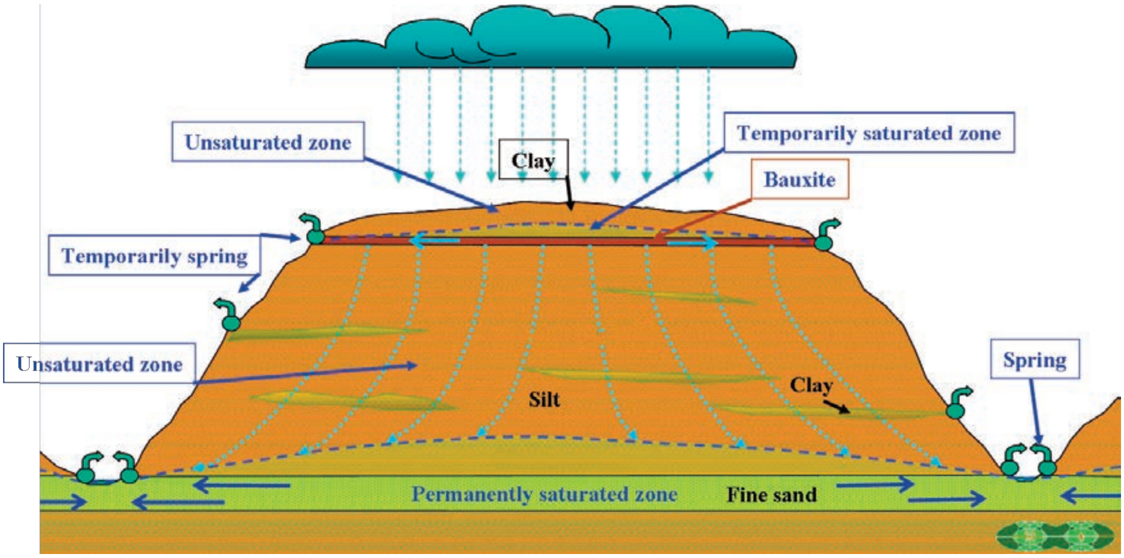

Fig. 5 *Regional hydrogeological model.*

4. Mining of the layer of bauxitic ore, leaving the zone of clay and silt beneath, which forms an aquitard, and contains the local suspended aquifer systems.

Following mining, the land is restored. This includes the installation of a protective fill berm around the edge of the mined area, with a minimum width of 10 to 30 m, higher elevation than that of the adjacent mining area, and a slope towards the interior of the mined area, so that the runoff from the exterior strip will always drain inward to the plateau.

Hydrological and environmental incidents

During prior operations, failure incidents occurred on the edges of the plateaus consisting of:

1. Erosion on the hillsides causing "bad-land" topography due to concentrated water flow and associated slope erosion, frequently leading to mud flow failures; and
2. Landslides near the edge of the plateau, due to relatively steep slopes and build-up of pore-water pressure due to precipitation.

In order to avoid slope failures, and to achieve better utilization of mining resources, we have designed a unique methodology that has allowed substantial progress towards stable, environmentally protective mining, and groundwater conservation.

Its application requires a detailed advance study of the edge conditions on the flanks of the plateaus, considering geotechnical, morphological, and hydrological parameters, edge conditions (whether natural or man-made), that may have an impact on stability. A final evaluation of the safety factor of the slope is made to establish the minimum edge border protection, which can vary between 5 and 30 m (added to by a 5 m wide service road).

A variety of methods are successfully applied to reduce the risk of erosion and landslides. This paper presents those aimed at surface water control and incremental infiltration of rainwater in the deep aquifer through artificial recharge, thus preventing the water from reaching drains at the edge of the plateau.

Runoff interception by micro-dams

The contribution of water to the edge drains is reduced by constructing a set of micro-dams for retention of water (Fig. 6), located in the mining areas and within the post-mining morphological reshaping within the plateau that is implemented during reclamation.

The effectiveness of this set of preventive structures for trapping water flow on the plateaus has been proven in all by noticeably reducing the intake of water to the edge drains, increasing infiltration of surface water to the deep regional aquifer system, increasing the evaporation rate, and also substantially reducing the discharge of suspended solids and colloids to creeks.

Mineração Rio do Norte has been building micro-dam structures on the plateaus in mining operations being reshaped for rehabilitation over the past three years, taking advantage of the excavation of drainage ditches and the movement of overburden materials. To date there has been no adverse hydrological or environmental incidents.

The micro-dams are constructed using transverse dikes extending away from the pe-

Fig. 6 *Micro-dam built on drainage channel.*

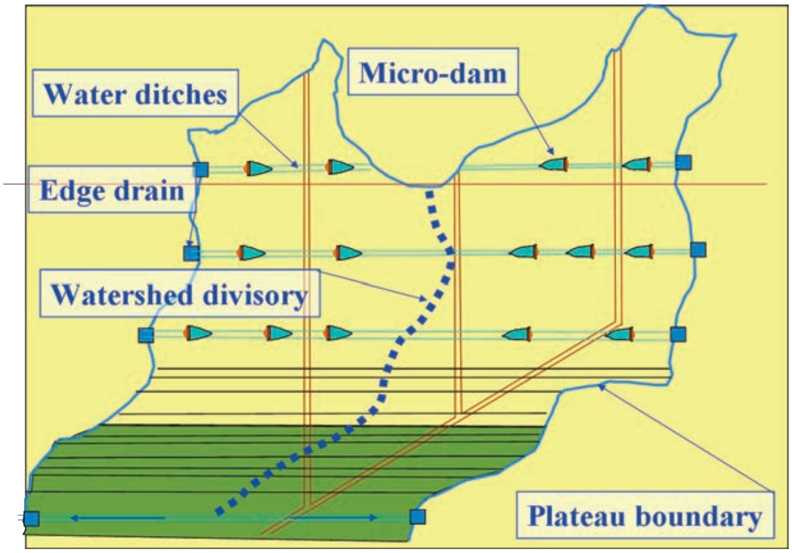

Fig. 7 Schematic sketch of the location of micro-dams in drainage channels.

riphery drains. These infrastructure features allow for retention of rainwater in local sub-basins, improving the safety of slopes by removing direct infiltration to the slope areas. Even though there are intense rainfall events, it has been shown to be practical to locally collect and store the stormwater flows on the mined-out surface during and after reclamation, thus preventing the storm surge of runoff from reaching the drains simultaneously (Fig. 7).

The implementation of micro-dams also favors sedimentation and settling of suspended solids, as well as retention of slash from processing and removal of tree trunks, branches and leaves. This retention results in the accumulation of material favorable to vegetative growth, and provision of a large number of seeds to begin that growth.

The crest height for each micro-dam dyke is located in a way that if it fills the water can overflow to the next micro-dam through a small side channel (effectively a spillway), directly on the rock base. This water finally reaches the drain, but with the flow peaks damped and the total flow peak substantially attenuated.

Other water retention structures

In addition to micro-dams, other intermediate settling boxes or small dams are constructed on the surface of the contributing mined basin, together with their servicing drains. While these have low capacity, they are very efficient for retaining rain-water and removing suspended solids.

Monitoring

In all main drainages rainfall is measured on a daily basis by local rain gauges. In addition, the height of water accumulated in front of the gabion-filter boxes is measured. These measurements demonstrate that the quantity of water received in the discharge drains has decreased very significantly, as shown in Fig. 8.

The reduction in water level is primarily the result of infiltration to the deep aquifer from the water pool in the micro-dams. The control of water flow has resulted in an important improvement in slope stability, in particular reducing the likelihood of landslides around the periphery of the bauxite mining area. In addition, the micro-dams have produced a total reduction in slope erosion accidents, and a very noticeable reduction in the contribution of solids in suspension to the drainage network.

In addition, piezometers were installed in micro-reservoirs to study the vertical filtration of stored water to the deep aquifer (Fig. 9).

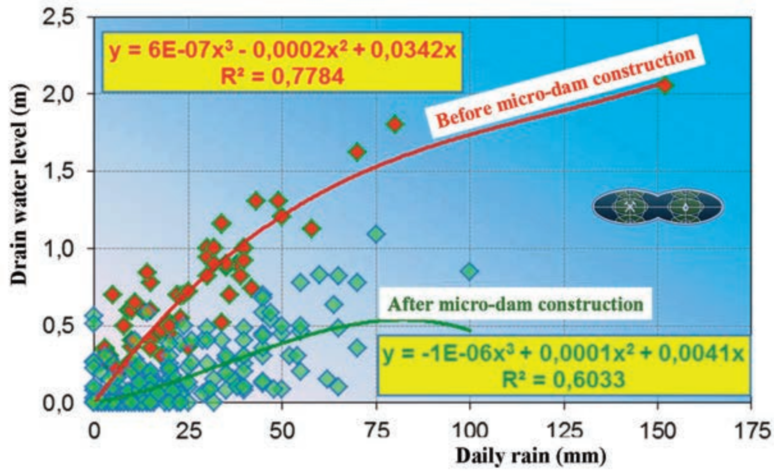

Fig. 8 Height of water next to the drain before and after the construction of the impoundments.

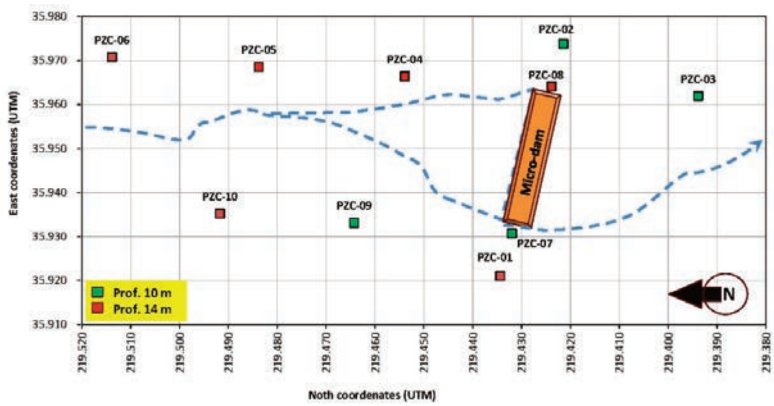

Fig. 9. Piezometers installed in micro-dam to study the vertical water infiltration.

Vegetal Cover

Another important aspect of micro-dams that was developed in this project is the reclamation of vegetation after mining. Revegetation comprising undergrowth, together with the planting of native forest trees was implemented, followed by the construction of "vegetal filters" immediately surrounding the drains, and placement of branches on drainage channels and in the vicinity of drains to provide surface stability and erosion protection.

Conclusions

A mini-dam program has been implemented in the Brazilian alumina mines in the Amazon basin to control the effects of very high rainfall. After three years of operation of the mini-dam program, they have been shown to be effective in reducing mine runoff and discharge, enhancing infiltration of water into the deep regional aquifer, and improving the stability of the plateau scarps surrounding the mined area. In this period no hydrological or environmental failures have occurred over the many kilometers of mine periphery along the edge of plateaus in operation or under rehabilitation.

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