Water Management of the Uranium Production Facility in Brazil (Caetité, BA). *Potential Impacts over Groundwater Quality*

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Abstract. The uranium unit of Caetité - in charge of all the "yellow cake" produced in Brazil - is located in the semi-arid Northeast region at Bahia State. The geological uranium content of the ore is 3000 ppm, which is mainly associated with albites (NaAlSi8O8), and its extraction is achieved by means of a Heap-Leach process. This process has a low water demand, which is supplied by a network of wells, but can contribute to change the groundwater quality and in some cases the extinguishing of wells was observed. The managing of liquid mining wastes formed by drainage waters from mine pit and solid waste piles is not enough to avoid unwarranted releases in the environment, which turn necessary the waste treatment through passing them into the industrial plant in order to reduce radionuclide concentrations. The groundwater is Na-HCO3 type water and relative high concentration of Cl are observed in some groundwater. It seems that levels of uranium in groundwaters are mainly a consequence of the complexation of the metal by carbonates (or other anions) and not by any sort of the contamination of these waters by the drainage accumulated in the open pit. The speciation modelling allows identifying some areas where the replenishment of the aquifer is more active, but in general the recharge is a fast process run by direct infiltration. The stable isotope data ($\delta\ ^{2}H$ and $\delta\ ^{18}O$) showed that evaporation plays a role during the infiltration, causing the groundwater salinization. These data discard the possibility that groundwater salinization was caused by discharge of deeper saline groundwater through faults associated to a regional groundwater flow system. The presence of an active shallow groundwater flow system offers better possibility for sustainable use of the groundwater resources in this semi-arid region of Brazil.

KEYWORDS: Uranium Mine; Water Management; Groundwater Contamination; Mining Wastes; Recharge.

1. Introduction

This paper provides some insight about the water management of the Uranium Production Unit and its potential impacts over the groundwater. The uranium unit of Caetité is located in the Semi-arid Northeast region at Bahia State. The extraction of uranium from the ore is achieved by means of a Heap-Leach process and the facility is currently in charge of all uranium production in Brazil. This process has a low water demand, which is supplied by a network of wells and from a dam, but can contribute to change the groundwater quality and in some cases the extinguishing of wells was observed.

The semi-arid region is characterized by a lack of superficial waters due to the low pluviometric precipitation and high evaporation rates. Owing to adverse climatic conditions with recurrent droughts, intense pressure is being put on the use of groundwater resources. However, there is still insufficient knowledge of the basic aquifers characteristics leading to an over exploitation of the water resources. The multiple uses of water and the potential conflicts between local communities and the uranium facility are very relevant issues that must be taken into account. The determination of the area of recharge is of course a major requirement for the evaluation of pollution risk associate to different land uses. For all types of aquifers in zones of internal drainage where the only discharge process is by evaporation, it is crucial to evaluate the diffuse discharge that produces soil salinization.

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The aim of this work is to examine the potential impacts of the wastes generated at the uranium mine of Caetité on the groundwaters, emphasizing the extent to which the composition of the ore, the operational process and the environmental conditions contribute altogether to the potential impact scenarios. One of the main contributions of this study stems from the fact that it is recognized that there are few new data on releases of radionuclides into the environment from uranium mining and milling operations. Most of the attention has been driven to the emissions of radon and very few studies have been giving attention to releases into water bodies during the past decades [1].

It is also reported [1] that for mining operations in semi-arid and arid areas, liquid waste releases are minimal, and radionuclide inputs through this pathway are evaluated as being of little consequence. As it will be showed in this paper, this belief is not necessarily true, and inaccurate information may lead international organizations and regulatory authorities to propose inadequate recommendations and regulatory requirements.

2. Site Description and Waste Characterization

2.1 Site Description

The Caetité plant is located in the central-southwestern region of Bahia state (latitude 13°56’36’’S and longitude 42°15’32’’W). The annual average precipitation rate is around 860 mm. The region is characterized as a semi-arid one. The geological uranium content of the ore is 3000 ppm and the average thickness of the ore body is about 7m. The uranium mineral is associated with albites (NaAlSi8O8). Thirty-five anomalies were identified in an area of about 1200km^2 [2]. Albitite (70%) is the predominant mineral, followed by pyroxene (10–20%), garnet (2–5%) and magnetite (1–3%). Pyrite is not present in the host rock.

The extraction of uranium from the ore is achieved by means of a Heap-Leach process. The ore crushing and the addition of a sulfuric acid solution, in the proportion of 15 kg$_{H2SO4}$ t^{-1} ore, piles containing between 25,000 and 35,000 t of ore are formed. Each pile is submitted to a three washing step cycle. The leached ore is encapsulated within the waste rock form mining operations to form a single unit.

The resulting solutions are collected in ponds where they are mixed in such a way that a final solution 2 gL^{-1} of uranium, as U3O8, is achieved. Uranium is extracted from this feed solution by means of an organic solvent that consists of 7% of tertiary amine, 3% tridecanol and 90% kerosene. Uranium is stripped with a NaCl solution from which it is subsequently precipitated by the addition of ammonium hydroxide solution The liquid effluent generated in the milling plant consists of an acid solution with high concentrations of other elements that have been dissolved along with uranium, as for example Al, Fe, Ca, Mg and Si. This effluent is treated with CaO to a pH of 8.0. The slurry is pumped to high density poly-ethylene (HDPE) lined ponds provided with drains that allow for the sedimentation of the solids in suspension. The supernatant is re-circulated to the process. Since the beginning of the operations, the original process was established as a closed circuit one with no liquid effluent being released into the environment under normal operation. However, intervening facts, which will be explained in the next section, drove the operator to seek for the possibility of releasing wastes in some scenarios with high rainfall in short-term events. For these aim, it were established derived limits for each radionuclide concentration in the wastes, which fulfill the dose restriction requirements for members of the public as demanded by the national regulatory authority.

2.2 Waste Characterization

Mining wastes can be divided into two categories: (1) solid wastes forming piles of associated material (waste rock and leached ore); (2) liquid wastes from the mine catchment drainages accumulated in the pit and also in some ponds and channels for the water management.

Annual rainfall rates in the semi-arid tropics usually amounts to between 500 and 900 mm. The potential evapotranspiration on the other hand is usually very high, approximately 1500–2000 mm. It is a highly seasonal environment with dry and wet seasons. The rainfall intensities are often high and erratic. If these ratios are taken in the long term a deficit in the water balance will be registered. However, a rainfall surplus develops during short-term events, i.e., monthly, weekly or daily. Hydrograph calculations on 3-month basis from a semi-arid region showed a surplus of 4mm while calculations based on daily intervals showed one of 200 mm [3]. Due to the soil and topography characteristics, the runoff is very high and infiltration is not enough to avoid massive transport during these high rainfall events. Under these conditions the drainage management system of a particular installation may not be able to hold the amount of water contributed to the mining and milling area and unwarranted discharges into the environment may take place.

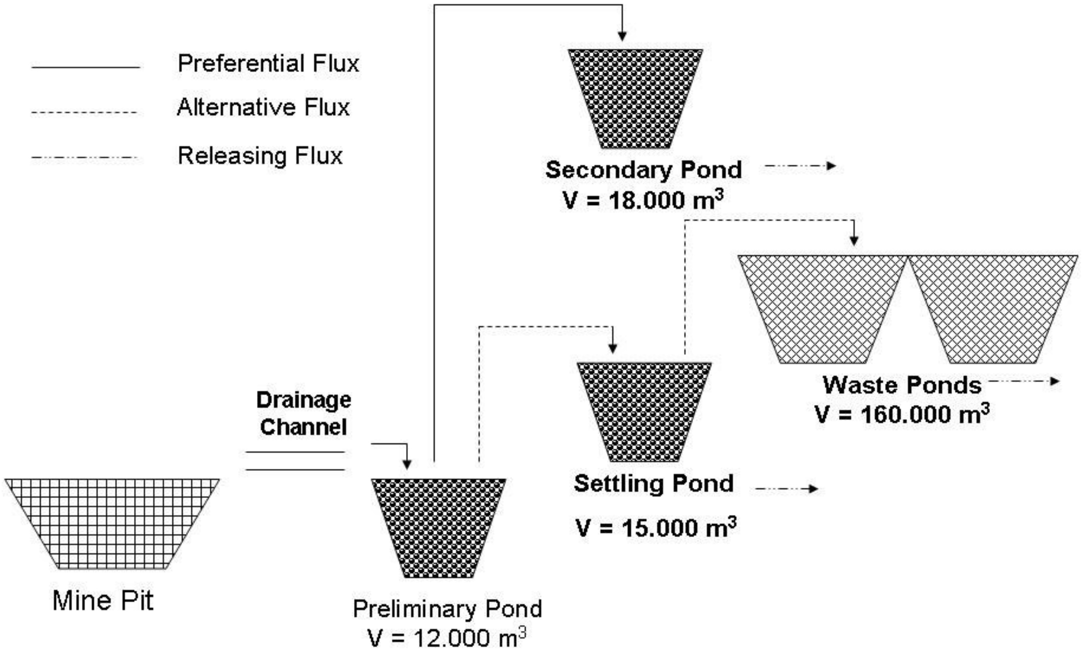
In the Caetité mining project it was assumed that the catchment area of the mine pit was $0.44km^2$. The original reservoirs of the site formed a simple drainage system composed only by a settling pond and a preliminary one with capacity smaller than 15.000 m^3. Since the beginning of operations the volume has been successively increased by adding another ponds or enlarging their capacities, actually reaching a total volume of 45.000 m^3 that could reach a volume higher than 200,000 m^3 if the waste ponds were used to receive drainage waters (Fig. 1). During heavy rainfall events the mine pit catches part of the drained waters and floods, leading to the interruption of mining activities. Despite the hydrological deficit in the long run, the operations cannot remain stopped waiting for water evaporation. As a consequence, this amount of water has to be pumped of from the mine pit and stored in the available holding ponds from where they could be released if their radionuclide concentrations are below the derived limits. However, as will be show in the next section, the uranium concentration of waters accumulated in the pit is usually much higher than the respective limit.

Table 1 shows the rainfall records from 2000 to 2006. It can be seen that approximately 70% of the annual rainfall are observed between November and March. Taking runoff rates in the range of 0.2–0.4 it can be roughly estimated that the amount of water contributed to the mine pit would fall in the range between 50,000 and $100,000m^3$. When the waste ponds in operation (see Fig.1) are completely full with liquids and solids, 160,000 m^3 must be subtracted from the overall available volume, leaving only $45,000m^3$ available for water retention. This amount is not enough to accommodate the water that needs to be pumped from the mine pit, even considering the three-fold capacity increase of the system.

Table 1: Month and Annual Precipitation at the Caetité site between 2000 and 2006.

Rainfall (mm)								
Month	2000	2001	2002	2003	2004	2005	2006	Average
January	87	108	157	163	332	177	0	146,3
February	158	17	138	5	245	123	69	107,9
March	95	175	17	17	174	99	126	100,4
April	79	38	14	73	32	21	93	50,0
May	87	67	17	12	5	29	17	33,4
June	95	36	23	3	6	23	15	28,7
July	17	23	0	14	6	21	8	12,7
August	66	14	11	20	0	8	3	17,3
September	64	38	117	9	0	8	2	34,0
October	78	105	3	8	58	24	108	54,9
November	186	65	40	120	247	104	235	142,4
December	363	73	248	96	76	52	37	135,0
Total	1375	759	785	540	1181	685	713	862,6

Figure 1: Drainage management scheme of the water management



The main mistake in water management was not to consider in a suitable way the water balance. Therefore, the time water in the pit would need to evaporate were not taking into account and so that by pumping these waters to holding ponds would make the available volume of these ponds be exhausted. Then, in order to solve these situations, the management system includes the waste ponds to allow the treatment of wastes through the flow of these waters into the industrial process to reduce uranium concentrations. If the processing waters result concentration below the limits, these wastes could be released. Thus, unauthorized discharges into the environment would be avoided if the water balance allowed the use of waste ponds to the drainage treatment. The worst case scenario for the treatment was adjusted to cope with a rainfall of 200 mm in three days.

3. Potential Impacts of Uranium Mining Wastes

The impact assessment from the milling wastes such as the reactive transport of nuclides from the waste ponds was already performed [4] by geochemical modelling. No significant impacts were identified for ^{226}Ra migration from the waste ponds, even if the geo-membranes (HDPE) were not regarded in this simulation. In the same study, it was made a preliminary evaluation of radium release from the leached ore, where this nuclide should be accumulated in larger amount, by means of the source volume routine of a computational code that estimated leach rates between 5.52 10^{-6} and 4.41 10^{-5} yr^{-1}.

Results from four monitoring wells were investigated, with the activity concentrations being showed in Table 2. Two of them are located just before and after the pit, respectively the wells PC18 and PC01. The other two are located far from the mine. The first one (LR211) is in a higher and flat area upward the pit (background area) and the second (PC20) is downward the mine in an alluvium channel of the Cachoeira Creek. ^{226}Ra and ^{210}Pb concentrations in groundwater near the pit are compatible to those observed in the reference (LR211) and downward (PC20) areas. This finding implies that there is no significant contribution from the drainages accumulated on the mine pit that can be assigned as influencing groundwaters. On the other hand, the elevated uranium concentrations in waters from PC01 in contrast with the low concentrations in the well just upward the pit (PC18), could suggest that the aquifer may be receives the contributions of drainage waters accumulated in the mine pit. Thus, this study will focus mainly on the uranium and the contribution of the drainage accumulated in the mine pit into groundwater.

Table 2: Activity Concentrations of U-nat (238+234), ^{226}Ra and ^{210}Pb in groundwaters.

Well	U-nat (Bq L^{-1})	^{226}Ra (Bq L^{-1})	^{210}Pb (Bq L^{-1})
PC01	7.66 ± 1.53	0.327 ± 0.0160	0,182 ± 0.019
PC18	0.66 ± 0.13	0.056 ± 0.0008	0.101 ± 0.016
PC20	0.15 ± 0.03	0.040 ± 0.0060	0.078 ± 0,014
LR211	0.12 ± 0.02	0.731 ± 0.0320	0.123 ± 0.018

3.1. Geochemical Modelling of Uranium and Recharge

It can be seen, from the results of radionuclides in water accumulated in the pit, presented in the Table 3 that uranium preferentially dissolves in relation to thorium, radium and lead. These high contents may be explained by the formation of carbonate complexes, associated with relatively high pH values [5]. These complexes largely replace the U (VI)- hydroxyl complexes above pH 6-7. The carbonate complexes are extremely important because they greatly increase solubility of uranium minerals, facilitate U (VI) oxidation, and also limit the extent of uranium adsorption in oxidized waters, thus increasing its mobility [6]. On its turn, carbonate species, like HCO_3^-, may result from the weathering during plagioclase evolution [5], which tends to form “new” dissolved inorganic carbon (DIC) in equilibrium with atmospheric CO_2. This could explain the recent ages of the carbonate as determined by ^{14}C DIC dating, which showed a nuclear explosion fingerprint [7] since the mid-20th century.

Table 3: Mean$^{(a)}$ radionuclide concentrations (Bq L^{-1}) and pH values in pit waters.

Station	U-nat	^{226}Ra	^{210}Pb	^{232}Th	^{228}Ra	pH
01 (n=16)	148.12 ± 29.65	0.44 ± 0.02	0.08 ± 0.03	0.08 ± 0.02	0.22 ± 0.05	8.1 ± 0.5
03 (n=12)	205.89 ± 42.41	1.39 ± 0.07	0.25 ± 0.05	0.07 ± 0.02	0.34 ± 0.18	8.0 ± 0.4

$^{(a)}$Dissolved concentrations in samples collected by the waste monitoring program along 2005

In order to investigate the potential role of carbonate complexation of uranium and discuss the probable process in charge of the elevated uranium concentrations in groundwater physical–chemical characterization of the waters from PC01, PC18, PC20 and LR211 (reference point) were taken. These values are presented in Table 4. The most outstanding differences between the composition of the studied waters have to do with the concentrations of bicarbonate, which are higher in PC01, PC18 and PC20 – all with neutral pH —and chloride, with higher concentrations in LR 211 that has acid waters.

The predominance of HCO_3^- and Na^+ ions is usual for fissured aquifers in geological settings formed by metamorphic fractured rocks with granite or gneissic composition, i.e. the significant sodium concentrations relies on the fact that the metal is a component of albite (NaAlSi3O8) which is present in the rocks of the study region. Groundwater salinization is mainly related to sources of sodium and chloride concentrated in the vadose zone. In this context, the groundwater coming from wells placed in shallower fractures should have higher salinity than others coming from deeper ones. On the other hand, the HCO_3^- ions may result from the weathering of the plagioclases as explained above.

Regarding also the Table 4 is easy to observe the huge difference between HCO_3^- in waters from PCs and the reference area (LR211). The reason for the difference may rely on the pH values found in both waters. In the first case the pH value is neutral (around 7,0) and drops to 4.8 in the second case. Thus, dissolution of inorganic carbon may be taking place during water percolation and should be reflected in the uranium speciation results as showed below.

Table 4: Chemical characterization of groundwaters from four monitoring wells

Chemical species (mg L^{-1})	PC01	PC18	PC20	LR211
Na	226.4	112.1	146.6	184.8
K	8.3	10.6	8.4	3.5
Mg	9.9	10.5	4.6	11.4
Ca	73.9	94.4	60.5	32.5
Ba	0.3	0.1	0.1	5.4
Mn	0.7	0.1	0.2	0.4
Fe	1.2	10,5	1.1	1.1
Al	0.2	0.2	0.2	0.3
SiO_2	49.6	31.3	47.1	80.7
PO_4	0.0	0.0	0.0	0.0
SO_4	23.2	7.7	14.5	2.3
NO_3	6.7	19.7	7.2	1.9
F	2.3	1.4	2.6	0.2
Cl	151.6	275.5	196.0	425.0
HCO_3	207.7	180.3	185.9	9.9
pH	6.6	7.2	7.1	4.8

Uranium speciation in samples of wells PC01, PC20 and LR211 was undertaken. The geochemical equilibrium modelling system MINEQL+ v. 4.6 [8] was used. The species distribution in PC01, considering the average value of pH, is showed in fig 2-A. It was only formed uranium aqueous complexes with carbonate, with dominance of moderately oxidized species. The results allow us to propose that the complexation with carbonates may be playing a very important role in the distribution of uranium in waters.

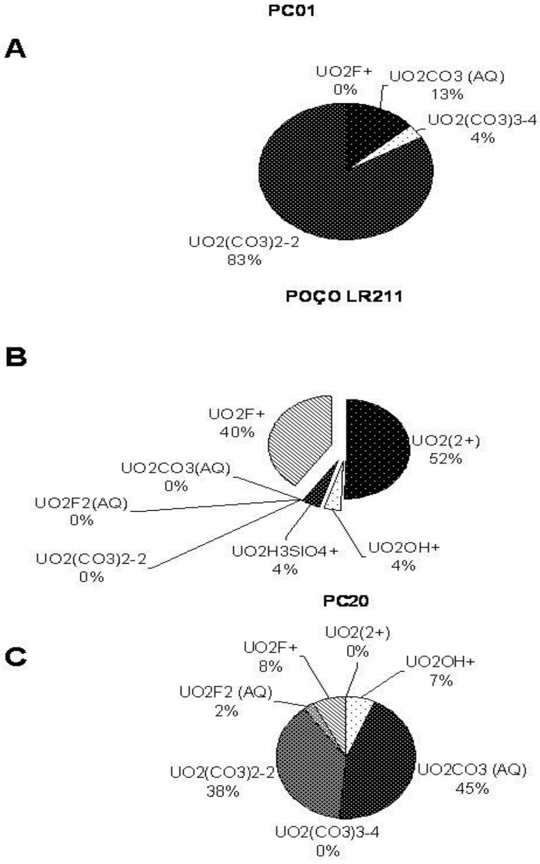
On the other hand, the other two wells showed speciation patterns more or least different from the previous one. The distribution of species from the reference well (LR211) is showed in fig 2-B. The dominance of free uranyl species (U-VI) points out for an open system characterized by exchange of gases in equilibrium with the atmosphere. Other important aqueous species are the uranium complexes with fluorides. Fluorides could be lately formed by sodium metasomatism (e.g. albite formation) and be disseminated in the weathering mantle.

The reference well (LR211) showed very clear behaviour from the others, probably because it is located in a recharge zone upward the mine. There is evidence for this assumption from the speciation findings and also from low value of pH in a hydrogeological setting marked by the presence of neutral waters typical of granites and gneisses. Other evidence comes from the high values of chlorides that have an origin associated with evaporation since rainfall events and after during percolation causing soil and groundwater salinization, as will be explained in section 3.3. Both conditions are related with rapid recharge process by macropores, which avoid attenuation of acid runoff and enhances the influence of soil solution on the groundwater geochemistry.

The well PC20 showed an intermediary distribution of uranium species (fig. 2-C) in relation with the first ones. The dominance turns again to carbonate complexes, with prevalence of redox equilibrate species. It was also observed, in minor amount, fluorides and hydroxides species. This result suggests the importance of the water-soil interaction to form complexes during the percolation in environments with faster recharge. In fact, this well is located in the alluvium fan of the Cachoeira Creek, which is supposed to constitute small reservoirs for the fissured aquifer, which are replenished during the rainfall period. In these systems, the recharge rate will be slower than the reference area, due to lower permeability of their tertiary-quaternary fine sediments, however much faster than the mine pit area.

It seems then elevated levels of uranium in groundwaters are mainly a consequence of the complexation of the metal by carbonates (or other anions) and not by any sort of the contamination of these waters by the drainage accumulated in the open pit would not be favoured.

Figure 1: Uranium speciation results from three wells (A) - PC01, (B) LR211 and (C) PC20



3.2. Uranium Activity Ratio and Isotopic Disequilibrium

The most useful characteristic of lithogenic nuclides in hydrology is that there are significant differences in isotopic compositions between different mineral types within the same rock or soil. This is because the ratios between the parent element (e.g. ^{238}U) and the daughter element (e.g. ^{234}Th) vary between the mineral phases within the rock or soil. Through geologic time the relative abundance of daughter nuclides will be different on each mineral phase [9].

^{238}U undergoes radioactive decay to produce ^{234}U through two very short-lived intermediate decays (^{234}Th with a half-live of about 24 days and ^{234}Pa with one minute half-live). ^{234}U (with half-live of 245,000 years) is also radioactive and decays to ^{230}Th. Over geologic time, equilibrium, termed secular equilibrium, is established between the production of ^{234}U from ^{238}U and the decay of the first. The uranium isotopes in any closed system will be in secular equilibrium after about five ^{234}U half-lives (about 1.25 million years). The equilibrium is generally discussed in terms of the activity ratio between the isotopes. For two nuclides to be in secular equilibrium, the ratio of their activities must equal one that means as many atoms area being produced as are decaying.

It has long been observed that the two uranium isotopes are seldom in secular equilibrium in natural waters [10]. The activity ratio $^{234}U/^{238}U$ is generally greater than one and values of 2 to 3 and up to 10 have been found. The cause of this is not entirely clear, although it is very likely a function of alpha decay process that produces ^{234}Th. The alpha particle is ejected from the nucleus with sufficient energy that the recoil of the atom (72 MeV recoil energy) causes damage to the crystal lattice, leaving a path or track along its trajectory. The length of the track will vary with material density, but it was estimated to be between 10 to 55 nm, with typical values around 30 nm [9]. The damage of the crystal provides an area of weakness from which the atom can be more easily leached by water. This may account for some of the enrichment of ^{234}U in the water, particularly in newly-recharged water with low uranium concentrations [11]. Another important consideration for $^{234}U/^{238}U$ disequilibrium is the redox condition of the groundwater. Under reducing conditions uranium is highly soluble and will tend not to enter into groundwater through leaching or dissolution processes. Therefore, under oxidizing conditions the $^{234}U/^{238}U$ ratios in groundwater would be expected to increase with time, whereas under reducing conditions the ratio would be expected to decrease with time [9].

The results of $^{234}U/^{238}U$ ratios and uranium concentrations of groundwaters collected at some wells and water samples from the mine pit are showed in the Table 5. The ratios varied in a restricted range from lower than unit (0,8) to around 1,7. The first remarkable fact may be observed for the waters accumulated in the pit which are have ratio close to the unit (1,07) and so the interconnection between these waters (in secular equilibrium) and the underlying groundwaters should not occur as can be demonstrated by the shift from the ratio (1,7) of the well just upward the pit (PC18). This finding is in agreement with the uranium speciation. The reason of the pit waters are in equilibrium for uranium activity ratio can be explained by its origin in precipitation. Thus, the resulting runoff could remove only the uranium portion sorbed in particles deposited on the rocks and not the uranium enclosed in them. This detrital uranium has a portion of "recoil ^{234}U" from rocks that tends to drop with the age of the deposit once alpha recoil has very limited effects on sorbed minerals. For the same reason, the wells located near recharge zones (PC74, PC23, PC05) presented lower ratios than PC18 and PC113, showing that uranium aqueous species in the first ones were formed from a mixing of sources between detrital uranium and dissolution of uraninite from rocks, while in the second group the uranium source is mainly related with the uraninite dissolution by water-rock interaction.

Table 5: $^{234}U/^{238}U$ activity ratio and concentrations of uranium in waters

Station	U-nat (Bq L^{-1})	$^{234}U/^{238}U$ activity ratio
PC01	7.66 ± 1.53	0.83
PC05	0.61 ± 0.43	1.23
PC18	0.66 ± 0.13	1.73
PC23	0.13 ± 0.08	1.28
PC74	0.14 ± 0.00	1.19
PC113	0.23 ± 0.06	1.70
Area 03	285 ± 356	1.07

On the other hand, the ratio of the well just downward the pit (PC01) was below the unit, meaning an impoverishment in ^{234}U greater than expected. Its high uranium concentrations had been discussed before in the section 3.1, however, such low value of PC01 (0,8) is not usually found in studies of uranium disequilibrium in groundwater [12]. This could be explained by anthropogenic reasons caused by the continuous pumping of the well during several years. This certainly lowered the water level of the aquifer and during the rain period the groundwater flow should selectively remove the oxidized ^{234}U from the exposed rock. Thus, the occurrence of successive events of prolonged lowering and quick flow should give place to a huge impoverishment. Such behaviour has already been identified in coastal aquifers subject to glacial-interglacial ocean level change [13].

3.3 Evaporation and Groundwater Salinization

The δ ^{18}O vs. δ ^{2}H relationship allow to understand how the isotopic signal from the precipitation is transferred to the groundwater and to evaluate the role of evaporation during recharge events. Groundwater can be lost by evaporation or transpiration from runoff or during infiltration in the unsaturated zone. Both evaporation and transpiration are possible causes for groundwater salinization, but only the first process causes a shift in the isotope composition of the water [14]. During summer storms, convective rains can suffer strong evaporation during flow over the hot landscape. The slope of these evaporative enrichments for semi-arid regions is usually between 4 and 6, defining a local evaporation line [15] that is different than the Local Meteoric Water Line (LMWL). For this study, due to the lack of on-site data, the isotope precipitation data [16] from Salvador (Figure 5), located 800 km far away from the study area was used to construct the meteoric water line. However, it is possible that precipitation in Caetité has a lower slope than Salvador (s = 7,4) and a greater deuterium excess due to evaporation affecting the rains. The groundwater data showed clearly an evaporative enrichment pattern with slope equal to 5.5, defining a local evaporation line (Figure 3). The average evaporative loss was calculated to be around 22 %. These data showed that evaporation is playing a role in the salinization of the groundwater.

Figure 3: Stable water isotope data for local meteoric and ground waters

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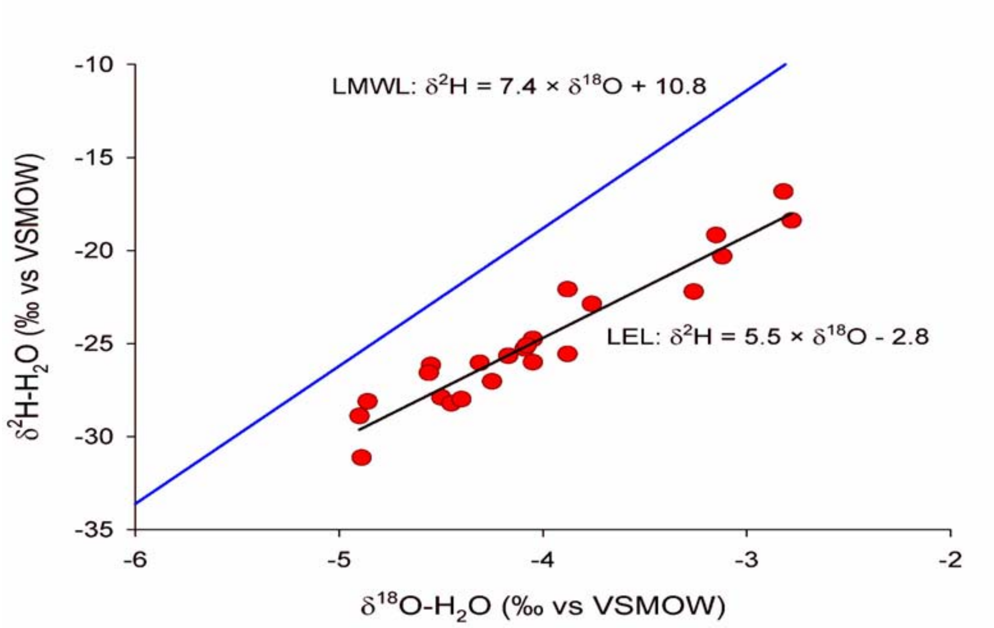

Conclusions

This paper provides some insight about the water management of the Uranium Production Unit and its potential impacts over the groundwater. The main findings of this work are:

i) The managing of liquid mining wastes formed by drainage waters from mine pit and solid waste piles is not enough to avoid unwarranted releases in the environment, which turn necessary the waste treatment through passing them into the industrial plant in order to reduce radionuclide concentrations.

ii) The groundwater is Na-HCO3 type water and relative high concentration of Cl are observed in some groundwater. It seems then that elevated levels of uranium in groundwaters are mainly a consequence of the complexation of the metal by carbonates (or other anions) and not by any sort of the contamination of these waters by the drainage accumulated in the open pit, although these waters generally should not be released to the environment because of high uranium concentrations derived by uranium mining activities.

iii) The speciation modelling allows identifying some areas where the replenishment of the aquifer is more active, but in general the recharge is a fast process run by direct infiltration. The stable isotope data ($\delta\ ^2H$ and $\delta\ ^{18}O$) showed that evaporation plays a role during the infiltration, causing the groundwater salinization. These data discard the possibility that groundwater salinization was caused by discharge of deeper saline groundwater through faults associated to a regional groundwater flow system. The presence of an active shallow groundwater flow system offers better possibility for sustainable use of the groundwater resources in this semi-arid region of Brazil.

iv) This work stresses the need for integrated approach between environmental impact assessment and radiation safety, in which radiological and non-radiological aspects are to be addressed simultaneously. If regulators do these evaluations in a separated form, the interactions between the relevant process in the mobilization and transport of radionuclides from the source to the receptors may be lost.

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