Integrating Hydrogeological and Geophysical Modeling for Sustainable Water Management in Phosphate Mining: A Case Study of the Beni Amir Deposit, Morocco

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Abstract

Mining operations below the water table poses critical groundwater management challenges, particularly in semi-arid regions like Morocco's Beni Amir phosphate deposit, where water volumes partially or completely submerge phosphate layers. A multidisciplinary study integrating Electrical Resistivity Tomography (ERT), Magnetic Resonance Sounding (MRS), and hydrogeological data from 580 wells and 692 boreholes characterized groundwater conditions. Findings indicate 73% of the deposit is at least partially submerged. Combined geophysical and hydrogeological analyses delineated aquifer geometry and hydrodynamic properties, identifying submerged phosphate layers and multi-aquifer systems. This approach provides detailed insights for optimizing dewatering strategies, aiding sustainable groundwater management in mining operations.

Keywords: Groundwater management, submerged phosphate layers, Electrical Resistivity Tomography (ERT), Magnetic Resonance Sounding (MRS), aquifer characterization, dewatering strategies.

Introduction

Water management is a critical challenge for the global mining industry, particularly in water-stressed semi-arid regions like Morocco 's Oulad Abdoun Basin (Bahir *et al.* 2020). As a leading phosphate producer (Lee *et al.* 2023), Morocco, faces complex hydrogeological challenges in the Beni Amir deposit (Fig. 1), where mining operations often encounter water-saturated layers.

In open-pit mines below the static groundwater level, groundwater inflows from surrounding strata (Bahrami *et al.* 2014) can impede production, increase equipment failures, compromise slope stability, increased explosive usage and create hazardous working conditions. These challenges demand efficient dewatering strategies to maintain safe and stable operations (Unsal and Yazicigil, 2016), particularly as mining advances from the northern zones to deeper submerged southern sections in the Ben Amir deposits. To provide safe and stable conditions for mining during the operational period (Unsal and Yazicigil, 2016), developing an efficient dewatering system is necessary, with groundwater level prediction playing a crucial role in its design (Najafabadipour *et al.* 2022). Effective dewatering operations is directly linked to an understanding of the geological structure and hydrogeological systems that govern water movement within the deposit (Morton and van Mekerk 1993). Traditional hydrogeological characterization methods often prove insufficient in sedimentary environments like phosphate deposits. ERT provides high-resolution lithological contrasts (e.g., distinguishing dry from saturated zones), while MRS directly quantifies hydraulic parameters, critical data unobtainable from sparse boreholes alone. To address this gap, geophysical methods such as Electrical Resistivity Tomography (ERT) and Magnetic Resonance Sounding

(MRS) are increasingly used to investigate near-surface conditions (Gomo *et al.* 2024) and groundwater pathways (Villain *et al.* 2011). The integration of these methods, combined with conventional geological and hydrogeological data help delineate aquifer geometry, identify submerged phosphate layers, and assess hydrodynamic parameters. This integrated approach is particularly relevant in North Africa, where research on hydrogeological processes in phosphate mining regions has been limited. This study integrates geophysical, geological, and hydrogeological data to improve groundwater characterization in the Beni Amir phosphate deposit. By combining conventional and advanced techniques, it aims to enhance water management strategies, providing mining operators with better tools for sustainable resource extraction.

Geological & Hydrogeological setting of the Study area

The Beni Amir deposit is situated within the Oulad Abdoun phosphate basin, located in Morocco's western Meseta structural region. The deposit measures approximately 22.5 km east to west and 8 km north to south, representing one of 13 phosphate deposits (Fig. 1) in the basin ranging from Late Cretaceous to Eocene age. The stratigraphic sequence of the basin comprises five main lithological units: (i) Cenomanian series of alternating marl and limestone, (ii) Turonian series of dolomites and massive limestones with occasional marly intercalations and karst features, (iii) Senonian series primarily of marl from the Coniacian to Campanian age, (iv) Maastrichtian to Ypresian series containing phosphate beds and barren interbeds, and (v) Lutetian series of marine biocalcarenites within the "Thersite slab"(Moutaouakil and Giresse 1993). The exploitable phosphate series in Beni Amir consists of multiple layers (Tab.1): Layer 3 (marl matrix-rich), Layer 2 (Danian-Thanetian loose phosphates), Layer 1 (two-part structure of loose and marly phosphates), Layer 0' (loose to indurated phosphates), Layer 0 (loose to calcified phosphates), and Furrows A and B (characterized by loose, coarse to fine-grained phosphates). Hydrogeologically, four main aquifers characterize the region: the Mio-Plio-Quaternary, Eocene, Senonian,

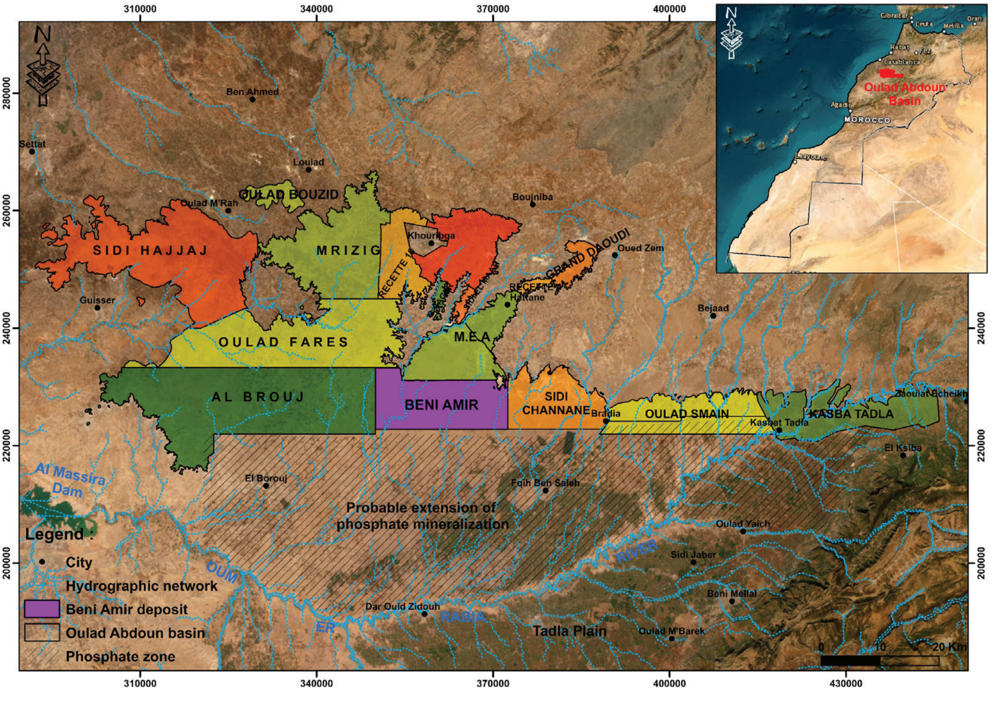

Figure 1 Map showing the location of the Oulad Abdoun phosphate basin and the Beni Amir deposit.

and Turonian aquifers. Unlike the northern and central parts of the Oulad Abdoun basin, the Beni Amir deposit, along with other southern deposits (EL Brouj, Sidi Chennane, Oulad Smain, and Kasba Tadla), regularly encounters water table interactions with phosphate layers.

Methods

The study employed an integrated methodology to assess submerged areas and hydrodynamic parameters in the Beni Amir phosphate deposit, combining multiple data sources and advanced geophysical techniques. The research utilized 580 piezometric measurements collected during September–October 2023 and elevation data from 694 drilling operations, with ERT profile and MRS surveys conducted in data-scarce locations identified during field reconnaissance.

Conceptual model of the study area

A comprehensive conceptual hydrogeological model was developed using Visual Modflow Flex 9.0, serving as a foundation for future numerical groundwater flow model. This approach involved defining the study area through polygon data, interpolating phosphate layer boundaries using drilling data, and creating three-dimensional geological zones. The resulting model (Fig. 3) illustrates the intersections between phosphatic layers and the piezometric level, delineating the deposit's drowned and dry zones.

Electrical Resistivity Tomography (ERT)

ERT was utilized to map subsurface structures by measuring electrical resistivity distribution (Loke *et al.*, 2021). The ERT survey employed Syscal Pro Switch equipment with six multi-core cables, featuring 16 electrodes spaced 5 meters apart and using an inverse Wenner-Schlumberger array to achieve investigation depths of 70–80 meters. Data processing involved filtering through ProsysIII software and inversion using RES2DINV, with root mean square errors maintained below 15%. Final visualization and validation were accomplished using Surfer 13, integrating borehole and piezometric data to ensure comprehensive hydrogeological characterization.

Magnetic Resonance Sounding (MRS)

Complementing the ERT, MRS detects groundwater by measuring nuclear magnetic resonance signals from hydrogen atoms (Legchenko *et al.*, 2002). Using a NUMIS Plus system with a 100-meter square loop antenna, we transmitted currents at the local Larmor frequency (1758.41 Hz at 41,276.15 nT) to excite subsurface water molecules. The resulting relaxation signals (16–20 pulse moments, 80–120 stackings) were processed through Samovar software using notch and bandpass filters to determine the volume of free water content and estimate permeability to 100 m depth.

Results & Discussion

The conceptual model (Fig. 2) developed by integrating piezometric map with phosphatic layers, provides detailed insights into subsurface structure and water distribution. Submersion patterns (defined as layers below the water table) vary across phosphatic layers. Some layers are fully submerged, while others remain partially or completely dry. For instance, Layer 3 (Maastrichtian), shown in Fig. 2(a), is 46.88% submerged, while Layer 2, depicted in Fig. 2(b), has 29.4% submerged. In contrast, Layer 1, shown in Fig. 2(c), is predominantly dry with only 13.3% submerged. Layer 0'and Layer 0, illustrated in Fig. 2(d) and Fig. 2(e), shows a gradual reduction in submerged areas, with 10.9% and 5.2% submerged, respectively, leaving the majority of their extents in dry zones. Finally, the Furrow A/B layers (Fig. 2(f)) exhibit minimal submersion, with dry zones dominating. The conceptual model highlights a southward slope of the phosphate layers, where the deposits increasingly submerge into the Beni Amir aquifer. A cross-section from east to west (Fig. 2), located in the southern part of the deposit and based on the generated 3D model, shows that the piezometric level is above most phosphate layers, indicating extensive submersion in this region. The aquifer primarily lies in the central study area, fully covering most deposits, while the water table only partially intersects Layer 3 in the western and northwestern regions. These variations in water distribution and submersion present significant implications for mining operations, particularly as they necessitate tailored water management strategies.

To assess the geometry and hydrodynamic properties of the aquifer, an Electrical Resistivity Tomography (ERT) profile and a Magnetic Resonance Sounding (MRS) surveys were conducted in the southern region where the data is scares (Fig. 3 and Fig. 4). The ERT profile, spanning 795 meters from East to West, reveals subsurface structure variations: a high-resistivity zone (>460 ohm·m) in the upper 10 meters corresponds to Lutetian limestone formations, followed by a medium-resistivity band (50–150 ohm·m) linked to dry Ypresian formations. A near-surface conductive zone suggests the presence of a recharge area or a shallow aquifer, possibly influenced by a nearby stream. Deeper low-resistivity zones indicate wet marl, clay, and phosphate facies from Maastrichtian formations, with localized high-resistivity zones interrupt these conductive layers, suggesting the presence of limestone blocks or geological disruptions.

Building on the insights from the ERT profile, the MRS surveys provided complementary hydrogeological data by quantifying the volumetric water content and permeability at different depths. Since MRS directly measures free water content, the results primarily represent the saturated zones within the formations. The estimation of hydraulic conductivity (*K*) was derived from the relaxation time, which serves as a proxy for pore size distribution. At MRS Site 1, located in the eastern part of the deposit, the inversion results reveal three

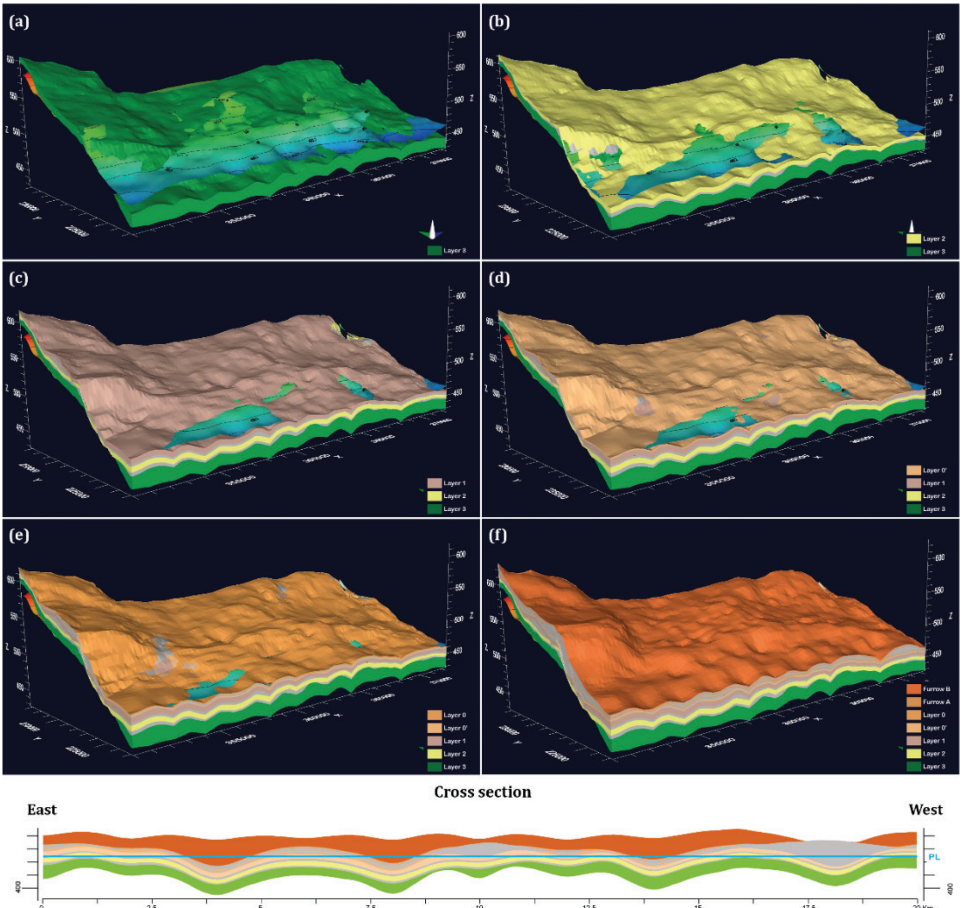

Figure 2 *Conceptual model showing the dry zone and drowned zone of each phosphatic layer starting from the bottom ((a): Layer 3 to the top (F): Furrow A/B) within the Beni Amir deposit.*

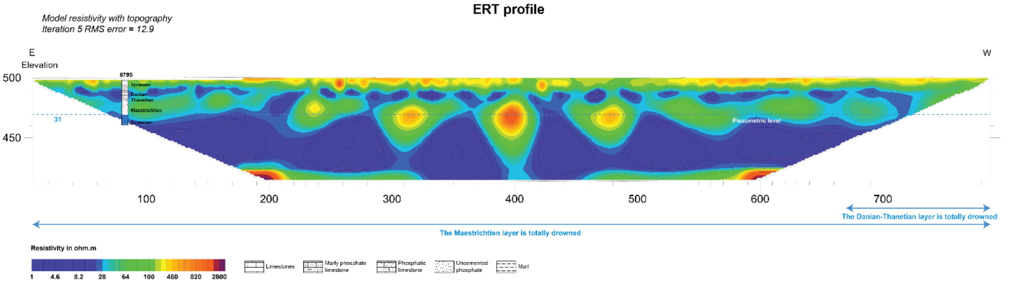

Figure 3 *Model resulting from ERT data inversion calibrated to lithological boreholes columns. The dashed blue line indicates the on-site measured piezometric level.*

distinct saturated zones. The first aquifer, associated with the Ypresian formation, lies between 4 and 18 meters depth and exhibits a water content of 0.3% with a permeability of 1.5 × 10^{-5} m/s. Below this, the primary Maastrichtian aquifer is found between 32 and 50 meters depth, with a water content of 0.9% and a permeability of 3.9 × 10^{-5} m/s. These results align well with a nearby borehole located 400 meters from the MRS site, which confirms the water level at approximately 35 meters. Deeper still, a third aquifer associated with the Senonian formations spans from 50 to 102 meters depth, with a water content of 0.6% and a permeability of 2.9 × 10^{-5} m/s. At MRS Site 2, three aquifers were identified. The first two occur within the Danian-Thanetian and Maastrichtian formations and are located between 16–20 meters and 20–35 meters depth, respectively. These aquifers exhibit water contents ranging from 1.2% to 1.9% and a permeability of 7.3 × 10^{-4} m/s. The third and deepest aquifer, associated with the Senonian formation, extends from 35 to 100 meters depth. It shows a higher water content of 2.9% and a significantly elevated permeability of 1.9 × 10^{-3} m/s, likely influenced by its proximity to a stream. The observed water levels at this site correspond well with the piezometric map, although borehole logs indicate a slightly deeper water level. In the southeastern part of the

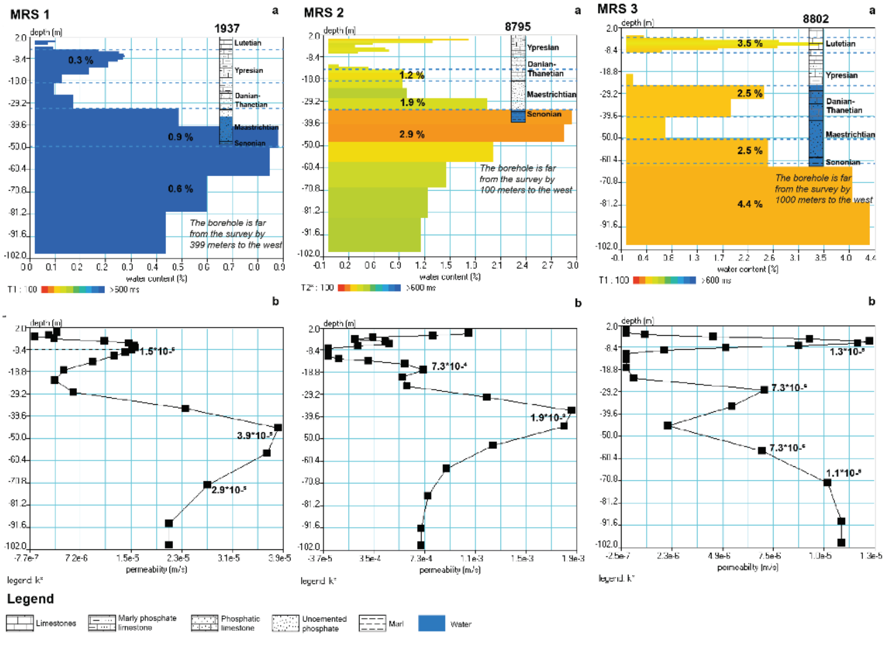

Figure 4 *MRS data measured in the deposit (a) Model resulting from MRS data inversion and its correlation with the hydrogeological column;(b) Permeability curves versus depth.*

Table 1 Synthetic table of the various divisions of the phosphate series of Beni Amir.

Chronostratigraphic division			Mining division
Era	Period	System	
		Lutetian	Cover layer
Tertiary (Cenozoic)	Eocene		Furrow B
			Furrow A
			Layer 0
			Layer 0′
		Ypresian	Layer 1
	Paleocene	Thanetian - Danian	Layer 2
Secondary (Mesozoic)	Upper Cretaceous	Maastrichtian	Layer 3

deposit, MRS Site 3 reveals the presence of multilayered aquifers. A shallow aquifer lies between 4 and 10 meters depth, with a water content of 3.5% and a permeability of 1.3×10^{-5} m/s. Beneath this, an aquifer located between 25 and 62 meters depth features an impermeable layer between 40 and 50 meters, associated with the upper part of the Maastrichtian formation. This intermediate aquifer, linked to the Danian-Thanetian and Maastrichtian phosphate layers, has a water content of 2.5% and a permeability of 7.3×10^{-6} m/s. The deepest aquifer, situated between 62 and 100 meters, lies within the Senonian formation and exhibits a higher water content of 4.4% with a permeability of 1×10^{-5} m/s. This aquifer demonstrates relatively higher permeability compared to the overlying phosphate layers. Notably, the water levels in this area align well with both borehole logs and the piezometric map, further validating the findings.

Conclusions

The study highlights the critical groundwater challenges faced in Morocco's Beni Amir phosphate deposit, where 73% of the area is partially submerged. By integrating geophysical techniques, such as ERT and MRS, with geological and hydrogeological data, the research provided a detailed understanding of aquifer geometry and hydrodynamic properties. Geophysical methods significantly enhanced the conceptual model by revealing multi-aquifer systems, impermeable layers, and direct measurements of volumetric water content and permeability, which traditional hydrogeological techniques could not provide. Developing conceptual models, especially for complex multi-layered sedimentary systems, is crucial for understanding the subsurface, and the 3D stratigraphic model created here offers valuable insights for future investigations. The study also highlights that the phosphate layers in the Beni Amir area slope southward under the Tadla plain, becoming gradually covered by the Beni Amir aquifer, with thickness variations from north to south. These findings will help optimize dewatering strategies, mitigate groundwater impacts, and inform sustainable resource management. This work supports global efforts in phosphate mining by enhancing our understanding of the hydrogeological and geological interactions, contributing to more effective groundwater management strategies in semi-arid regions.

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