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Sustainable water management in the Jordanian phosphate mining industry

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Abstract

Jordan is a very water stressed country with very low annual renewable water resources per capita. The effluent wastewater from two Jordanian phosphate mines (the Al-Abiad and the Eshidiya mine) was analysed and compared with the national and international standards and regulations for irrigation and industrial effluent wastewater. The water management at the mines was examined from a sustainable management point of view, to achieve the SDGs in Jordan. The effluent water was high in salinity at both mines, mainly because of the high chloride concentrations. Some heavy metals were over the guidelines by FAO and the Jordanian standard and the effluent water did not meet the water quality requirements for irrigation or discharge into surface water. The phosphate mining industry brings economic benefits to society, including the provision of regional employment and the generation of wealth, and will continue to be an important part of Jordan’s economy and development. But, the mining is not sustainable in the way it is operated. Investment in the effluent wastewater treatment needs to be done, in order to reach a sustainable water management.

Sammanfattning

Jordanien är ett land med mycket hög vattenbrist och med mycket låga årliga förnybara vattenresurser per capita. Avloppsvattnet från två jordanska fosfatgruvor (Al-Abiad- och Eshidiya-gruvan) analyserades och jämfördes med nationella och internationella standarder och regler för bevattning och utsläpp av industriellt avloppsvatten. Vattenhanteringen vid gruvorna undersöktes ur ett hållbarhetsperspektiv för att uppnå FN:s hållbarhetsmål för Jordanien. Båda gruvorna hade höga salthalter i det utgående avloppsvattnet, detta främst på grund av de höga kloridkoncentrationerna. Även vissa tungmetaller överskred riktlinjerna från FN och den jordanska standarden, avloppsvattnet uppfyllde därför inte kraven på vattenkvalitet för bevattning eller utsläpp till ytvatten. Fosfatgruvindustrin medför ekonomiska fördelar till samhället, inklusive sysselsättning på regional nivå och generering av välstånd för landet. Industrin kommer att fortsätta vara en viktig del av Jordaniens ekonomi och utveckling men gruvdriften är inte hållbar på det sätt den bedrivs idag. Investeringar i rening av utgående industriellt avloppsvatten behöver göras för att uppnå en hållbar vattenhantering.

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1 Introduction

In a world where the population continues to increase, and with it, food and water demand, the water-energy-food nexus will continuously be challenged (Emeish, Au-Arabi, Hudaib 2012). The industrial, agricultural, and domestic sectors are all demanding more water and other resources, which presents great challenges now and in the future. The World Resources Institute (WRI) (2019a) has found that water withdrawals have more than doubled globally since the 1960s as a result of growing demand and their models show no signs of slowing. The United Nations (UN) estimates that approximately 1.9 billion people live in water-scarce areas and that this number will increase to approximately 3 billion by 2050 (WRI 2020) if current trends continue.

The Hashemite Kingdom of Jordan is developing rapidly, with a rapid population growth which has doubled since 2000, now reaching 11.3 million people (World Bank 2024), and is expected to almost double again by 2050 (Saidan, Al-Addous, Al-Weshah, Obada, Alkasrawi and Barbana 2020). The significant development over the last decades of the Jordanian economy has brought prosperity to the country. This has, however, with the population growth, had an adverse impact on the environment, natural resources, and possibly also on the population's health (Mohsen and Jaber 2002). The water demand is expected to exceed the available water resources by more than 26% by 2050 (Saidan, et. al. 2020).

Jordan is one of the most water-stressed countries in the World (WRI 2019b, Aljaradin and Bashitialshaaer 2017), with one of the lowest available water supplies in the World, on a per capita basis. The Syrian crisis has led to an extreme increase in population, with 1.36 million Syrian refugees, placing additional pressure on the Kingdom's already limited resources (Ministry of Planning and International Cooperation [MoPIC] 2020). Other tensions and hydro-political disputes in and with neighbouring countries have also affected the situation in Jordan (Abu Qdais, Abdulla, and Kurbatova 2019).

Jordan is a small Middle Eastern developing economy, which is classified as a “medium human development” country by the United Nations Development Program. Phosphate and potash are dominating the Jordan mining industry, with 40% and 60% of revenues in 2018, respectively. These minerals have been a significant generator of economic growth and national income since Jordan’s independence in 1946. The mining industry represented 2.9% of the gross domestic product (GDP) in Jordan in 2022 (Central Bank of Jordan [CBJ] 2024).

Phosphorus is a limited resource and essential for plant growth, hence mined to produce fertilizers to meet the increasing food demand. The mining of phosphate damages the environment and leaves a scarred landscape behind when mined close to the surface. About 25% of the mined phosphorus ends up in aquatic environments or buried in landfills or other sinks. (World Health Organisation [WHO] vol 1 2016, Morse, Brett, Guy and Lester 1998, Emeish, Au-Arabi and Hudaib 2012).

Jordan is the world's fifth largest exporter of phosphate (Pistilli 2020), and the production consumes large quantities of Jordan's limited freshwater.

Maybe the most significant impact of mining is its effect on water quality and availability of water resources within the mining area. Key questions are whether surface and groundwater supplies will remain fit for human consumption, and whether the quality of surface waters in the mining area will remain adequate for native aquatic life and terrestrial wildlife (Alliance Worldwide [ELAW] 2010). Increased mining could lead to an increase in wastewater discharges, causing even greater loads of pollutants discharged into the environment (Al-Hwaiti, Brumsack and Schnetger 2015).

1.1 Aims and Objectives

This work aims to perform a Minor Field Study (MFS) as a Master thesis at the Department of Water Resource Management at the Faculty of Engineering, Lund University. The purpose of this MFS is to get a deeper understanding and to study the phosphate mines in Jordan, and how they affect the local, regional and national society.

This thesis aims to answer the following problem statement:

- How is the mining of phosphate in Jordan affecting the local, regional and national society?
- How polluted is the effluent wastewater from the phosphate mines?
- What is the aquatic pollution from the Jordanian phosphate mines relative to the discharge demands in Jordan and the UN?
- How does the phosphate mining business impact economic, social, and environmental sustainability?

A water quality analysis will be performed to find the pollutant content in the wastewater to be compared with local and international standards and regulations. A literature study of recent reports and studies of the mines and their effluent wastewater will be conducted. Reports about the environmental and public health impact of phosphate mines will also be studied.

The result of the MFS has been written in the format of a master thesis report which will be presented as an oral presentation at the Department of Water Resource Management (TVRL), LTH, Lund University and will be open to the public. The finished report will be submitted and available at the official database at LTH, Lund University, and the higher education council's webpage regarding MFS. The paper will also be distributed to the professors, the phosphate company, organizations, and other important people, that I have come across during my fieldwork.

1.2 Limitations

This report focuses on industrial effluent wastewater from two phosphate mines in Jordan. The sampling occurred three times, one at the Eshidiya mine and two at the Al-Abiad mine. The conclusions of this thesis are drawn from 1-2 snapshots of the effluent water. The work has been limited to 3 samplings due to limitations in financial resources and time. Other obstacles during the work were limited Internet access in Jordan, limited resources in lab equipment and failing equipment, language barriers and cultural differences.

2 Background

2.1 Sustainable Development

Today, in January 2024, it is 31 years since the UN Conference on Environment and Development in Rio de Janeiro took place, and it is 36 years since the Brundtland Commission Report (Our Common Future) introduced the concept “sustainable development” to a broader public, and it is 51 years since the first UN conference on Environment took place in Stockholm.

Sustainable Development has been defined in many ways, but the most commonly quoted definition is from Our Common Future (1987): *Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*.

Sustainable Development is based on three fundamental pillars: the environmental, the economic and the social. How they are interrelated is widely discussed but to achieve sustainable development you need to consider all three. The three pillars are creating the foundation for us to meet the needs of today and the future (Our Common Future 1987, International Institute for Sustainable Development 2024 and Hedenus, Persson and Sprei 2018). The environmental pillar is about preserving nature's production capacity and not exceeding nature's assimilation capacity. The economic pillar consists of efficient and long-term management of finite natural resources and human-saved capital. The social pillar consists of well-functioning horizontal relations (in forms of social capital, or trust), and vertical relations (in forms of formal institutions) (Hedenus, Persson and Sprei 2018).

2.2 Water stress

The European Environment Agency (EEA) defines water stress as when the water demand exceeds the available amount during a certain period or when poor quality restricts its use. Water stress causes the deterioration of freshwater resources in terms of quantity (aquifer over-exploitation, dry rivers, etc.) and quality (eutrophication, organic matter pollution, saline intrusion, etc.) (EEA 2024).

The Baseline Water Stress measures the ratio of total water withdrawals to available renewable water supplies. Water withdrawals include domestic, industrial, irrigation, and livestock consumptive and non-consumptive uses. Available renewable water supplies include surface and groundwater supplies and consider the impact of upstream consumptive water users and large dams on downstream water availability (WRI 2019b). The freshwater is a scarce commodity in Jordan. The World Resource Institute (WRI) classifies the

Baseline Water Stress as extremely high or high for all of Jordan, see Figure 1 (WRI 2019b).

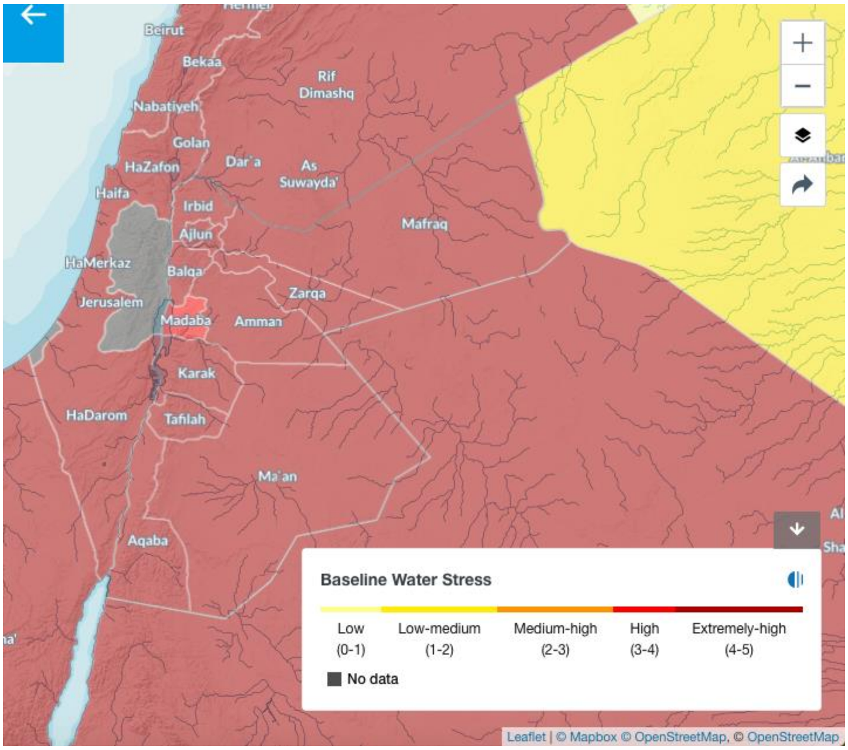

Figure 1. WRI classification of Baseline Water Stress for Jordan (WRI 2019b).

On the 7th of November 1999, H.M. King Abdullah II of the Hashemite Kingdom of Jordan stated, "*Our water situation forms a strategic challenge that cannot be ignored. We have to balance between drinking water needs and industrial and irrigation water requirements. Drinking water remains the most essential and the highest priority issue*". H.M. King Abdullah II here addresses a very important issue and challenge for the Middle Eastern Kingdom (Ministry of Water and Irrigation [MWI] 2016a). Jordan is a monarchy where power is largely concentrated in H.M. King Abdullah II. The king has a strong influence over politics and social development, including the final say in all exercises of power (Utrikesdepartementet 2019).

Jordan is one of the most water-stressed countries in the World (WRI 2019b, Aljaradin and Bashitialshaaer 2017), with one of the lowest available water supplies in the World, on a per capita basis. The annual per capita water budget is about 160 cubic meters per person per year, which could be compared with 400 cubic meters per person per year for Israel and 950 cubic meters for Egypt (Nazzal, Mansour, Al Najjar, McCornick 2000 and Ammary 2007). Thus, the renewable water resource share is only about 60 cubic meters per capita per year, which is far less than the 500 cubic meters that is internationally recognised as the absolute water scarcity line (MWI 2023). Jordan faces increasing deterioration in the quality and quantity of its water resources (MWI 2014). The country receives about 75 mm of rainfall annually, with regional variations, the southern part receives about 50 mm, and the northeast mountain part about 600 mm (Nazzal, et al. 2000). Approximately 92.2% of the rainfall evaporates, 5.4% recharges the groundwater and the rest, 2.4%, becomes surface water (Ammary 2007). These hydrological parameters have forced Jordan to be economical with its water resources but also be innovative and create different ways to cope with the water shortage. Jordan has considered several options that include elements of supply expansion and demand management. Over-abstraction of the groundwater above the safe yield is one supply expansion option. In 2017 the annual safe yield of renewable groundwater resources was 275 million cubic meters (MCM), while the over-pumping was 200 MCM, which accounted for 72% above the safe yield. This over-abstraction is neither rational nor sustainable, as it leads to lowering the groundwater table and hence deterioration of the groundwater quality due to saline water intrusion (Abu Qdais, Abdulla, and Kurbatova 2019). The groundwater resources have been overexploited for a while to bridge the gap between water demand and sustainable water resources (Ammary 2007). Another supply expansion method is the desalination of brackish water and seawater, which contributed about 10 MCM in 2015 (Ministry of Water and Irrigation 2016a), but these methods are costly and the available water is far from highly populated areas (Ammary 2007).

The water shortage problems in Jordan have been exacerbated further as a result of high natural population growth, influxes of refugees and returnees to the country in response to the political situation in the Middle East, rural-to-urban migration, and increased modernisation and higher standards of living (Ammary 2007). The Syrian crisis is in its 12th year and spillover continues to impact Jordan as it has met and exceeded its carrying capacity. The crisis has had a severe impact on the infrastructure, public service delivery, and overall economic well-being. The impact reversed many hard-earned development gains, increased public debt, and has taken Jordan off its sustainable development path (MoPIC 2020).

The physical planning of the development has generally been inadequate with little concern for the environment. There are many signs of significant pollution and environmental degradation, in particular, in the Amman-Zarqa region, which is the largest urban centre in Jordan and is home to more than half of the population of the Kingdom. This area is also the largest industrial region, where the majority of the Jordan industry is located (Mohsen and Jaber 2002 and Saidan, et. al. 2020).

Environmental pollutions come from many sources in society. Domestic sewage is the largest source of water pollution, followed by industrial effluents and agricultural activities. Industrial waste, however, particularly when it contains harmful chemicals, heavy metals, and other toxic substances, can have far more serious outcomes than domestic waste. These toxic substances pollute the surface water, the soil, and the groundwater, they become concentrated in the food chain and therefore need treatment before being discharged. At the same time intensive pumping of groundwater has lowered the water table, so that the rivers in Jordan today are dry most of the year. As untreated wastewater to some extent is discharged to the valleys, this has worsened the situation significantly (Mohsen and Jaber 2002).

In addition to the pressure imposed on the water resources by population growth and frequent influxes of refugees, climate change has also deeply affected the water stress and the environment in Jordan. This creates an imbalance in water management and increases the gap between the demand and the supply. Many studies indicate that water scarcity is a major challenge that is facing the sustainable development of the country. They also conclude that water scarcity will be even more intensified by climate change, and this will manifest itself through an increase in temperature, a decline in precipitation and an increase in the frequency of drought (Abu Qdais, Abdulla, and Kurbatova 2019). MWI records show that precipitation has decreased by 20% over the last eight decades (MWI 2016b) and various models predict the annual precipitation to decrease by 1.2 mm per year (Abu Qdais, Abdulla and Kurbatova 2019), simultaneously, the mean air temperature tends to increase by 0.02 °C per year (Abu Qdais, Abdulla, and Kurbatova 2019). Consequently, the amounts of runoff and groundwater recharge will decrease and freshwater will become even more scarce in the coming decades, hence conservation and utilization are therefore key factors facing Jordan's national authorities (, Au-Arabi, Hudaib 2012). Wastewater reclamation and reuse are becoming more popular in light of the climate change impacts on water resources. Wastewater reuse is an opportunity to decrease the gap between demand and supply (Abu Qdais, Abdulla and Kurbatova 2019).

Considering the very alarming situation, Jordan has given top priority to the use of reclaimed wastewater in the agriculture and industrial sectors, hence the reuse of wastewater in agriculture has replaced freshwater resources (Saidan 2020, Saidan, et. al. 2020). For example, in 2014 Jordan reused approximately 93% of its treated municipal wastewater for irrigation in agriculture to reallocate freshwater to domestic purposes (MWI 2014).

The agricultural sector in Jordan is facing challenges in the near future. Severe deterioration of water resources quality due to agricultural activities has been witnessed in many areas recently. The agricultural sector requires around 52% of the total national water and only contributed about 2% to GDP in 2017 (MWI 2018, Saidan, et. al. 2020). The depletion of the water table, the decreased precipitation together with the growing water demand have increased the salinity in the groundwater in Jordan. This is a serious problem, for industries, the public and agriculture. In some agricultural areas, which have been irrigated by saline water, the soil has been so loaded with salt that crop productivity has decreased, or only special saline-resistant crops like tomatoes can grow (Mohsen and Jaber 2002, Saidan, et. al. 2020).

The industrial sector demand for freshwater in Jordan was about 32 MCM of water in 2017, this accounts for 3% of the total freshwater consumption during that year (MWI 2018). A major part of this was consumed by large industries such as phosphate mining, the production of potash, ceramics, cement and soft drinks, as well as the energy sector. The industrial sector has a higher allocative efficiency than other uses (for example tourism and agriculture). The financial return of water use in industry is 40 JOD/m^3 while each 1 m^3 of water created 3 777 jobs in the industrial sector during 2014 according to the Jordanian Department of Statistics (MWI 2016a). Almost all local industries have suffered from shortages in water supplies during the last decades and the water shortage is also the limiting factor for the establishment of new industries as well as the expansion of established high-rate water consumption industries (Mohsen and Jaber 2002). Industries can be considered as a source of reusable wastewater. The reuse of industrial wastewater may take four forms: water conservation and recycling internally at the plant, wastewater treatment at the plant for late reuse in the process, wastewater treatment at the plant and later reused for irrigation or disposed to the public sewer system, in which the water is treated and later reused for irrigation. Suppose industrial wastewater was to be reused in the industrial or agricultural sector. In that case, most industrial facilities need to improve their wastewater management practices and upgrade their on-site treatment units to treat the wastewater before use (Saidan, et. al. 2020).

2.3 Wastewater Treatment in Jordan

Wastewater in Jordan is characterized as very strong with high salinity, the high strength is due to the low per capita consumption of water, caused by shortages in water resources. For several years, Jordan has been dependent on wastewater stabilization ponds (WSP) to treat wastewater for reuse in agriculture. Because of the high evaporation rates, especially during the summer, this would inevitably increase the salinity therefore farmers used to mix the water with freshwater to use it in agriculture. For most crops in the Jordan Valley, the yield capacity lies between 50-80% if effluent wastewater alone is used for irrigation (Ammary 2007).

The wastewater treatment plants (WWTP) play an important role in decreasing the environmental impacts of municipal and industrial discharges. When the WWTPs have an advanced (tertiary) treatment, wastewater recycling and reuse can be promoted, as well as, enhancing the recovery of materials or energy. The reuse of wastewater is one of the recommended solutions for the problem of water scarcity although the process may be complex and costly (in terms of resources and energy), depending on the quality of the wastewater, the quality demanded of the treated wastewater and the adopted technology (Saidan et. al. 2020). The majority of the conventional municipal WWTPs (uses mechanical, chemical and biological treatment) do not eliminate emerging pollutants (hormones, steroids, pharmaceuticals and personal care products, persistent organic pollutants, heavy metals, etc.), which can be induced into the food chain, subsequently causing ecological and human health effects (Saidan et. al. 2020).

The wastewater treatment in Jordan focuses on municipal (domestic) wastewater and not on industrial wastewater. Still, only 34% of the domestic wastewater reached a wastewater treatment plant in 2010 (Seder and Abdel-Jabbar 2011), in 2012 the number of Jordanians connected to the sewage system was 64% (Uleimat, Ahmed, Ali 2012). Today, Jordan has 31 WWTPs and the most used treatment technology is activated sludge (approximately 60%) the second most common method is wastewater stabilization ponds. The WWTPs are mainly located in the northern part of Jordan, near cities and refugee camps, and treat mainly domestic wastewater, the geographical distribution indicates that there is higher reallocation potential in the northern and central part of Jordan due to the amount of wastewater collected and treated in those regions. The largest WWTP in Jordan, the Al Samara WWTP, is located between Amman and Zarqa and generates approximately 120 MCM of treated wastewater per year, which is equal to about 70.5% of total reclaimed wastewater in Jordan. In 2023, the 31 WWTPs were providing 186 MCM to Jordan’s total water supply, and about 90% of the treated wastewater was reused in agriculture which accounted for about 25% of the total amount of water used for irrigation. The WWTPs are expected to treat 240 MCM per year by 2025 (Ammary 2007, Saidan et. al. 2020, MWI 2023 and UN – Policy Brief 2022).

The regulations and standards of Jordan allow treated wastewater to be used for agricultural irrigation and industries only, and not for domestic purposes (MWI 2016a). Recycling of water is necessary for Jordan to manage the increasing water demand and the limited water supply. Yet, water recycling presents some risks to public health and the environment, and it is perceived negatively in the public eye. In the future, it will be increasingly necessary for wastewater plant designers and planners to carefully consider wastewater reuse as an important part of the planning for wastewater treatment systems (Nazzal, et al. 2000).

Saidan et. al. (2020) discussed the purpose of the reused wastewater and concluded that treated wastewater in the Ma'an and Karak governorates is preferable to prioritize the reclaimed wastewater for irrigation purposes where applicable. Also, their environmental assessment showed positive impacts of the reclaimed wastewater reuse scenario in terms of water depletion (expressed in MCM of groundwater savings) and climate change (expressed in $CO_{2\ \mathrm{equivalent}}$ reduction).

2.4 Industrial Wastewater Treatment in Jordan

According to a survey made by Saidan (2020), the most common wastewater disposal practices among industries were the following: direct discharge to sewers, off-site disposal, on-site treatment, recirculation and others (i.e. road cleaning, industry ground washing, etc.). Saidan (2020) also concluded that the industrial sector in the whole of Jordan demands 26.7 MCM of water and produced 12.5 MCM of wastewater in 2020.

The regulations on effluent wastewater from industries are described in Chapter 4 and in Appendix 1 & 2.

2.5 Phosphate mining

Phosphorus is a plant macronutrient which is necessary for plant growth and often scarce in soils and must almost always be added to the fields and plants. It is considered a key element causing eutrophication, which leads to abundant plant growth. Phosphate is the form of phosphorus that is bioavailable to plants and this is used in fertilizers. Phosphorus is relatively stable in soils and may accumulate, especially in the topsoil. Phosphate can, when added to a receiving water body, cause eutrophication, resulting in further environmental damage. Some of the dangers are excessive aquatic plant and algae growth (with some of them being toxic to public health), degraded water quality needed for flora and fauna, and likely permanent loss of habitat in and around the recipient.

Wastewater normally contains low concentrations of phosphorus, so it is beneficial and does not impact the environment negatively when used for irrigation. This is also true for cases when wastewater with high amounts of phosphorus is used for irrigation over long periods. But, because phosphorus builds up in the topsoil, the use of wastewater with high concentrations could affect surface waters through soil erosion and runoff. To reduce the pollution of phosphate, municipal and industrial wastewater are often treated before being discharged to meet local, regional and national regulations. The treatment process usually utilizes physical, chemical and/or biological methods to remove the phosphorus. Generally, total phosphorus concentrations over 100 g P/l provide sufficient nutrient enrichment in water bodies. However, if wastewater with high phosphorus concentration is used in the agricultural sector, the phosphorus is recycled, which minimizes environmental impacts and reduces the cost of wastewater treatment to meet the environmental regulations.

The prediction for the accessible phosphate reserves says it will run out within 60-130 years, hence phosphorus is a limited resource (WHO vol 1 2016, Morse, et. al. 1998, Emeish, Au-Arabi and Hudaib 2012). Jordan is the world's fifth largest exporter of phosphate (Pistilli 2020), and the production consumes large quantities of Jordan’s limited freshwater. The water is used in the mining beneficiation processes such as washing and flotation. The freshwater is usually drained from nearby groundwater supplies, which puts a lot of stress on the groundwater resources. The phosphate mines themselves are assumed to use around 20 MCM of freshwater per year, where the wastewater from the washing process is discharged along the wadis and valleys and lost through evaporation and infiltration (Rimawi, Jiries, Zubi and El-Naqa 2008).

Contaminants in wastewater produced by typical mining industry can be classified into five categories, physical, chemical (organic), chemical (inorganic), biological and radiological. The biological pollutants in phosphate mining emanate from domestic and sanitation facilities within the amenity building and usually, they should be connected to an urban sewer or a properly designed on-site waste disposal system (Dharmappa, Sivakumar and Singh 2002).

The phosphate industry consumes a large amount of freshwater. The freshwater is contaminated throughout the beneficiation (separation of phosphate-containing minerals from the matrix of ore) process at the plant and can no longer be used for any other purpose and is dumped in an evaporation pond. The largest phosphate mine and beneficiation plant in Jordan is the Eshidiya mine and it produces about 10 000 tons of clay slurry per day. This slurry is polluted with various toxic substances and is pumped to clay storage ponds where the clay slowly settles. The ponds cover about 20% of Eshidiya mined lands and have generally not been reclaimed, causing negative environmental and economic impacts. Large amounts of freshwater are lost through evaporation in the clay-settling ponds. Heavy metals are naturally present in the phosphate rock and they become concentrated in the clay waste and even more in the settling ponds. The accumulation of toxic substances in the clay could also cause a potential risk to human health due to the transfer of these heavy metals in aquatic media, uptake by plants and subsequent introduction into the food chain. Increased mining could lead to an increase in clay discharges, causing even greater loads of pollutants discharged to the environment (Al-Hwaiti, Brumsack and Schnetger 2015).

With a continuous production of phosphate, most ores decrease in quality over time. To obtain the same product rate, an increasing quantity of the ore therefore must be mined and processed. Increased mining and processing require greater energy and water use. Jordan is a major importer of oil and also a (water-stressed) arid-semi-arid country, the results will, amongst others, be higher production costs and larger stress on the water resources (GRAJ 2017, and Hadadin, Qaqish, Akawwi and Bdour 2009, Al-Hwaiti et. al. 2016 and Al-Hwaiti et. al. 2018).

The location of the phosphorus in Jordan is shown in Figure 2. Shallow and deep potential phosphate deposits stretch across the country (doted area and dark-coloured area). The Eshidiya mine is located at the bottom of the deep potential phosphate deposit area (dark-coloured area) and the Al-Abiad mine is located in the central parts of Jordan in the shallow potential phosphate deposit area (dotted area).

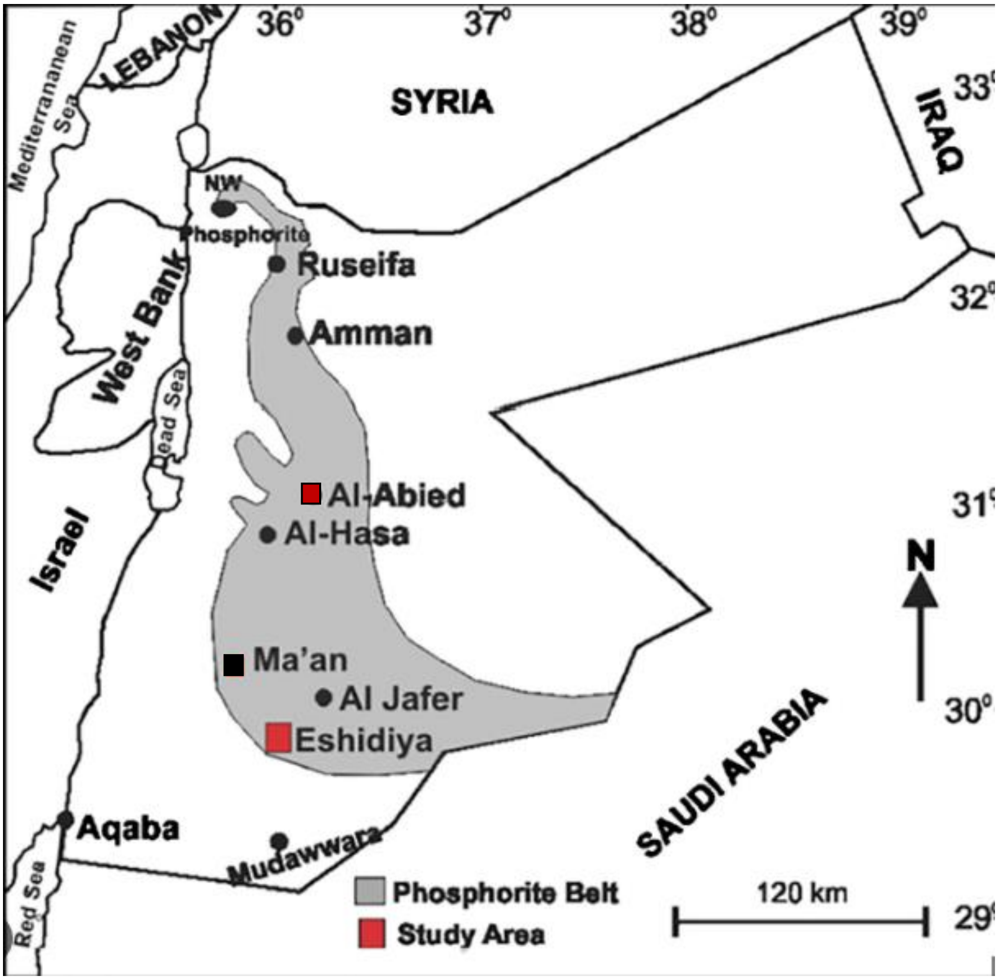

Figure 2. Location of phosphorus deposits in Jordan and the names of the sites (Al-Hwaiti, Aziz, Ahmad and Al-Shawabkeh 2022).

2.5.1 Economy

Jordan is a small Middle Eastern developing economy, which is classified as a "medium human development" country by the United Nations Development Program. Phosphate and potash are dominating the Jordan mining industry, with 40% and 60% of revenues in 2018, respectively. These minerals have been a significant generator of economic growth and national income since Jordan's independence in 1946. The mining industry represented 2.9% of the gross domestic product (GDP) in 2022 (CBJ 2024). One of the constraints for the production is the amount of freshwater the beneficiation process requires, especially for a semi-arid country like Jordan. The industrial sector mostly relies on freshwater, which could be reallocated to domestic purposes. The whole industrial sector uses 32.2 MCM of groundwater, 4.8 MCM of surface water, and 1.7 MCM of treated wastewater annually (Saidan et. al. 2020). The phosphate mines in Jordan themselves are assumed to use around 20 MCM of freshwater (mainly groundwater) per year which is mentioned above.

Phosphate was discovered in Jordan in 1908 while building the Hejaz Railway in the Russaifa and Al-Hassa region. The Russaifa mine, the Al-Hassa mine and the Al-Abiad mine started operating in 1935, 1962 and 1979, respectively. The Hashemite Kingdom of Jordan has the fifth largest reserves of phosphate in the world, with an estimation of 3.7 billion tons. The Jordan Phosphate Mines Company (JPMC), which mines phosphate in Jordan, was founded in 1949 and its current capital is JOD 247.5 million and considered a major block in the national economy (JPMC 2024). It is today ranked as the second-largest exporter and the fifth-largest producer of phosphate in the world with a capacity exceeding 10 million tons per year. The biggest mine, the Eshidiya mine, started operating in 1988 and produced 7.6 million tons of phosphate in 2022. 1992 the Indo Jordan Chemicals Ltd. Co. was founded in the Eshidiya area, to enhance the cooperation between India and the Hashemite Kingdom of Jordan for the production of high-quality phosphoric acid (interviews with managers at JPMC in 2018 and JPMC 2020). In 2018 about 4 000 people were working at JPMC (Titi, Al Rawashdeh and Al Tarawneh 2019, interviews with managers at JPMC in 2018 and JPMC 2020).

About 90 % of the world's known reserves of phosphate are controlled by only five countries (Morocco, Jordan, South Africa, USA and China), which causes concern. Morocco itself controls around 50 000 million tonnes (in 2010) which makes it the promising leader and the exclusive controller of the global market in the future (Titi et al. 2019). Phosphate is crucial for the world's food supplies and has therefore a great impact on the world's economy and inequalities between rich and poor countries.

JPMC is currently the monopoly producer of phosphate in Jordan. The company was founded in 1949 as a privately controlled company and the government owned around 25% of its shares at the start. The government share increased during the second half of the 20th century and reached around 90% in 1989. From then until 2005 the government share declined to 65%. In 2006, the government sold 37% of its shares and owns now only 28% of the total shares (Titi et al. 2019). The economic competitiveness of the phosphate sector has been important for the development of Jordan (Titi et al. 2019).

2.5.2 Description of two phosphate mines in Jordan

In total, there are four phosphate mines in Jordan, the Russaifa mine, the Al-Hassa mine, the Al-Abiad mine, and the Eshidiya mine, all owned and governed by the JPMC. The latter two mines were chosen for this project. The mines' locations are shown in **Fel! Hittar inte referenskälla.**.

The Al-Abiad mine is located in the central part of Jordan, the closest bigger city is Al-Karak, and the mine is situated in the Karak governorate. The major industries in the governorate are phosphate mines (Al-Hasan mine and Al-Abiad mine), potash, chemical fertilizers, cement, mining etc. The industries in the Karak governorate (in total) abstract about 11.5 MCM groundwater per year, which represents 54% of the total abstraction by major industries in Jordan (Saidan et. al. 2020).

Al-Abiad mine is close to the desert highway and many farmers are working in the area, farming tomatoes, melons, dates and other vegetables. The phosphate is mined close to the surface to a depth of about 30 m. The freshwater, which is used in the production, is extracted from five wells in the surrounding area, pumping about 5400 m^3 of freshwater per day. The Al-Abiad mine pumps its freshwater from the underlying aquifer, the Amman/Wadi Es-Sir formation (B2/A7). The plant has four operating open pits. In 2018, 300 people were working at the mine in a two-shift schedule from 7 AM to 11 PM (interviews with managers at JPMC in 2018 and Bender 1974). The mine produced 1.2, 1.6, 1.4, 1.4 and 1.6 million tons of phosphate in 2018-2022 (JPMC 2024).

The production chain at the Al-Abiad phosphate mine is the following: First, the ore is mined in the open pits around the beneficiation plant. The ore is then transported with large trucks to the plant where it is crushed and filtered with a screen to be the right size. The reject is stored in piles south of the plant. The crushed ore is transported to the beneficiation part to increase the concentration of tricalcium phosphate (TCP) up to seven times, to the concentration of about 65 to 70%. In the beneficiation step, the ore is washed with freshwater to separate it from any impurities and slime from the phosphate, mainly to decrease the chloride concentration in the product from 1000 ppm to 500 ppm or less. After refining the phosphate (the product) is transferred to the dryers to decrease the water content from 18-20% to 3%. This is done by burning oil to create a temperature of 1 200 °C in the dryer. The benefaction plant produces about 1000 m^3 of slurry (effluent wastewater) per day. In 2019 the Al-Abiad mine produced 1.6 million tons of phosphate (JPMC 2020).

The Al-Hassa mine just south of Al-Abiad uses approximately 3 MCM of freshwater per year (in 2004) and it produces about 1 million tons of phosphate during the same period, this means that the production of phosphate requires about 3 m^3 of freshwater per 1 ton of produced phosphate rock (JPMC 2020 and Al-Dustour Newspaper 2005). These numbers correlate with the amount of water used at the Moroccan phosphate plants (2.6-3.8 m^3 per ton of phosphate, depending on production variations) (Aroussy, Nachtane, Saifaoui, Tarafoui, Farah and Abid 2016).

The Eshidiya mine is located in the south of Jordan, approximately 125 km northeast of Aqaba, and the mine is situated in the Ma'an governorate. The major industries in the governorate are phosphate (industry and mine), cement, etc. The industries in the Ma'an governorate abstract about 4.4 MCM groundwater per year, which represents 21% of the total abstraction by major industries in Jordan (Saidan et. al. 2020).

At the Eshidiya site, two different companies are operating, the JPMC (the same as in the Al-Abiad mine) and the Indo-Jordan Chemicals Company Ltd [IJC], which produces phosphoric acid and sulphuric acid (JPMC 2020 and IJC 2009). The phosphate mine was established in 1989 and its reserves are approximately 1500 million tonnes (Al-Zoubi and Al-Thyabat 2012). The mine produced 5.8, 6.0, 5.9, 7.0 and 7.6 million ton phosphate in 2018-2022. The mining area is 315 km^2 and consists of four phosphoric bed layers (A0, A1, A2, and A3). The beneficiation process is different depending on the quality of the ore. A2 has a very high TCP content and needs only crushing and screening before leaving the plant. The other needs further process steps to separate the phosphate from clay and particles before it reaches the wanted quality (JPMC 2020 and JPMC 2024). A2 does not contribute to the increased pollution in the effluent water. Eshidiya has both washing and flotation processes to upgrade the phosphate to the desired concentration.

The Eshidiya phosphate plant uses a large amount of water in many stages, mainly in flotation cells, to wash up clay and impurities to increase the concentration of phosphate to above 70%. The mine has expanded three times and used more than one thousand cubic meters of washing water per hour (in 2012), which contains about 20% solid impurities (Emeish, Au-Arabi, Hudaib 2012).

The phosphate rock is mined in several open pits at the Eshidiya mine. Later it is crushed, dry screened and then washed with water guns, turning it into slurry. The slurry is transported to the next step but this step depends on the quality of the ore. The A1 and A3, which have the lower concentration of phosphate, are washed with freshwater to separate them from clay, but A3 also contains sand particles which have the same weight and therefore require an extra process step. After the washing A3 is pumped to a flotation plant where a collector agent is added to coat the phosphate particles. The slurry is then introduced to air bubbles and the chemically coated phosphate adheres to the bubbles causing them to float to the surface while the sand particles sink to the bottom (Al-Hwaiti, Brumsack and Schnetger 2015). The last step for all lines is the drying process. Today, the phosphate mines discharge the wastewater to a pond or an old open pit to let the slurry settle and water evaporate and/or infiltrate into the groundwater.

The latest large investment at the Eshidiya plant is the start of establishing an industrial water recycling plant for phosphate washing operations. It is projected to yield around 2.5 MCM of water annually and is expected to over time preserve a total of 50 MCM of groundwater, decreasing the pressure on local groundwater and lowering the environmental impact of untreated industrial wastewater. The project is a collaboration between the JPMC, the United States Agency for International Development (USAID) and Engicon (a consulting engineering firm) and funded by the USAID and Engicon.

2.6 Pollution from phosphate mining

In general, the most important environmental impacts from mining are the impact on water resources, air quality, wildlife, soil quality, social values, and climate change (ELAW 2010).

Perhaps the most significant impact of mining is its effects on water quality and the availability of water resources within the mining area. Key questions are whether surface and groundwater supplies will remain fit for human consumption and whether the quality of surface waters in the project area will remain adequate to support native aquatic life and terrestrial wildlife.

The impacts of wet tailings[1] impoundments, waste rock, heap leach, and dump leach facilities on water quality can be server. These impacts include contamination of groundwater beneath these facilities. Toxic substances can leach from these facilities, percolate through the ground, and contaminate groundwater, especially if the bottom of these facilities is not fitted with an impermeable liner. Most mining companies dispose of the tailings by mixing them with water and disposing of the slurry in a dam, meaning the waste contains large amounts of water and can be a threat to wildlife.

Airborne emissions occur during each stage of the mining cycle. Mining mobilizes large amounts of material, and waste piles containing small size particles which are easily dispersed by the wind. Examples of air pollution in mining are particles transported by the wind as a result of excavation, transportation of materials, wind erosion, waste dumps, and fugitive dust from

[1] High-volume waste from beneficiation processes, which is the residue of an ore after milled and desired elements extracted.

tailings facilities. But also, emissions from cars, trucks and heavy equipment and gas emissions from the combustion of fuels in excavations, mineral processing, etc. Noise and vibrations are also pollutions associated with mining which can significantly affect wildlife and nearby residents.

Habitat loss and soil quality impacts are other factors to consider. Agricultural activities near a mining area may be particularly affected.

The social impacts of mining are controversial and complex. Mining industries can create jobs, roads, and schools and increase the demand for goods and services in remote and impoverished areas, but the benefits and costs may be unevenly shared. Communities feel particularly vulnerable when environmental impacts of mining (soil, air, and water pollution) affect the subsistence and livelihood of local people. Mining industries must ensure that the basic rights of the individuals and communities affected, including the right to control and use land, the right to clean water, a safe environment, and livelihood, etc. When contamination is not controlled, the cost of the contamination is transferred to other economic activities, such as agriculture, which are critical to the local people. Also, hazardous substances and waste in soil, air and water can have serious, negative impacts on public health. Frequent public health problems related to mining include the deposition of toxic elements from air emissions in soil; Exposure to high concentrations of sulphur dioxide, particulate matter, and heavy metals in the air; and Surface and groundwater contamination with metals and elements, microbial contamination from sewage and waste in campsites and min worker residential areas.

In this subchapter, the impact on water resources and social values is highlighted, focusing on water pollution. A couple of environmental research studies have been carried out in Jordan to identify the environmental impact of phosphate mining activities. The following text summarises these studies.

The Al-Abiad mine

The results of a study performed by Rimawi, et. al.

in 2008 at the Al-Abiad mine showed that mining activities increased all ions in the mine wastewater, especially sulphate (SO_4^{2-}), calcium (Ca^{2+}) and chloride (Cl^-), which increases the salinity in the water. The results also indicated that there was a large increase of zinc (Zn^{2+}) and chromium 6 (Cr^{6+}) in the wastewater, compared to the freshwater. These pollutants are mainly produced in the washing and flotation processes. Jiries, El-Hasan, Al-Hweiti and Seiler (2004) investigated the hydro-chemical and isotopic characteristics differences between the incoming freshwater and the outgoing industrial wastewater (excluding the slime phase) of the same mine. Jiries, et. al. (2004) came to similar conclusions declaring that the Al-Abiad effluent wastewater had high contents of Cl^-, SO_4^{2-} and HCO_3^-, which caused an increase of EC and the pH to about 7.5. The results indicated an extreme difference in the influent and effluent water chemistry: increased concentration of electrical conductivity (EC), calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), sodium ions (Na^+), potassium ions (K^+), bicarbonate (HCO_3^-), nitrate (NO_3^-), chloride (Cl^-) and sulphate (SO_4^{2-}). The Cl^- had great variations which Jiries et. al. (2004) believed depended on the ore quality. Jiries et. al. (2004) also noticed that the groundwater had a large variation in EC, and the difference in salinity between some of the wells was due to over-pumping the groundwater beyond the safe yield (saline water from a lower aquifer is being drawn up). The studies performed by Jiries et. al., (2004) and Rimawi et. al. (2008) both concluded that the wastewater from the Al-Abiad mine was suitable for the irrigation of salt-tolerant plants in the area

A study by El-Hasan (2006) showed a high concentration of heavy metals in the solid phase (slime) produced at the Al-Abiad mine (which is discarded with the effluent water). Although heavy metals occur in the effluent sediments and slime, concentrations in the industrial wastewater were relatively low. The low concentrations of heavy metal and Uranium (U) in the industrial wastewater are controlled by the water quality (high pH) and by the absorbance on the surface of, fine suspended materials (Jiries et. al. 2004). Nonetheless, the heavy metals that increased the most in the study were zinc (Zn) and copper (Cu). Rimawi et. al. (2008) believed that the low concentrations of the heavy metals in the liquid phase of the wastewater were due to the pH conditions contributing to the precipitation of a large portion of soluble heavy metals into the slime. El-Hasan (2006) also concluded that the mineralogical and chemical characteristics of the wastewater components reflected the parent phosphoric rocks. The results of the study showed that the water was highly oxygenated, mildly alkaline and rich in fine-grained materials.

A study performed by Batarseh and El-Hasan in 2009 of the phosphate rocks at Al-Abiad mine concluded that the phosphate rock in Jordan is highly enriched in vanadium (V), uranium (U) and mercury (Hg) compared to the average world phosphate rock. They also found out that the Jordanian phosphate deposit is uniquely enriched in U and depleted in lead (Pb) compared to other deposits worldwide and has a higher concentration of U and cadmium (Cd) than the safe permissible limits for soil for growing crops. Batarseh and El-Hasan (2009) stated that the concentration of U and Cd in the phosphate rock of Al-Abiad was higher than the safe permissible limits for soil for growing crops.

In 2006 a study was performed by Abed, Sadaqah and Al Kuisi (2008). They studied the pollution during the production of phosphate rock (to be used in fertilizers) and the possible environmental hazards of the mining activity. Their result was that the beneficiation process at the Al-Abiad mine produced a final product that had lower metal concentrations than the original phosphate ore and an effluent slime that was enriched in some metals, where potential toxicity was a concern. The slime water had higher concentrations of almost all elements compared to the groundwater in the area. More precisely, they found that there was a significant amount of phosphorite in the effluent slime, about 17.4% phosphorus pentoxide (P_2O_5) was present in the Al-Abiad slime. Also, the detrital elements were enriched by a factor of three in the slime. The trace metals were also enriched; Cr, V and nickel (Ni) by a factor of more than 2.5, Hg and Zn by a factor of about 2, Cd, Cu, Pb, Se and thorium (Th) by a factor of about 1.5. Arsenic (As), molybdenum (Mo) and cobalt (Co) were practically unchanged, and strontium (Sr) and U were depleted in the slime relative to the original sample of the phosphate ore. The concentration of the potentially toxic metals was very low in the effluent wastewater (separated from the slime). This indicates that the elements are not readily dissolved in the freshwater, and are either strongly adsorbed on the clay minerals or strongly held in the apatite structure. The study concluded that the phosphate mining and upgrading in central Jordan did not appear to adversely affect the region's groundwater (Abed, Sadaqah and Al Kuisi 2008).

The Eshidiya mine

The Eshidiya mine produces approximately 1 MCM of effluent water per month. Some previous studies have focused on how to reuse and recycle wastewater to extract more phosphate from the wastewater of the Eshidiya mine. A water analysis study of the wastewater from the Eshidiya mine performed by Al-Zoubi and Al-Thyabat (2012) showed that the main problems in the filtered wastewater samples were the high concentrations of suspended solids (SS), total dissolved solids (TDS), Cl^- and SO_4^{2-}. The main problems in the solid part were the high content of phosphate (PO_4^{3-}), Ca and silicon oxides (SiO_2). Al-Zoubi and Al-Thyabat (2012) also stated that about 9600 m^3 of water and 200 tons of pentoxide (P_2O_5) were discharged every day.

In the study performed by Abed, Sadaqah and Al Kuisi (2008), as mentioned before, the phosphate ore from the Eshidiya mine was also studied and compared to the Al-Abiad ore. Most of the studied metals were less abundant in the ore from Eshidiya compared to Al-Abiad. Still, the concentration of uranium (U) in the A0 layer (the top one) was twice as high as of Al-Abiad and five times the U concentration in A1 and A3. The final results showed that the metal concentrations in the slime were much lower than the concentration in the effluent water at Al-Abiad. Therefore, Abed, Sadaqah and Al Kuisi (2008) concluded that the mining activity did not pose any environmental hazard to the groundwater.

A study performed in 2012 by Al-Hwaiti, Brumsack and Schnetger (2016) to characterize the pollution in the Eshidiya wastewater concluded that the effluent water had increased electric conductivity (EC) and total dissolved solids (TDS), higher concentration of Na^{+}, Ca^{+}, Cl^{-}, NO^{3-}, Cd^{2+}, Cr^{2+}, Fe^{2+}, Ni^{2+} and U^{6+} but depleted concentrations of $PO_4{}^{3-}$, HCO^{3-} and Si^{+} compared to the freshwater used in the process. These parameters were also used to calculate and compare the effluent with the Food and Agriculture Organization of the United Nations (FAO) guidelines and Jordan Standards (JORS) for irrigation. EC, TDS, and SAR (sodium adsorption ratio) were higher than FAO and JORS recommendations. The study also showed that the concentration of heavy metals was low in the effluent which is of significant environmental and competitive aspect of the Jordanian phosphate (Al-Hwaiti et. al. 2016). The study also concluded that many parameters of the wastewater from the Eshidiya mine were under the JORS and the FAO guidelines for irrigation. The concentrations of the pollution in the effluent categorized the water as “slightly to moderate” suitable for irrigation except for the salinity, which defined the water as “severe” and therefore unsuitable for irrigation. The authors' recommendation was to mix the effluent with freshwater when using the effluent for irrigation and therefore ease the water stress in the area (Al-Hwaiti et. al. 2016).

A study by Al-Hwaiti, Brumsack and Schnetger (2015) examined the heavy metal concentrations in clay waste (slime/slurry) from the two different beneficiation process streams at the Eshidiya mine and then compared it with uncontaminated soil at Eshidiya. The study stated that As, Cd, Cr, Cu, Pb, V and Zn are higher in the clay than in the uncontaminated soil and that they are leached from clay waste and transferred and accumulated in the soil horizons. Especially the Cd was enriched in the clay waste for both the streams and ore qualities. The study stated that the Eshidiya mine produces large amounts of industrial process clay waste, which could eventually affect the surrounding environment and ecosystem. The clay which is filtered during the processing and the sand tailings contains toxic levels of As, Cd, Cr, Cu, Pb, U, V and Zn and therefore cannot be put back into the environment. Instead, the clay waste is stored in settling ponds at the site. The total amount of freshwater used by the Eshidiya mine is 15 MCM per year, and water consumption can reach 4-6 m^3 per ton of produced phosphate (Al-Hwaiti, Brumsack and Schnetger 2015).

Emeish, Au-Arabi, and Hudaib (2012) studied the two different processes for A1 and A3 at Eshidiya mine. Cd, Co, Cr, Li, Mn, Mo, Ni, Pb, U, V and Zn were analysed. The results showed that the average trace metal concentrations in both effluent wastewater samples were found to be below the limits of the Jordanian standard for the discharge of water to streams, wadis or other water bodies (JS 202:1991)[2] and that the phosphate mine process has not caused environmental pollution and health risks regarding the studied elements. The authors conclude that there is a slight risk of heavy metals accumulation in plants and bodies (animal and human) if the mine wastewater is reused for irrigation. They also suggest that the long-term use of mine wastewater is not recommended due to the possible health risks for consumers.

[2] The standard at the time for the study, it is now replaced with JS 202:2007.

3 Sustainable Development Goals

In September 2015, at the Sustainable Development Summit, United Nations Member States adopted the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals [SDG] to end poverty, fight inequality and injustice, and tackle climate change by 2030. The SDGs are built on the Millennium Development Goals (MDGs) but the new SDGs have a broader sustainability agenda and go much further than the MDGs. The SDGs are designed to apply to both rich countries as well as developing countries, addressing the root causes of poverty, inequalities and unsustainable production and consumption and the obstacles to achieving development that works for all. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality and incite economic growth - all while tackling climate change and working to preserve the environment. To make the 2030 Agenda a reality, broad ownership of the SDGs must translate into a strong commitment by all stakeholders to implement the global goals (UN - Sustainable Development Goals [UN SDGs] 2020 and Awad 2016).

The Hashemite Kingdom of Jordan is a small, resource-starved, middle-income country with a fast-growing population and insufficient sources of water, oil and other natural resources. The country is largely dependent on imports and international financial assistance and has struggled to withstand the impact of gradual economic and demographic shocks. Regional conflicts have affected several key trade routes and decreased tourism revenue. The influx of refugees and migrant workers has contributed to depleting the government resources and the national infrastructure and has aggravated unemployment (UN SDGs 2020). The impact has reversed many earned development gains, increased public debt, and taken Jordan off its sustainable development path (MoPIC 2020).

In the period from 2000 to 2015, Jordan was amongst the first countries, both globally and in the Arab region, to take action towards realizing the MDGs. Considerable achievements were obtained in many prioritised areas, such as maternal and child health, communicable disease, poverty obliteration, universal primary education and environmental sustainability (Awad 2019). The key challenges identified in the 2015 National MDG report confirm the need to address water shortages amongst others. Jordan’s First National Voluntary Review from 2017 (The Hashemite Kingdom of Jordan 2017) confirmed the importance of addressing water scarcity (together with enhancing awareness of environmental issues and promoting renewable energy) as one of four critical areas for Jordan to prioritize when realizing the 2030 Agenda for Sustainable Development.

4 Water and environmental policies, laws etc

The Ministry of Water and Irrigation and the Water Authorities of Jordan have written many policies, strategies, laws and by-laws for the water management sector, for example:

- *JS 202:2007 Water - Industrial reclaimed wastewater*
- *National Water Strategy 2023-2040*
- *Groundwater Resource Assessment of Jordan 2017*

The following subchapters will touch upon parts of those that are of interest to this thesis.

4.1 Discharge requirements

The following subchapter highlights discharge requirements of interest for this paper, the full Jordanian Standard (JS:202/2007) (JORS) by the Water Authorities of Jordan and the Food and Agriculture Organization of the UN (FAO) discharge limits and guidelines for irrigated water are gathered in Appendix 1 and 2. The numbers in the JS:202/2007 are for the maximum allowed (mg/l), with exceptions.

Table 1. Selected discharge requirements, maximum allowed (mg/l), with exceptions, according to JS:202/2007.

			Irrigation to Group			***Discharge to Surface waters***
Parameter		*unit*	**A**	**B**	**C**	
TSS	Total Suspended Solids	mg/l	50	200	300	60
pH		-	6-9	6-9	6-9	6-9
Turbidity		NTU	10	-	-	15
NO_3	Nitrates	mg/l	30	45	70	80

Table 2. Selected discharge requirements, maximum allowed (mg/l), with exceptions, according to JS:202/2007.

Parameter		*unit*	*For irrigation*	*Discharge to Surface Waters*
TDS	Total Dissolved Solids	mg/l	2000	2000
Ca	Calcium	mg/l	230	-
Cl	Chloride	mg/l	400	350
HCO_3	Bicarbonate	mg/l	400	400
Mg	Magnesium	mg/l	100	-
Na	Sodium	mg/l	230	-
SO_4	Sulphates	mg/l	500	300
Total PO_4	Phosphates	mg/l	30	15
SAR	Sodium Adsorption Rate	-	9	9
		Heavy Metals		
Ag	Silver	mg/l		0.1
Al	Aluminium	mg/l	5.0	2.0
B	Boron	mg/l	1.0	1.0
Cd	Cadmium	mg/l	0.01	0.01
Co	Cobalt	mg/l	0.05	0.05
Cr	Chromium	mg/l	0.1	0.1
Cu	Copper	mg/l	0.2	1.5
Fe	Iron	mg/l	5.0	5.0
Hg	Mercury	mg/l	0.002	0.002
Mn	Manganese	mg/l	0.2	0.2
Mo	Molybdenum	mg/l	0.01	0.01
Ni	Nickel	mg/l	0.2	0.2
Pb	Lead	mg/l	0.2	0.2
Se	Selenium	mg/l	0.05	0.05
Zn	Zinc	mg/l	5.0	5.0

The guidelines from FAO do not take into consideration different vegetables but do however have degrees of restrictions of use.

Table 3. Selected values from FAO guidelines for trace metals in irrigation water.

Element	*Recommended maximum concentration (mg/l)*	*Remarks*
Al	5.0	Can cause non-productivity in acid soils (pH <5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate and toxicity.
As	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to > 0.05 mg/L for rice.
Cd	0.10	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	0.10	Not generally recognized as an essential growth element. Conservative limits are recommended due to lack of knowledge on its toxicity to plants.
Cu	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solutions.
Fe	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Mn	0.20	Toxic to a number of crops at a few tenths to a few mg/L, but usually only in acid soils.
Mo	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	0.20	Toxic to a number of plants at 0.5 mg/L to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Pb	5.0	Can inhibit plant cell growth at very high concentrations.
Se	0.02	Toxic to plants at concentrations as low as 0.025 mg/L and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Sn	-	Effectively excluded by plants; specific tolerance unknown.
Zn	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

Table 4. Selected values from FAO guidelines for interpretation of water quality for irrigation.

Potential irrigation problem	*Units*	*Degree of restriction on use*		
		None	Slight to moderate	Severe
Salinity (affects crop water availability)				
ECw	dS/m	< 0.7	0.7-3.0	>3.0
(or)				
TDS	mg/l	<450	450-2000	>2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using ECw and SAR together)				
SAR = 0-3	and ECw =	>0.7	0.7-0.2	<0.2
= 3-6	=	>1.2	1.2-0.3	<0.3
= 6-12	=	>1.9	1.9-0.5	<0.5
= 12-20	=	>2.9	2.9-1.3	<1.3
= 20-40	=	>5.0	5.0-2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Na	SAR	<3.0	3.0-9.0	>9.0
Surface irrigation	mg/l	<69.0	>69.0	-
Cl	mg/l	<142.0	142.0-355.0	>355.0
Surface irrigation	mg/l	<106.5	>106.5	-
Sprinkler irrigation	mg/l	<0.7	0.7-3.0	>3.0
Miscellaneous effects (affects susceptible)				
NO3-H	mg/l	<5.0	5.0-30.0	>30.0
HCO3 (overhead sprinkling only)	mg/l	<91.5	91.5-518.5	>518.5
pH	Normal range 6.5-8.4			

4.2 National policies and strategies

4.2.1 National Water Strategy 2023-2040

The National Water Strategy 2023-2040 (NWS) publicised by MWI 2023 "*provides the vision and pathway to work across government and in partnership with the people to achieve lasting water security for our health, prosperity, and growth. This updated strategy is developed in response to environmental and calling for devising a long-term strategy that addresses the challenges calling for devising a long term strategy that addresses the challenges facing Jordan.*"

The NWS includes provision for water-energy-food nexus, climate change, focus on water economics and financing, sustainability of overexploited groundwater resources, decentralized wastewater management and the adaptation of new technologies and techniques available. The strategy touches upon all parts of water management in Jordanian society it also includes an operations strategy which includes "*strengthening career development and attracting youth and women to the sector as our next generation leaders".* The NWS contains many goals and targets to reach sustainable water management in Jordan. It also states that the groundwater is being pumped at double the safe yield of aquifers and that the aquifers are shrinking, groundwater levels are dropping, and water quality is deteriorating (MWI 2023).

The municipal water demand is projected to continuous increase, see Figure 3. Continuously increasing demand is driven by rapid population growth, influx of refugees, economic development needs, and continuous pressure to expand agricultural areas. Today the renewable freshwater per capita is 61 cubic meters per year (2021), in 2040 the projected number is 35 cubic meters per year (MWI 2023).

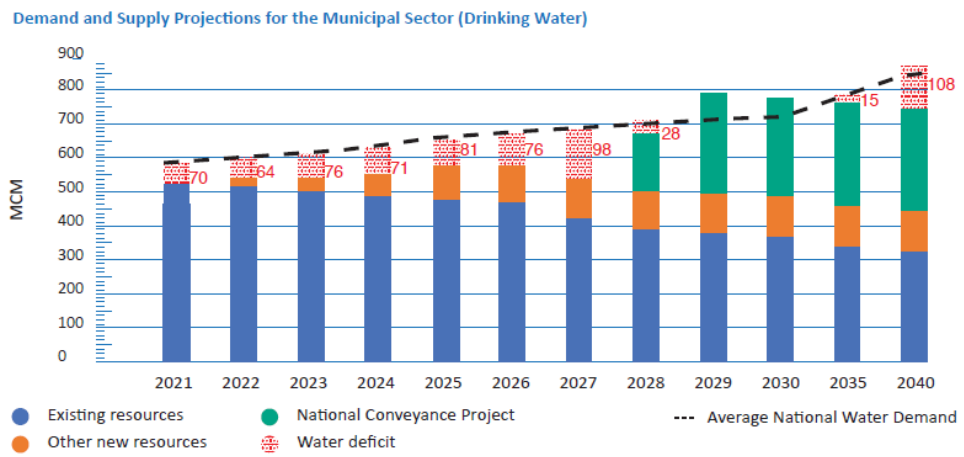

Figure 3. Projected water demand and supply for the municipal sector (MWI 2023).

The projected water demand for irrigation is shown in Figure 4 and is also increasing and the supply is projected to not meet the demand.

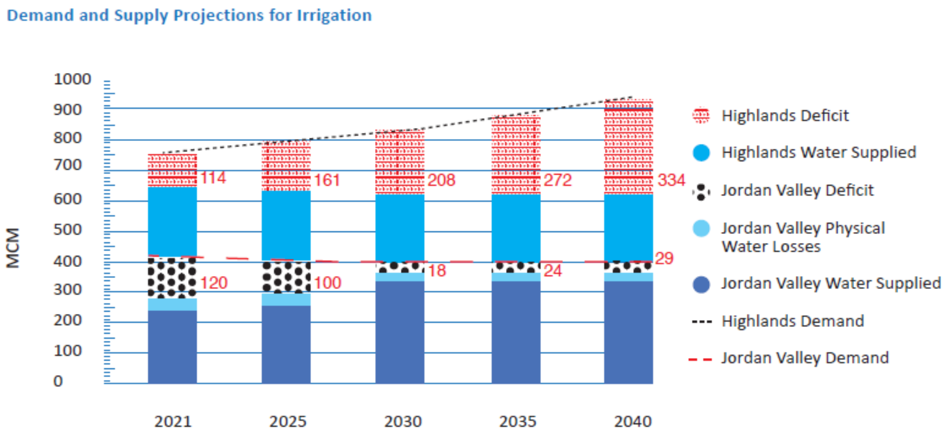

Figure 4. Projected water demand and supply for Irrigation (MWI 2023).

The water demand in the Industrial sectors is projected to increase and later have no deficit in supply versus demand, see Figure 5.

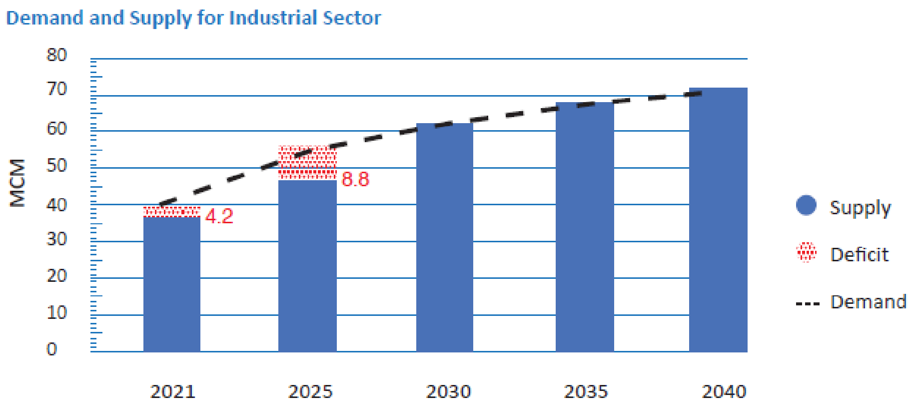

Figure 5. Projected water demand and supply for the Industrial sector (MWI 2023).

In total Jordan uses 1 093 MCM (2021) of water per year at the cost of severe over-pumping of groundwater and around 25% of Jordan's renewable freshwater from aquifers and rivers originate from neighbouring countries (MWI 2023).

To meet the future demand of freshwater Jordan is investing in large-scale desalination plants "*wherever possible*". The MWI is counting on meeting the demand by the combination of the new supply resulting from desalination and the sustainable management of renewable freshwater. It is projected to not only halt the deterioration but also restore groundwater resources while still meeting demand projections, leading to sustainable water security. Jordan's largest national infrastructure project, The National Conveyance Project, will desalinate water in the Gulf of Aqaba and then be pumped to Amman (across a large part of the country). The ministry is counting on the National Conveyance Project to bridge the demand-supply deficit until 2035 and allow groundwater to recover by reducing groundwater extraction or stopping some of it.

Another large infrastructure project which will increase the available drinking water is the Prosperity Green - Blue Line project. Prosperity Green includes a 600-megawatt solar photovoltaic plant, complemented with electric storage, which will be built in Jordan and produce clean energy for export to Israel. Prosperity Blue is a sustainable water desalination program, located in Israel, to exports 200 million cubic meters of potable water per annum to Jordan.

The NWS (MWI 2023) also states that the *"Industrial sector is by far the water user with the highest economic return per cubic meter of water used, while agriculture is lowest particularly in the highlands."*

The Jordanian government is relying on future water supplies will mainly consist of seawater desalination and reclaimed water of better quality. Figure 6 and Figure 7 show the projected water supply for the municipal sector and the industrial sector in detail.

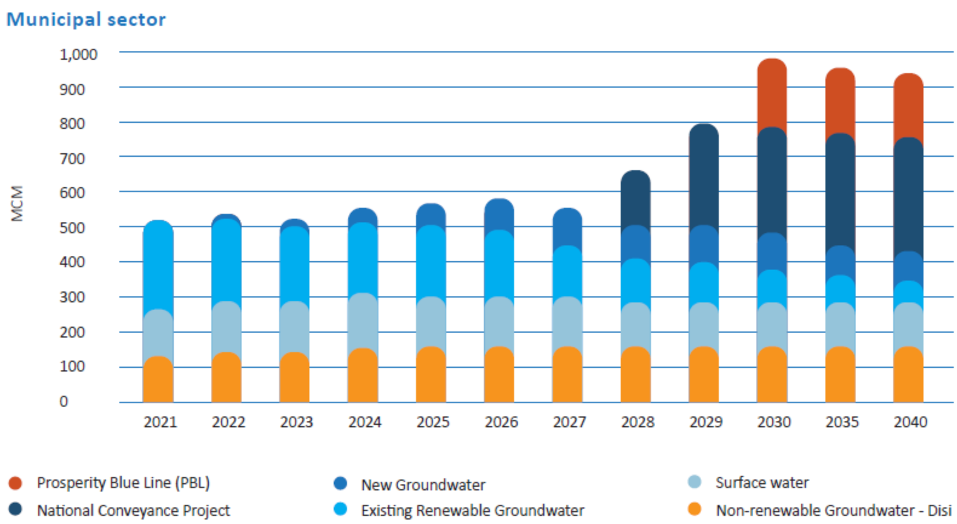

Figure 6. Detailed projected water supply for the municipal sector (MWI 2023).

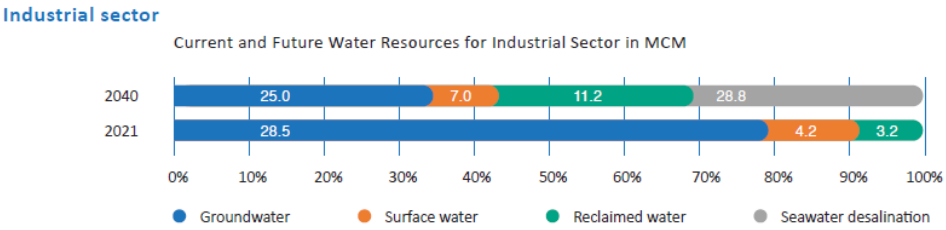

Figure 7. Detailed projected water supply for the industrial sector (MWI 2023).

One of the goals of the National Water Strategy is to "*Minimize pollution risks to protect groundwater quality*".

4.2.2 Groundwater Resource Assessment of Jordan 2017

The scarcity of water resources in Jordan is a well-known fact. Groundwater resources have been abstracted beyond their safe yield for many years. The Groundwater Resource Assessment of Jordan (GRAJ) presented in 2017 by MWI, concluded that the groundwater level around the Al-Abiad mine has depleted 0-25 m between 1995-2017 and the groundwater level for the Eshidiya mine is not monitored but it is concluded that the salinity is high and it is a potential unsaturated area. The simulated drawdown for the Al-Abiad area by 2050 is -5 to -25 meters and for the Eshidiya area <-5 meters according to the GRAJ (MWI 2017).

5 Methodology

The methodology of the paper consists of three parts; a literature study, two site visits at the phosphate mines, including interviews with the mine managers as well as industrial wastewater sampling, and laboratory analysis.

A literature study of existing data and studies about the mines and an overview of Jordanian law and restrictions about wastewater reuse were performed at the beginning of and were continuously followed up throughout the project. A summary of the overall achievement of the relevant UN SDGs was conducted to evaluate the country's renewable water management and industrial wastewater management towards a sustainable future.

On the 6th of March 2018, study visits and water sampling took place at the Al-Abiad mine and the Eshidiya mine, located in the central and southern parts of Jordan, respectively. The following mine managers received me at the mines: Eng. Mahmoud Jaradeen, Eng. Mohamad Y bani Fawaz, Eng. Alameen Alrwashdeh and Eng. Ismael H. Hasan.

The mines have one wastewater stream each, which leads to an old open pit where the water is left to evaporate and infiltrate. A 2.5-litre sample of effluent wastewater was collected at the effluent pipe in connection to the open pit dam and transported to the University of Jordan in Amman, and when stored in a fridge at 2 °C.

The second sampling event occurred on the 17th of April 2018. This time two times 3 litres of wastewater from the Al-Abiad mine was collected. HCL was added to one of the bottles to reach below pH 2 and then stored at 2 °C, to maintain the heavy metal concentration at a constant level.

The sampling took place to characterize the wastewater quality. The analysis of the water was conducted at the Chemical Engineering Department at the University of Jordan, Amman.

pH, turbidity, electric conductivity (EC), salinity, and total dissolved solids (TDS) were measured in all samples. The pH was measured with a WTW series inoLab pH 720. The turbidity was analysed by a Lovibond Water Testing Tintometer group TB 210 IR. The EC, TDS and salinity were measured with a Mettler Toledo Seven multi.
The Total Suspended Solids (TSS) were calculated according to the method described in Appendix 3.

The concentration of heavy metals in samples in the industrial wastewater was analysed with the Flame Atomic Absorption Spectrometry (FAAS) method with a Thermo Electron Corporation S Series AA Spectrometer. The samples were filtered before the analysis and stored cold. The sensibility for this method is 0.005 Abs which corresponds to 0.110-0.962 ppm sensibility depending on the examined element. The corresponding absorption sensibility was calculated during the operation of the method. Samples with an absorption less than 0.005 Abs (the adsorption sensibility limit) were determined to have a concentration of 0 ppm (Thermofisher 2020a and 2020b).

Different chemical analysis was performed to calculate the concentration of total phosphorous, total nitrate and chloride, sulphate, alkalinity, SAR, SSP, and ESP, these are described in Appendix 3. The settling velocity of the particles in the slurry was also studied during the experiments.

The generated results from the laboratory work were gathered and brought back to Lund and were further analysed and evaluated. The results were compared with the legalisation and recommendations from the literature study. The obtained results were summarized in a master thesis report.

6 Results

In the following subchapters, the results are presented, starting with the SDGs statistics for Jordan, followed by the observations during the site visits and finally the water quality analysis.

6.1 SDGs statistics

Jordan has many challenges to achieve the SDGs, the following subchapters present a summary of some of the SDGs important for this thesis, the numbers and information are collected from Gapminder (2024), Our World in Data [OWD] (2024) and the Sustainable Development Report [SDR] (2024).

6.1.1 Sustainable Development Goal 1 – No Poverty

The description: End poverty in all its forms everywhere.

The overall evaluation by SDR (2024) concludes that Jordan has achieved SDG 1 - No poverty.

The estimated percentage of the population that is living under the poverty threshold of US$ 2.15/day is 0.6% in 2023, see Figure 8. The indication for this value has a stagnating trend, and the Sustainable Development Report concludes that Jordan has achieved the SDG achievement (SDR 2024).

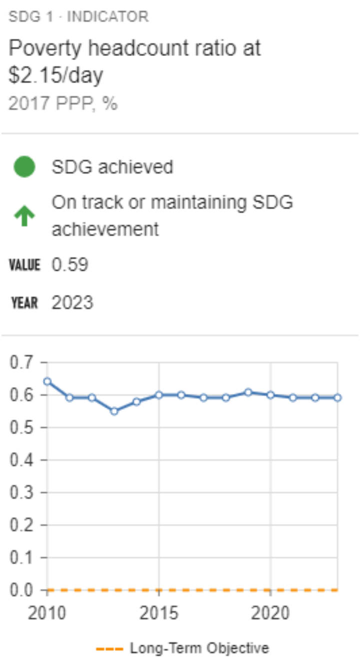

Figure 8. The povertyUS$2.15/day (SDR 2024).

The income per person expressed as GDP/capita is shown in Figure 9. The income has fluctuated up and down during the last decades, but the total trend is positive (Gapminder 2024). The annual growth of GDP per capita in Jordan from 1977 to 2021 is shown in Figure 10.

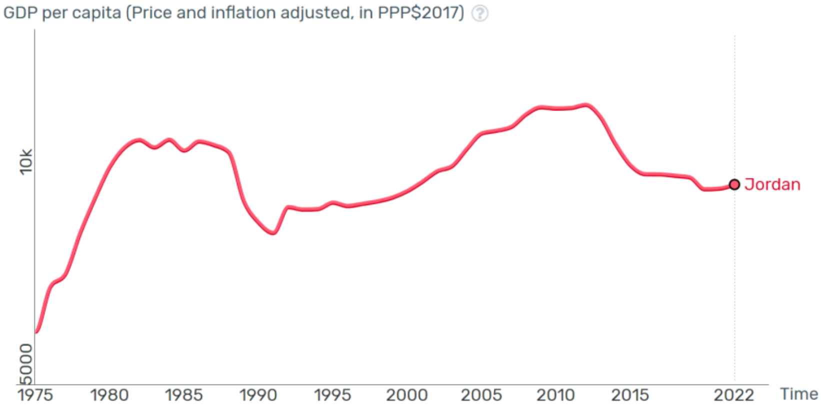

Figure 9. The income per person is expressed as GDP per capita (Gapminder 2024).

Figure 10. Annual growth of GDP per capita, 1977 to 2021 (Our World in Data (OWD) 2024).

6.1.2 Sustainable Development Goal 6 – Clean Water and Sanitation

The description: Ensure availability and sustainable management of water and sanitation for all.

The overall evaluation by SDR (2024) concludes that Jordan has significant challenges remaining and the score is stagnating or increasing at less than 50% of the required rate the SDG 6 - Clean Water and Sanitation.

The estimated percentage of the population using at least a basic drinking water service was 98.94% in 2020. Sustainable Development Report concludes that Jordan has achieved the SDG and that Jordan will maintain the SDG (SDR 2024).

The income per person expressed as GDP/capita is shown in Figure 9. The income has fluctuated up and down during the last decades, but the total trend is positive (Gapminder 2024). The annual growth of GDP per capita in Jordan from 1977 to 2021 is shown in Figure 10.

The level of water stress is the ratio between total freshwater withdrawn by all major sectors and total renewable freshwater resources. For 2019 the ratio was 104.3 according to SDR (2024). The SDG Tracker (2020) has also looked into the freshwater withdrawal data and concluded the ratio between total freshwater withdrawn by all major sectors and total renewable freshwater resources to be 124.5% in 2014, compared to 66.1% in 1977. Withdrawals can exceed 100% of total renewable resources where extraction from non-renewable aquifers or desalination plants is considerable. The desalinated water production was 136.3 MCM in 2016 (FAO - Aquastat 2020), which is equal to about 10% of the total withdrawal. The SDR (2024) states that major challenges are remaining. The measured ratio has not been under 100% (e.g. less withdrawal compared to renewable freshwater resources) since 1987, see Figure 11 (SDG Tracker 2020).

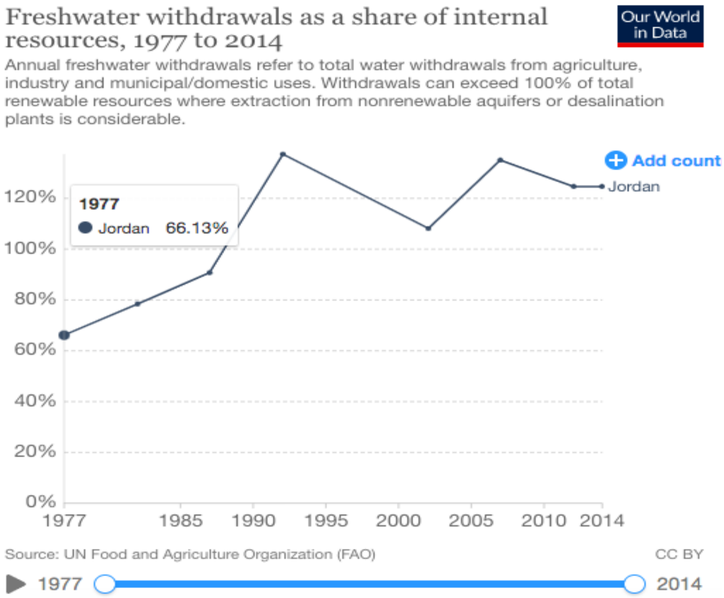

Figure 11. Freshwater withdrawals as a share of internal resources, 1977 to 2014 (Our World in Data [OWD] 2020).

The total withdrawal of freshwater has increased since the 1970s. The following graph shows how much freshwater was withdrawn in billion cubic meters per year (until 2015), Figure 12.

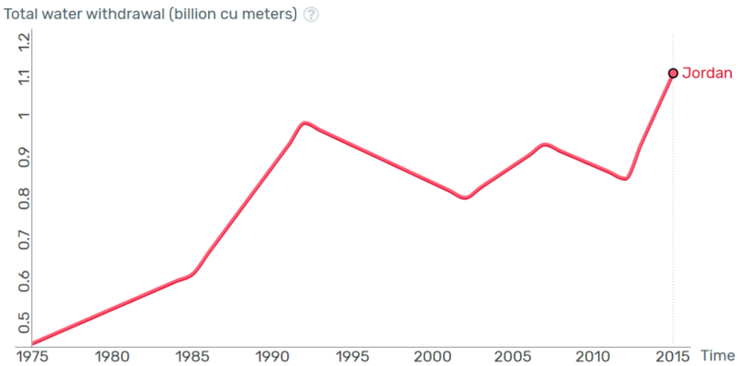

Figure 12. Total water withdrawal in billion cubic meters (Gapminder 2024).

The industrial water withdrawal as a percentage of the total water withdrawal has varied since 2007, and was around 3.44% in 2015 (Gapminder 2024).

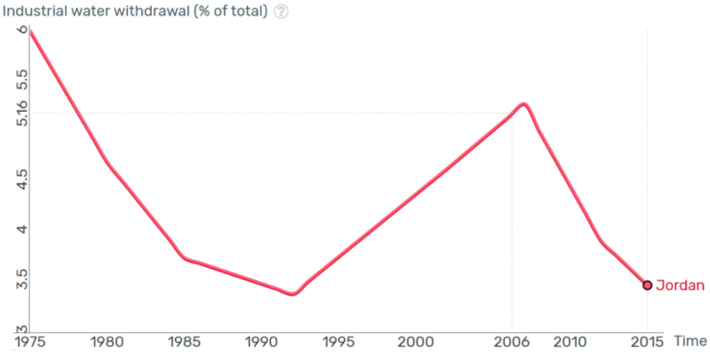

Figure 13. The industrial water withdrawal is expressed as a percentage of the total (Gapminder 2024).

The agricultural water withdrawal as a percentage of the total water withdrawal has decreased since 1992, and was around 52% in 2015 (Gapminder 2024).

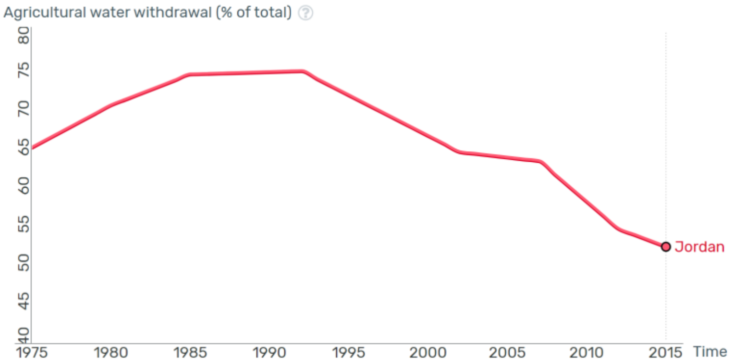

Figure 14. The agricultural water withdrawal is expressed as a percentage of the total (Gapminder 2024).

The percentage of anthropogenic wastewater that receives treatment was 18.63% in 2018, e.g. the amount of collected, generated, or produced wastewater that undergoes at least primary treatment, in Jordan (SDR 2020). The SDG tracker (2020) reported that 82.9% of all domestic wastewater was safely treated in 2018. The SDR (2020) states that significant challenges remain and that information about the trend for the goal is unavailable.

The total amount of water withdrawal, expressed as cubic meters per person, has decreased since the 1990s (OWD 2024).

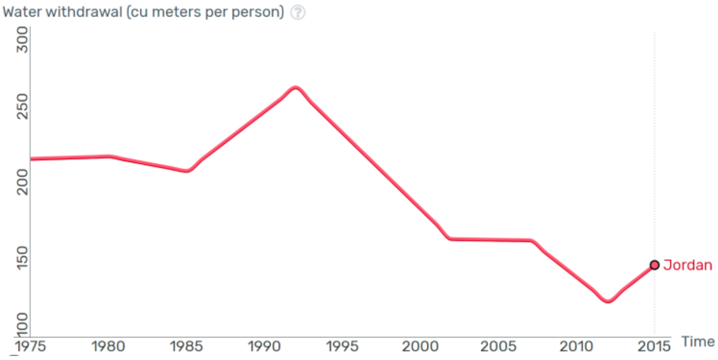

Figure 15. Total water withdrawal in cubic meters per person (Gapminder 2024).

The amount of renewable water per capita in Jordan has decreased since the 1960s (at least), but the population has at the same time increased, see Figure 16 and Figure 17 (mind the time differences along the x-axis).

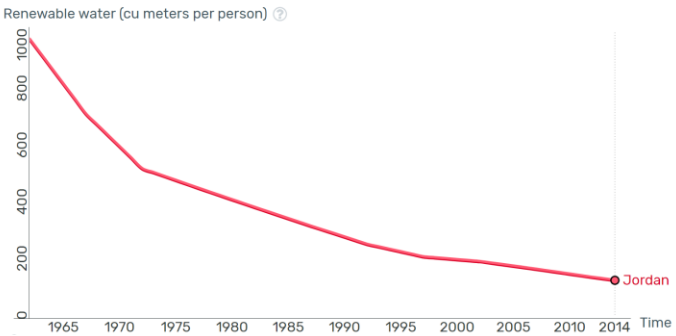

Figure 16. Renewable water is expressed as cubic meters per person (Gapminder 2024).

Jordan’s annual renewable water resources per capita of 123 m^3 (in 2014) is much lower than the global threshold of severe water scarcity of 500 m^3/capita (NWS 2016).

The population of Jordan has grown extensionally over the last decades, see Figure 17. The growth rate is at an average of 1.9%, compared to the global average growth rate of 1.7% (NWS 2016). The population was 11,3 million in 2022 (Gapminder 2024).

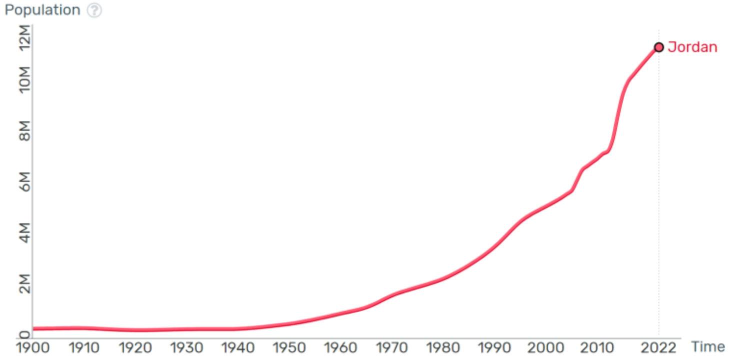

Figure 17. The total population in Jordan (Gapminder 2024).

The total annual freshwater withdrawal as a percentage of the total internal resources drastically increased during the 1970s and 1980s, and then decreased between 1992 and 2002, later increasing again. Since 2007 the freshwater withdrawal has slowly stabilized around an over withdrawal of about 2-5%. The following graph shows the annual freshwater withdrawal of the total internal resources (until 2020), which is a measurement of a country's water stress, see Figure 18 (Gapminder 2024).

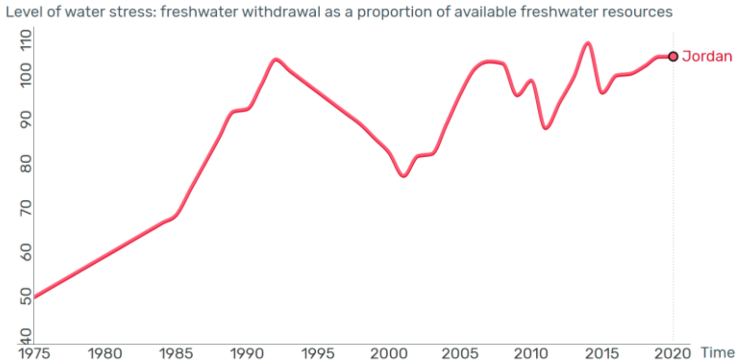

Figure 18. The annual freshwater withdrawal is expressed as a percentage of the total amount of internal resources (Gapminder 2024).

6.1.3 Sustainable Development Goal 8 – Decent Work and Economic Growth

The description: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

The overall evaluation by SDR (2024) concludes that Jordan has major challenges remaining, they have a moderately improving score and they are insufficient to attain SDG 8 - Decent work and economic growth.

The unemployment rate was 17.7% in 2023 (SDR 2024). The SDR states that major challenges remain and that the trend for the score is decreasing, see Figure 19.

Figure 19. The unemployment rate in Jordan is expressed in percentage (SDR 2024).

As a measurement of the industries' importance on the economy the value of the net output after adding up all outputs and subtracting intermediate inputs has been calculated and expressed in the following graph, see Figure 20. The industries' importance has increased since the 1960s to 2009 and then stagnated, as shown in Figure 20 (Gapminder 2024).

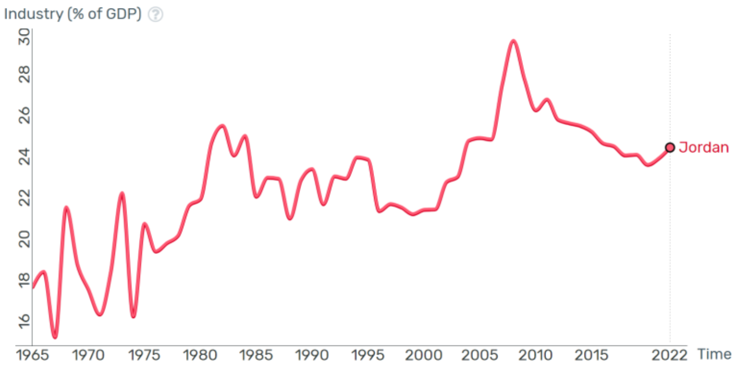

Figure 20. The industries' importance for Jordan is expressed as a percentage of the total GDP (Gapminder 2024).

As a measurement of the agricultural importance on the economy the value of the net output after adding up all outputs and subtracting intermediate inputs has been calculated and expressed as a percentage of the total GDP in the following graph. The agricultural importance decreased from the 1960s to 2000 and then slowly increased again (Gapminder 2024).

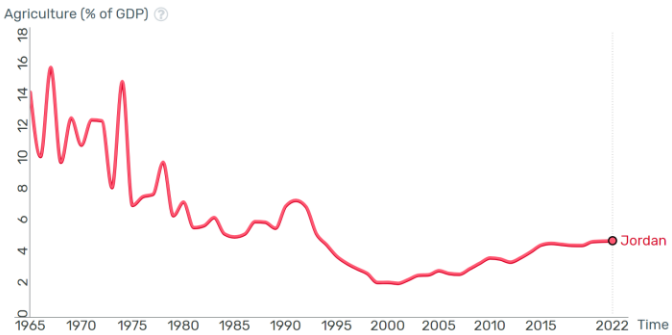

Figure 21. The agricultural importance of Jordan is expressed as a percentage of the total GDP (Gapminder 2024).

6.2 Site visits

On the 21st of February 2018 a visit to the Jordan Phosphate Mines Co. PLC office in Amman to meet Exploration Manager Eng. Mohammad A. Abu Hazeem took place. We introduced ourselves and I presented the project.

The study visits and sample collection took place on the 6th of March 2018, both the Al-Abiad mine and the Eshidiya mine were visited. I was introduced to the mine managers (Eng. Mahmoud Al-Jaradeen mine manager at Al-Abiad mine and Eng. Mohamad Y bani Fawaz, mine manager at Eshidiya mine) at both of the two mines and I got to visit the plants. The second sample collection took place on the 17th of April 2018 at the Al-Abiad mine.

The Al-Abiad mine

The Al-Abiad mine's beneficiation plant (1.) is located close to the Desert Highway and a small village (Al-Abiad) and a community of farmers (4.) is located approximately 5 kilometres south of the beneficiation plant. The mine effluent water was released in an open pit just 2 km east of the plant and the farmers took their water for irrigation from the pond just southwest of the mine (3.). The mining occurs in various pits around the beneficiation site, see Figure 22.

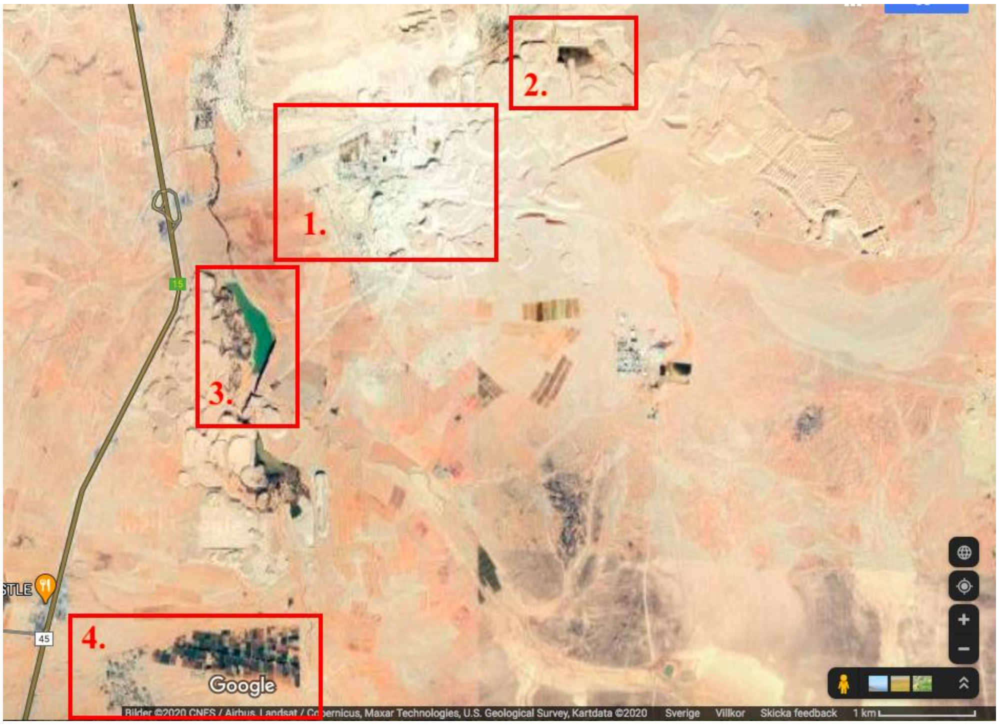

Figure 22. Map over the Al-Abiad mine (Google Maps 2020).

A previous study by El-Hasan (2006) states that the effluent water has been dumped in the pond (3.) where the farmers take their water for irrigation. The mine managers at the Al-Abiad plant also confirmed that the farmers sometimes took water from the open pit where the effluent wastewater was discharged. The farmers around the plant were farming olives, tomatoes, melons, and watermelons amongst other vegetables.

Camels were seen wandering around in the mining area.

According to the mine managers, the production was around 1.6 million tons of phosphate in 2017 and the beneficiation plant produced around 1000 m3 effluent wastewater/day (which includes 400 m3 slime/day) and summed up to 15 000 m3/month. In 2018 the plant had 5 groundwater wells which pumped around 3 000 m3 of freshwater/day to be used in the process and 20 000 m3 of water/month was recycled and reused in the plant as technical water. The mine managers assumed about 3 m3 of freshwater was used to produce 1 ton of phosphate.

The final step at the Al-Abiad mine is the drying step, here the dryers dry the "washing cake" (which contains 18-20% water) by burning oil and raising the temperature to 1 200 °C which reduces the water content to 3%.

The Eshidiya mine

The Eshidiya mine (2.) is remotely located in the desert. The closest large city (Ma'an) (1.) is located approximately 50 km away, see Figure 23 and Figure 24. The JPMC has built a small village of houses and buildings for the workers to live in, and also a bank, a petrol station and a guesthouse are located in the small village. The entire factory area (including IJC) contributes to 4000 jobs.

Figure 23. Map over the Eshidiya mine (Google Maps 2020).

Figure 24. Close-up over the Eshidiya mining site (Google Maps 2024).

Wisbech (2020) has reported that some local farmers use the effluent water from the Eshidiya mine (and the IJC) for livestock and drinking, even though it is not drinkable, but according to the mine managers, there were no farmers active in the area in 2018.

According to the mine managers, the production in 2017 of the Eshidiya mine was around 6.35 tons of phosphate. In 2018, only the washing process was operating, due to high cost and problems with the flotation process, the flotation process hasn’t been used in 6 years they reported. The Eshidiya mine pumped water from 28 nearby wells with a daily flow rate of about 33 000 m3/day or 1 MCM/month in 2018. Of this volume around 35-40% of the freshwater was recirculated in the process, the rest is transferred to an open pit to evaporate or infiltrate into the groundwater. The mine produces and deposits 540-570 m3 of slurry (with effluent wastewater) every hour which is equal to about 400 000 m3/month, the total amount of wastewater produced from the benefaction plant was around 1 000 000 m3/month. The Eshidiya mine doesn’t dry the final product because the factory next door handles the final 18-20% of water in the “washing cake” (interviews with managers at JPMC in 2018).

Both of the mines are located in the desert and the environment around the mines is very dry and dusty. The crushing of the ore creates more dust which travels with the wind and is spread around the mining area and the beneficiation plant.

6.3 Laboratory analysis

The analysis of the samples took place at the Chemical Engineering Department at the University of Jordan, Amman, with great help from Eng. Arwa Sandouqa and her colleagues.

The analysis of pH, turbidity, electric conductivity (EC), salinity, total dissolved solids (TDS) and the total suspended solids (TSS) is shown in Table 5, A1 stands for sample 1 at the Al-Abiad mine and E1 stands for sample 1 at the Eshidiya mine. Salinity is measured in parts per thousand (ppt), which is responding to, kg salt/kg water.

Table 5. Results of the physical analysis of mine wastewater samples of Al-Abiad, sample 1 (A1) and Eshidiya, sample 1 (E1) on the 6th of March.

Sample	*pH*	*Turbidity (NTU)*	*EC (μS/cm)*	*TDS (mg/l)*	*Salinity (ppt)*	*TSS (g/l)*
A1	7.55	AIDL[1]	2900	1450	1.51	33.57
E1	7.62	AIDL[1]	1575	788	0.77	52.79

[1] AIDL= Above Instrument Detection Limit

The pH values (average of 7.6 and 7.7) of both of the mines were slightly alkaline but within WHO recommendations for drinking water (pH 6.5-8.5), within the JORS limits (pH 6.0-9.0), and also within the FAO guidelines for irrigation (pH 6-8). The EC was measured to 2900 μS/cm for Al-Abiad and 1575 μS/cm for Eshidiya. The measured average turbidity of the samples was above the instrument's detection limit, which was 0.01-1100 NTU. The samples were orange-brown and very milky, completely opaque.

The total concentration of elements of interest is shown in the table below (Table 6) for the full list of elements analysed in the first sampling of the Al-Abiad and Eshidiya mine, see Appendix 4.

Table 6. Heavy metal content in each sample.

	Al-Abiad (A1)		*Eshidiya (E1)*	
Element	Concentration (mg/l)	Concentration (meq/l)	Concentration (mg/l)	Concentration (meq/l)
Al	BDL[1]	-	5.0	0.19
Ca	161.5	8.08	146.5	7.33

[1] BDL= Below Detection Limit

The concentration of aluminium was less than the blank sample for the Al-Abiad mine and 5.0 mg/l for the Eshidiya mine. These values are below the Jordanian Standard for effluent reuse for agricultural irrigation (JORS). The calcium level is 161.5 mg/l and 146.5 mg/l for Al-Abiad and Eshidiya, respectively. JORS limits for irrigation is 230.0 mg/l and therefore both the samples are fit for irrigation according to these regulations.

Table 7 shows the results from the analysis of total phosphate, total nitrate, total sulphate, chloride and bicarbonate.

Table 7. Pollutant concentration in samples.

Subsidence	*Al-Abiad (A1)*	*Eshidiya (E1)*
Total Phosphate (PO_4) (mg/l)	4.4	1.7
Total Nitrate (NO_3^-) (mg/l)	18.3	62.4
Total Sulphate (SO_4^{2-}) (mg/l)	458.5	149.3
Chloride (Cl^-) (mg/l)	684.2	384.0
Bicarbonate (HCO_3^-) (mg/l)	52.9	42.7

Sodium Adsorption Ratio (SAR) is a measurement of salinity to evaluate alkalinity hazard. Soluble Sodium Percentage (SSP) is used to evaluate sodium hazard. Exchangeable Sodium Percentage (ESP) is an indicator of soil structure deterioration, see Table 8 for the results.

Table 8. Results from SAR, SSP and ESP analysis of the wastewater of the Al-Abiad mine and the Eshidiya mine, first sampling (A1 & E1).

Sample Site	*Na^+ (meq/l)*	*Mg^{2+} (meq/l)*	*Ca^{2+} (meq/l)*	*K^+ (meq/l)*	*SAR*	*SSP*	*ESP*
Al-Abiad (A1)	18.3	5.2	8.1	0.085	7.1	57.76%	8.44
Eshidiya (E1)	7.4	2.2	7.3	0.027	3.4	43.72%	3.62

Due to wrong storage and accessibility of sample sites, the second mine visit resulted in two representative samples from the Al-Abiad mine and a more accurate analysis of the element content was conducted. Table 9 and Table 10 show the results from the second sampling.

Table 9. Results of the physical analysis of the mine wastewater samples of Al-Abiad (A2) on the 17th of April.

Sample	*pH*	*Turbidity (NTU)*	*EC (μS/cm)*	*TDS (mg/l)*	*Salinity (ppt)*	*TSS (mg/l)*
Al-Abiad (A2)	7.47	AIDL[1]	3780	1900	2.03	132.2

[1] *AIDL= Above Instrument Detection Limit*

Table 10. Chloride concentration in the sample (A2).

	Chloride (Cl^-) (mg/l)
Al-Abiad (A2)	968.9

The turbidity was again very high in the second sample from the Al-Abiad mine (A2). Therefore, a settling experiment was performed and the turbidity was measured of the clear phase 72 hours after the settling experiment, see Table 11 and Figure 25.

Table 11. Results from settling experiment for A2.

Settling time (h)	*Clear phase for A2 (mm)*
1	3
1.5	6
2	9
2.5	10
3	12
3.5	13
4	15
4.5	16
5	16.5
5.5	17
6	18
[…]	-
72	25

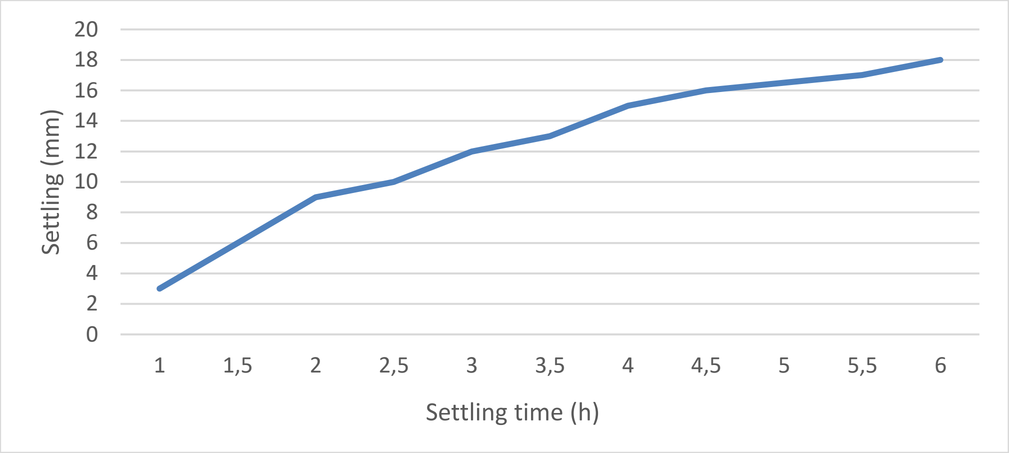

Figure 25. Settling experiment Al-Abiad sample (A2).

The turbidity in the clear phase after 72 hours of settling was very low, 35.3 NTU, see results below in Table 12.

Table 12. Turbidity of clear phase after 72 hours of settling.

Sample	*Turbidity (NTU)*
Al-Abiad (A2)	35.3

The following table highlights some interesting concentrations of heavy metals from the FAAS analysis of the Al-Abiad effluent water, second sampling, the full list of concentrations is found in Appendix 5.

Table 13. Dissolved heavy metal content in Al-Abiad effluent water, sampling 2 (A2).

Element	*Concentration (mg/l)*	*Concentration (meq/l)*	*Detection limit (mg/l)*
Ag	BDL[1]	"less than blank"	
Al	BDL[1]	"less than blank"	
As	BDL[1]	-	0.167
Ca	8515.15	425.76	0.037
Cd	0.32	0.002	0.320
Co	0.74	0.013	
Cr	BDL[1]	"less than blank"	
Cu	0.62	0.010	0.297
Fe	0.34	0.006	0.450
Hg	BDL[1]	"less than blank"	
Mg	326.93	13.451	0.568
Mn	0.64	0.0116	
Mo	BDL[1]	"less than blank"	
Na	930.83	40.490	0.735
Ni	1.15	0.0196	0.962
P	BDL[1]	-	
Pb	0.44	0.0021	0.5
Se	BDL[1]	"less than blank"	
Zn	8.53	0.130	0.173

[1] *BDL= Below Detection Limit*

7 Discussion and Conclusion

In this study, water management of the mining industry in Jordan has been assessed in relation to sustainable development. Sustainable water management is the ability to meet the water needs of the present without compromising the ability of future generations to do the same. This is one of the aims of the Sustainable Development Goals (SDGs).

The increased demand for fertilizers will increase the need for more phosphate mining, which will increase the water demand. The limited amount of renewable freshwater in Jordan is therefore a local, regional, national and global issue. A regional problem since the over-abstraction increases the salinity in the water at a local scale which reduces productivity which in turn increases the demand for more freshwater. A national problem since a part of the mining company is owned by the government and the export of phosphate contributes to the national economy. A global problem since the world is growing and the demand for food is increasing, and with it the demand for fertilizers.

If the over-abstraction of groundwater continues in Jordan the effects on the local groundwater table could be irreversible. The GRAJ (Groundwater Resource Assessment of Jordan) predicts the drawdown in the groundwater table by 2050 to be 5-25 meters in the Al-Abiad area and less than 5 meters in the Eshidiya area. The prediction does not say what impacts these drawdowns might cause but if the groundwater pumping causes saltwater intrusion (which would be irreversible) the damages do not only affect the phosphate mine but also the local farmers and other stakeholders in the region.

Since the government partly owns the JPMC, the production and economy of the mining company affect the national economy directly, in addition to income from export tariffs. This means the government has a double interest in the company’s production but also a responsibility towards the nation's interest in sustainable water management and sustainable development.

Particles which could contain toxic pollutants (e.g., heavy metals and radioactive elements etc.) released by phosphate mining activities and/or derived from phosphate ore and its by-products (which Abed, Sadaqah and Al Kuisi (2008) found in the ore) may be, under physicochemical circumstances, mobilized from the soil to plants and shallow groundwater aquifers, or directly pumped from the open dams by the local farmers. Exposure to these toxic pollutants is a direct health hazard to the mine workers, local farmers and local population, and also to the environment and the terrestrial life around the mine. These pollutants have for example been associated with the prevalence of respiratory, and cardiovascular diseases, cancer, infertility in young people,

and poos training in newborns by a genetic mutation. A study made by Hamed, et.al. (2022) about the local population in a phosphate mining region in Tunisia concluded that family history has relatively limited control over new cancer incidences but daily exposure to mining pollution had a greater impact in the region. Statistics of City residents showed that more frequent cases of cancer are registered within the mining area, and most of the cases were over 60 years old. But also, a great share of the cancer incidences had one family member working in the mining industry which revealed at what level the residents were exposed to pollution. Othman and Al-Masri (2006) conducted a study on the impact of the Syrian phosphate industry on the environment, based on an evaluation of naturally occurring radionuclide concentration in the surroundings of the mine, fertilizers factory and export platforms. Samples of air particles, soil, sediment, plants, water and biota around the industry showed elevated levels of radioactivity, with phosphate dust being the most important risk.
Likewise, could be assumed for the Jordanian phosphate mining industry.

This paper´s analysis of the samples concluded high salinity in the effluent wastewater from both of the beneficiation plants, this is backed up by the Ministry of Water and Irrigation and other researchers, for example, Al-Hwaiti et. al. (2016) and Rimawi, et. al (2008). According to FAO recommendations for irrigation, the salinity (looking at EC and/or TDS) was medium severe and only with "slight to moderate degree of restrictions for irrigation purposes". High salinity in the wastewater released in the evaporation and infiltration ponds could amplify the salinity in the groundwater and make it unsuitable for use in the production chain. However, Jiries, El-Hasan, Al-Hweiti and Seiler (2004) concluded, by studying stable isotopes, an indication of little or no mixing between the effluent water and groundwater in the area of Al-Abia. The same study also suspected some of the wells to be affected by saltwater intrusion at the Al-Abiad mine (i.e. saline water from a lower aquifer was being drawn up). This could affect the productivity chain and increase the withdrawal of groundwater.

The turbidity in the samples before and after settlement was high compared with the Jordanian Standards (JS). The turbidity in the second sampling from the Al-Abiad mine was higher than the first. Therefore, the water needs some type of treatment process to reduce the turbidity to be released in a recipient or to be reused for irrigation. The treatment could for example be enhanced settling (i.e. adding a coagulant) or some kind of filter. TSS and TDS were also high for both of the mines but if most of the sediments get to settle the clear phase will pass the standard for irrigation and discharge to surface waters.

Chloride (Cl) was over the limits for both Al-Abiad and for Eshidiya, also the second sampling in Al-Abiad showed values over the limit. Sulphate (SO_4) was too high for the Al-Abiad mine to be discharged to surface waters, but still under the JS for irrigation. The Eshidiya mine effluent sulphate was under the limits.

Saline effluent water increases heavy metal mobilization in soils. The extent of mobilization depends on the type of heavy metal present, the total amount of heavy metal present and the type of salt causing the salinization. This means that all these factors must be explicitly considered when assessing the risk of salinization on heavy metal release from soils. Metal mobilization through dissolution in runoff or leachate water poses a direct risk of groundwater contamination. Acosta, Jansen, Kalbitz, Faz and Martinez-Martinez (2011) studied the effect of salinity induced by $CaCl_2$, $MgCl_2$, NaCl and Na_2SO_4 on the mobility of Cu, Cd, Pb and Zn, which is of interest in this paper. They found that an increase in ionic strength by any salts promoted a higher release of Cd than the other metals. When $CaCl_2$ and NaCl were applied, Cd and Pb showed the highest degree of mobilization. When $MgCl_2$ was applied, Cd and Cu were mobilized the most. Finally, an increase of Na_2SO_4 also promoted the strongest mobilization of Cd and Cu. These results are very interesting for this paper. Future research is needed to investigate the impact of the infiltration by the effluent saline wastewater from the mines.

The following concentrations of heavy metals are only for the Al-Abiad mine. The calcium (Ca) was very high, almost 40 times more than the restrictions, cadmium (Cd), cobalt (Co), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb) and zinc (Zn) were also over the limits for both irrigation and discharge to surface water according to the JS. Cd, Co, Mn, Ni and Zn were also over the recommended maximum concentration guidelines for irrigation from FAO. Copper (Cu) was over the limit for irrigation but under the limit for discharge to surface waters for the JS, but also over the recommended maximum concentration guidelines from FAO.

The above concentrations of different elements are observed during only 1-2 samplings, daily and monthly variations must be taken into consideration and conclusions should not be drawn only based on these two samplings. The samples only give a snapshot of the effluent water during these three sampling events (two for Al-Abiad and one for Eshidiya).

The following processes are efficient at removing or are tested for their efficiency in removing heavy metals: activated carbon, adsorption, chemical coagulation, chemical precipitation, electrocoagulation, electro-dialysis, ion exchange, membrane filtration, nanofiltration, etc. Unfortunately, many of the above treatment methods are considered costly and sometimes inefficient, especially if the concentration of the pollutant in the water is lower than 1-100 mg/l. Also, some processes require large amounts of reagents and energy to remove the heavy metals completely and are technically advanced (Al-Qodah and Al-Shannag 2017).

The high salinity could for example be removed by dissolved air flotation (DAF) and nanofiltration (NF) process, membrane filtration or reverse osmosis (Al-Zoubi and Al-Thyabat 2012 and Saidan, et. al. 2020).

To stop the infiltration of the polluted water, the effluent water could be collected and stored in a dam with an impermeable layer in the bottom. This would constrain the wastewater to pollute the groundwater, decrease possible heavy metal mobilization in soils and also stop the possible increase in salinity in the nearby wells. The remaining masses could later be dried up and collected to be treated or relocated to a close landfill.

If the mining company would invest in the treatment of the effluent water, the water and the nutrients in it could be used for example irrigation or reused at the plant. Today's management of effluent water probably mainly occurs because of the regulations. The Jordanian standards do not apply to industrial effluent water which does not end up in surface water or is reused for irrigation, the water from the mines evaporates or infiltrates the groundwater, none of those two are controlled by the regulations for industrial water, only for domestic wastewater. It might need management control measures or voluntary measures for the company to invest in a treatment facility for the effluent water, to stop the pollution of the environment and groundwater.

The economic competitiveness of the phosphate sector has been important for the development of Jordan. JPMC brings economic benefits to society, including the provision of regional employment and the generation of wealth. There is a large potential for diversifying the national economy away from its traditional reliance on the export of phosphate. Titi et al. (2019) conclude in their report that the mining industry mustn't be constrained because the industry's additional expansion offers a large potential for growth and economic development. The sector contributes to GDP and to export income, and also creates linkages to other sectors of Jordan's economy. All that is true, but economic growth should not be at the expense of the environment or society to reach sustainable development. Looking at the global SDGs the government of Jordan has many responsibilities, towards its residents, the environment, and creating the conditions to favour entrepreneurship and economic growth. On one hand, the mining industry creates jobs, and it resolves income and economic growth for the country. On the other hand, it pollutes the environment and could be a threat to public health and challenging the future generation's right to clean water, their right to fulfil their needs. The government is situated in a conflict of interest between SDGs 6, 8 and 1 (clean water), (decent work + economic growth) and (no poverty). The government is also sitting on two chairs as both the part-owner and as supervisory authority, this could be lucrative since the government depends on the income from the phosphate mines but at the same time, the Water Authority of Jordan (who sets the regulations and standards for the industrial effluent water) is directly linked with the Prime Minister of Jordan (and the government). But, this position could (and maybe also should) be used as an opportunity to take the initiative to lead the way towards more environmentally friendly entrepreneurship in Jordan, by investigating and taking responsibility for the effluent wastewater. The newest investment with the treatment plant to recirculate more water back into the benefaction plant is a first step but the effluent wastewater must also be treated before it is released into nature. One of the goals in the National Water Strategy 2023-2040 is after all to "*Minimize pollution risks to protect groundwater quality*".

Lastly, an increase in Jordan's phosphate production, with several times its current production, issues such as water availability, access to energy, local environmental impacts and geopolitical threats should be addressed on a regional level.

In conclusion, the phosphate mining industry in Jordan has been and will continue to be an important part of Jordan's economy. But, the mining (as it is today) is not sustainable in the way it is operated. Investment in the effluent wastewater treatment needs to be done, and soon. The phosphate mining industry in Jordan has had a debt of environmental pollution and over-abstraction of groundwater for many years.

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Appendix

Appendix 1 - Jordanian Standard (JS:202/2007) for industrial effluent reuse for agricultural irrigation, and for discharge to surface waters

Appendix 2 - Food and Agriculture Organization (FAO) guidelines for interpretation of water quality for irrigation and FAO guidelines for trace metals in irrigation water

Appendix 3 - Laboratory analyses methodology

Appendix 4 - Full list of concentration in Al-Abiad and Eshidiya effluent wastewater, first sampling (A1 & E1).

Appendix 5 - Full list of concentration in Al-Abiad effluent wastewater, second sampling (A2).

Appendix 1

Jordanian Standard (JS:202/2007) for industrial effluent reuse for agricultural irrigation, and for discharge to surface waters

This standard specifies the requirements and restrictions on the discharge of reclaimed wastewater from industrial facilities or treatment plants to surface waters - streams, wadies or water bodies, or reuse for irrigation purposes. The standard consists of different groups which is based on what type of vegetable would be irrigated.

Table 14. Description of the different vegetable groups for the Jordanian Standard.

Group A	Cooked vegetables, parking areas, parks, playgrounds and side of roads within cities
Group B	Plenteous trees and green areas, side of roads outside cities and landscaping
Group C	Field crops, industrial crops and forestry

The different groups have different limits for various parameters/pollutions, see Table 15.

Table 15. Jordanian Standard (JS:202/2007) for effluent reuse for agricultural irrigation, according to Table 10 and for discharge to surface waters.

Parameter		*unit*	***Irrigation to Group***			***Discharge to Surface waters***
			A	**B**	**C**	
BOD_5	Biochemical Oxygen Demand	mg/l	30	200	300	60
COD	Chemical Oxygen Demand	mg/l	100	500	500	150
DO	Dissolved Oxygen	mg/l	>2.0	-	-	>2.0
TSS	Total Suspended Solids	mg/l	50	200	300	60
pH		-	6-9	6-9	6-9	6-9
Turbidity		NTU	10	-	-	15
NO_3	Nitrates	mg/l	30	45	70	
T-N	Total Nitrogen	mg/l	45	70	100	70
E. Coli	Escherichia Coli	MPN/ 100ml	100	1000	-	1000
Intestinal Helminth eggs		eggs/l	≤ 1	≤ 1	≤ 1	≤ 1

The standard also consists of parameters/pollutions which have the same limits for all the groups of vegetables but different for discharge to surface waters.

Table 16. Jordanian Standard (JS:202/2007) for effluent reuse for agricultural irrigation, and for discharge to surface waters.

Parameter		*unit*	*For irrigation*	*Discharge to Surface Waters*
FOG	Fat, Oil and Grease	mg/l	8	8
Phenol	Phenol	mg/l	< 0.002	< 0.002
MBAS	Methylene Blue Active Substance	mg/l	100	25
TDS	Total Dissolved Solids	mg/l	2000	2000
Ca	Calcium	mg/l	230	
Cl	Chloride	mg/l	400	350
HCO_3	Bicarbonate	mg/l	400	400
Mg	Magnesium	mg/l	100	
Na	Sodium	mg/l	230	
SO_4	Sulphates	mg/l	500	300
Total PO_4	Phosphates	mg/l	30	15
SAR	Sodium Adsorption Rate	-	9	9
		Heavy Metals		
Ag	Silver	mg/l		0.1
Al	Aluminium	mg/l	5.0	2.0
As	Arsenic	mg/l	0.1	0.05
B	Boron	mg/l	1.0	1.0
Be	Beryllium	mg/l	0.1	0.1
Cd	Cadmium	mg/l	0.01	0.01
CN	Cyanide	mg/l	0.1	0.05
Co	Cobalt	mg/l	0.05	0.05
Cr	Chromium	mg/l	0.1	0.1
Cu	Copper	mg/l	0.2	1.5
F	Fluoride	mg/l	2.0	2.0
Fe	Iron	mg/l	5.0	5.0
Hg	Mercury	mg/l	0.002	0.002
Li	Lithium	mg/l	0.075 (2.5 for citrus crop)	2.5
Mn	Manganese	mg/l	0.2	0.2
Mo	Molybdenum	mg/l	0.01	0.01
Ni	Nickel	mg/l	0.2	0.2
Pb	Lead	mg/l	0.2	0.2
Se	Selenium	mg/l	0.05	0.05
V	Vanadium	mg/l	0.1	0.1
Zn	Zinc	mg/l	5.0	5.0

Appendix 2

Food and Agriculture Organization (FAO) guidelines for interpretation of water quality for irrigation and FAO guidelines for trace metals in irrigation water

The guidelines from FAO do not take into consideration different vegetables but do however have degrees of restrictions of use, see Table 17 and Table 18.

Table 17. FAO guidelines for trace metals in irrigation water.

Element	*Recommended maximum concentration (mg/l)*	*Remarks*
Al	5.0	Can cause non-productivity in acid soils (pH <5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate and toxicity.
As	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to > 0.05 mg/L for rice.
Be	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Cd	0.10	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	0.10	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.
Cu	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solutions.
F	1.0	Inactivated by neutral and alkaline soils.
Fe	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Li	2.5	Tolerated by most crops up to 5 mg/L; mobile in soil. Toxic to citrus at low concentrations (< 0.075 mg/L). Acts similarly to boron.
Mn	0.20	Toxic to a number of crops at a few tenths to a few mg/L, but usually only in acid soils.
Mo	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	0.20	Toxic to a number of plants at 0.5 mg/L to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Pb	5.0	Can inhibit plant cell growth at very high concentrations.
Se	0.02	Toxic to plants at concentrations as low as 0.025 mg/L and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Sn	-	Effectively excluded by plants; specific tolerance unknown.
Ti	-	Effectively excluded by plants; specific tolerance unknown.
W	-	Effectively excluded by plants; specific tolerance unknown.
V	0.10	Toxic to many plants at relatively low concentrations.
Zn	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

Table 18. FAO guidelines for interpretation of water quality for irrigation.

Potential irrigation problem	*Units*	*Degree of restriction on use*		
		None	Slight to moderate	Severe
Salinity (affects crop water availability)				
ECw	dS/m	< 0.7	0.7-3.0	>3.0
(or)				
TDS	mg/l	<450	450-2000	>2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using ECw and SAR together)				
SAR = 0-3	and ECw =	>0.7	0.7-0.2	<0.2
= 3-6	=	>1.2	1.2-0.3	<0.3
= 6-12	=	>1.9	1.9-0.5	<0.5
= 12-20	=	>2.9	2.9-1.3	<1.3
= 20-40	=	>5.0	5.0-2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Na	SAR	<3.0	3.0-9.0	>9.0
Surface irrigation	mg/l	<69.0	>69.0	-
Cl	mg/l	<142.0	142.0-355.0	>355.0
Surface irrigation	mg/l	<106.5	>106.5	-
Sprinkler irrigation	mg/l	<0.7	0.7-3.0	>3.0
Miscellaneous effects (affects susceptible)				
NO3-H	mg/l	<5.0	5.0-30.0	>30.0
HCO3 (overhead sprinkling only)	mg/l	<91.5	91.5-518.5	>518.5
pH	Normal range 6.5-8.4			

Appendix 3

Laboratory analyses methodology

Methodology of calculating Total Suspended Solids (TSS)

The amount of Total Suspended Solids (TSS) in the samples was analysed by Jar test filtration assembly. This was done by letting 100 ml of sample be filtered through a filter paper folded twice to fit into a funnel. The filter paper used for this analysis was 125 mm Whatman No. 40. The paper with the TSS was dried at 104 ± 1°C until dry (approximately 2 hours). The paper was weighed before and after the filtration and drying. The TSS was later calculated via the following equation:

$$TSS = \frac{Weight\ filtrate\ (on\ dry\ paper) - Weight\ dry\ paper}{volume\ sample}$$

Analysis of total phosphorus

The total phosphorus (T-P) in the samples was determined by a spectrophotometric assay. Five different standard solutions (STDs) were prepared, 5 ppm, 10 ppm, 20 ppm, 30 ppm and a blank. 10 ml of the regent, consisting of ammonium molybdate and ammonium vanadate in HNO3, was prepared and added to 10 ml of all STDs and 10 ml of each wastewater sample. The solutions were left for 30 min before reading the absorption at a wavelength of λ = 410 nm by an Ultra Videt Spectrophotometer. The T-P content was determined via the fitted linear absorption curve calculated from the absorption of the STDs.

Analysis of total nitrate

The total nitrate (T-NO_3) in the samples was analysed by a spectrophotometric assay. Five different standard solutions were prepared, 5 ppm, 10 ppm, 20 ppm, 30 ppm and a blank. Add 2 ml of 1.0 N HCl to the standards and the wastewater samples. Analyse the absorption at λ = 220nm by an Ultra Videt Spectrophotometer. The results of the STD solutions were fitted to a linear adsorption curve, which was used to calculate the total nitrogen in the wastewater samples.

Analysis of chloride

The amount of chloride (Cl^-) in the samples was calculated with a 0.1 N silver nitrate ($AgNO_3$) titration. 5 ml of NaCl together with 3 drops of potassium chromate indicator was titrated with 0.1 N silver nitrate solution ($AgNO_3$) to perform standardization of the solution. 3 drops of the indicator were added to 10 ml of each sample, which later were titrated with 0.1 N $AgNO_3$. The chloride concentration was calculated by the following equation:

$$c[Cl^-] = \frac{N(AgNO_3) * V(AgNO_3) * M(Cl^-)}{V\ (sample)}\ (g/l)$$

Analysis of sulphate

The concentration of sulphate (SO_4^-) in the samples was examined by a sulphate spectrophotometric assay. A set of standard solutions (STDs) were prepared (5, 10, 20 30 ppm respectively). 10 ml of each STD, samples and a blank were mixed with 2 ml of 1 N HCl and 2 ml of $BaCl_2$ (25%). The absorption of the solutions at λ = 492 nm was read by an Ultra Videt Spectrophotometer after 45 minutes. The concentration of sulphate in the samples was determined via the fitted linear absorption curve calculated from the absorption of the STDs.

Analysis of alkalinity

The samples' alkalinity was determined by titration with H_2SO_4. 3 drops of phenolphthalein (phph) indicator were added to 10 ml of the sample. The samples were titrated with 0.02 N H_2SO_4. The titrated volume (V1) was read when the solution turned from pink to colourless. 3 drops of mixed indicator (methyl orange and bromocresol green) were later added and the solution was again titrated with H_2SO_4. This time the solutions changed color from greenblue to orange at pH FAFAS. The titrated volume (V2) was read and the alkalinity was calculated according to the following equation:

$$c[HCO_3^-] = \frac{(V2 - V1) * M(HCO_3^-) * 1000 * N\ (H_2SO_4)}{V\ (sample\ in\ ml)}\ (ppm)$$

Analysis and calculations of SAR, SSP, ESP

SAR (Sodium Adsorption Ratio) is a measurement of salinity to evaluate alkalinity hazard. SSP (Soluble Sodium Percentage) is used to evaluate sodium hazard. ESP (Exchangeable Sodium Percentage) is an indicator of soil structure deterioration.

$$SAR = \frac{Na^{+}(meq/l)}{\sqrt{\frac{Ca^{2+}(meq/l) + Mg^{2+}(meq/l)}{2}}}$$

$$SSP = \frac{(Na^{+}(meq/l)) * 100}{Ca^{2+}(meq/l) + Mg^{2+}(meq/l) + Na^{+}(meq/l) + K^{+}(meq/l)}$$

$$ESP = \frac{100(-0.0126 + 0.01475 * SAR)}{1 + (-0.0126 + 0.01475 * SAR)}$$

Appendix 4

Full list of concentration in Al-Abiad and Eshidiya effluent wastewater, first sampling (A1 & E1).

Table 19. Heavy metal concentration in sample 1 at Al-Abiad and Eshidiya mine.

	Al-Abiad (A1)		*Eshidiya (E1)*	
Element	Concentration (mg/l)	Concentration (meq/l)	Concentration (mg/l)	Concentration (meq/l)
Al	BDL[1]	-	5.0	0.185
Ca	161.5	8.075	146.5	7.325
Cd	0.15	0.001	BDL[1]	-
Co	0.47	0.008	0.19	0.003
Cu	0.22	0.003	0.22	0.003
Fe	BDL[1]	-	BDL[1]	-
K	3.3	0.085	1.05	0.027
Mg	62.7	5.225	26.9	2.242
Mn	BDL[1]	-	BDL[1]	-
Na	420	18.3	172.4	7.5
Ni	0.42	0.008	0.19	0.003
Pb	BDL[1]	-	BDL[1]	-
Zn	BDL[1]	-	BDL[1]	-

[1] BDL= Below Detection Limit

Appendix 5

Full list of concentration in Al-Abiad effluent wastewater, second sampling (A2).

Table 20. Heavy metal concentration in sample 2 at Al-Abiad.

Element	Concentration (mg/l)	Concentration (meq/l)	Detection limit (mg/l)
Al	BDL[1]	“less than blank”	
Ag	BDL[1]	“less than blank”	
As	BDL[1]	-	0.167
Au	BDL[1]	“less than blank”	
B	BDL[1]	“less than blank”	
Ca	8515.15	425.76	0.037
Cd	0.32	0.002	0.320
Co	0.74	0.013	
Cr	BDL[1]	“less than blank”	
Cu	0.62	0.010	0.297
Fe	0.34	0.006	0.450
Hg	BDL[1]	“less than blank”	
K	12.04	0.308	0.110
Mg	326.93	13.451	0.568
Mn	0.64	0.0116	
Mo	BDL[1]	“less than blank”	
Na	930.83	40.490	0.735
Ni	1.15	0.0196	0.962
P	BDL[1]	-	
Pb	0.44	0.0021	0.5
Pt	BDL[1]	“less than blank”	

Se	BDL[1]	"less than blank"	
Si	BDL[1]	"less than blank"	
Sn	BDL[1]	"less than blank"	
Zn	8.53	0.130	0.173

[1] BDL= Below Detection Limit