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Discussions

A Water-Energy-Food Nexus Approach for Conducting Trade-off Analysis: Morocco's Phosphate Industry in the Khouribga Region

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Abstract

The aim of the study is to apply the Nexus approach to conduct trade-off analysis between industrial and agricultural areas. A Water-Energy-Food Nexus-Phosphate (WEF-P) Tool was developed, based on integrating the supply chain processes, transportation, and water-energy footprints. The study evaluated the impact of the phosphate industry on regional water, energy, and food in Khouribga, the representative phosphate mining area of Morocco, using the developed WEF-P Tool. To address the potential impacts on the water supply in agricultural areas, the field data of processes (from mining to transportation) were collected and applied to possible supply chain scenarios according to type of product (phosphate rock and slurry). Analysis of positive impacts of dynamic management suggests that seasonal management of phosphate production allows less phosphate production during the irrigation season (thereby increasing water available for agriculture) and greater phosphate production during wetter seasons (when less water is demanded for agricultural production). Additionally, the transport of raw phosphate slurry through a pipeline increases the total water required to 34.6 million m^3, an increase of 76% over the "business as usual scenario" (BAU), but results in an energy savings of nearly 80% over BAU, as slurry transport requires only 40.5 million litres of fossil fuel, compared with 204 million litres for rock transport. During the dry or "water scarce" season (May to July) when irrigation is needed, total ground water use decreased from 5.8 to 5.2 million m^3. Dynamic management of the phosphate industry can also save 143 MWh of electricity annually and is accompanied by a reduction of 117 tons of CO_2 emissions. In a changing climate, making water available at the correct season and location requires analysis of complex scientific, technical, socio-economical, regulatory, and political issues. The WEF-P Tool can assist in assessing user-created scenarios, thus becomes a management-decision aid for effectively ensuring more sustainable management of limited resources and increased reliability of water resources for both agricultural and industrial use. This study on the application of WEF Nexus to the Phosphate industry can be a roadmap for other industrial application where trade-offs between the primary resources exist.

Keywords: *Phosphate, Water-Energy-Food Nexus, Morocco, WEF-P Tool*

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1 Introduction

The debate surrounding effectively addressing water and food security challenges stems from questions about whether the water-food crisis is due to a poor understanding of these resources and/or to their improper management (Mohtar et al., 2015). One long-standing challenge to water management lies in the lack of integration between the sectors interacting with water across geographical areas or within large, transboundary, basins (Mohtar and Lawford, 2016). Projections about available water, food, energy, or soil (quality) resources are often alarming. A fundamental shift is needed away from traditional 'silo' approaches and toward more integrative, systems approaches (Daher and Mohtar, 2015).

Nexus thinking emerged from the understanding that natural resource availability is limited by, and can limit, economic growth and the goals associated with human well-being (Hoff, 2011; Keulertz, 2016). The 2015 World Economic Forum identified water, food, and energy shocks as primary future risks and called for increased efficiency in water use across all sectors and implementation of integrated water resources management. The interlinkages across key natural resource sectors and improved production efficiency offer a win-win strategy for environmental sustainability, whether for current or future generations (Ringler et al., 2013). Nexus frameworks identify key issues in food, water, and energy securities through the lens of sustainability, seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The Water-Energy-Food (WEF) Nexus offers a platform for development of the analytics necessary for understanding the trade-offs and catalysing a dialogue between stakeholders (Mohtar and Daher, 2016; Mohtar, R. H. and Daher, 2014). The core of the Nexus concept is that the production, consumption, and distribution of water, energy, and food are inextricably inter-linked: decisions made in one sector typically impact the other sectors (Hoff 2011, Mohtar and Daher, 2012). WEF Nexus tool analytics (Daher and Mohtar, 2015) allow holistic quantification of the impact of resource allocation strategies to support informed, inclusive dialogue between all stakeholders, including policy makers, private sector firms, and civil society. Each of these stakeholders becomes involved at different stages and scales in the decision-making process. The WEF Nexus approach is useful for assessing and managing the water, food, and land securities in regions where resources are shared among various stakeholders such as industry and farmlands.

Morocco's phosphate and agriculture industries offer an example of increasing resource pressures attributable to near- and medium-term growth across these sectors (Taleb 2006). A holistic approach that considers the needs of all stakeholders is needed to resolve the resource allocation pressures. Between 1990 and 2016, Morocco's population grew from 25 million to 35 million people (https://data.worldbank.org). Both crop production and total cultivated land significantly increased since 1971, and half of Morocco's arable land receives less than 350 mm of rainfall annually and nearly 87.3% of Morocco's total water withdrawals are used for agriculture (http://www.fao.rg/ag/aquastat). Per capita consumption of electric power increased from 358 kWh (1990) to 901 kWh (2014); energy use by oil equivalent per capita increased from 306 to 553 kg during the same period (https://data.worldbank.org). Proper management of water, energy, and food resources is critical to economic, social, and environmental well-being.

Globally, phosphates lie at the heart of agriculture and soil enhancement. More than 75% of global phosphate reserves, representing 30% of the global market share, are found in Morocco, positioning that country for a leading role in global food security (OCP 2013). Phosphate mining and its chemical processing require considerable water, energy, land, and other resource inputs. Morocco uses recycling and reverse osmosis desalination to help secure the water needed for phosphate production processes and to relieve some of the pressure on its fresh water resources. Each water source carries a distinct energy tag that must be accounted for, especially in a country that imports nearly 90% of the energy it consumes. Water, energy, land, and financial resources are frequently shared between multiple, sectors, especially agriculture (food production) and municipal (growing urbanization): Morocco is no exception. It is critical that this potential sectoral competition be understood, quantified, and accounted for when planning for the sustainable progress of all sectors. To minimize inevitable competition for resources, an integrated approach to resource allocation is needed, an approach that quantifies the trade-offs associated with possible pathways. As Morocco heads toward achieving its phosphate production goals, its ability to account for the resources associated with that achievement should be balanced with the associated (and increasing) agriculture and municipal demand projections: this is key to sustainable resource allocation.

This study adapted the WEF Nexus Tool linking industry and agriculture to also integrate the supply chain for industrial products. Using the Tool, we evaluated the impacts of Morocco's phosphate production on the water, energy, and food resource systems of its mining region, and addressed the resource elements in the supply chain management of phosphate production. Specifically, we assessed the impacts of phosphate mining and transportation by slurry pipeline on potential water and energy savings in the mining area. The results suggest the need for a dynamic management of phosphate production, one that adjusts monthly phosphate production in consideration of its potential impacts on water and energy management in agricultural areas.

The specific objectives of the study is to quantify the water, energy, food, energy of phosphate industry in the Khouribga region of Morocco and to assess the trade-offs water and resources allocation between agricultural and industrial use.

2 Materials and methods

2.1 Overall Framework of Water-Energy-Food-Nexus - Phosphate (WEF-P) Tool

Water resources are shared by the phosphate industry and the agricultural interests in the region of study. Sustainable water management must holistically consider the allocation of water resources for both industrial production and the irrigation of agricultural crops. New water (grey, produced, brackish, and waste) is a resource with the potential to significantly contribute to bridging water and food gaps (Mohtar et al., 2015); however, new water also carries an energy footprint that must be considered when increasing local food production. Agriculture's demand for water potentially competes with the demands of a growing industry. The WEF-P tool can assess various scenarios and help account for the interdependencies between food and industrial production, between water and energy consumption. Only thus can the trade-offs associated with potential resource allocation pathways be quantified.

The developed WEF-P Tool, adapted from the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015), considers the supply chain of final product in terms of its resource consumption. It assesses the impacts of various scenarios and possible responses to regional resource management needs. The structure of the WEF-P Tool is illustrated in Fig.1. The Tool quantifies the use of water and energy and the amount of CO_2 emitted for each scenario. It also quantifies the water and energy savings that result from choices made regarding transportation scenarios. The tool assesses the effects of decisions regarding dynamic management of phosphate production as these impact water and energy securities.

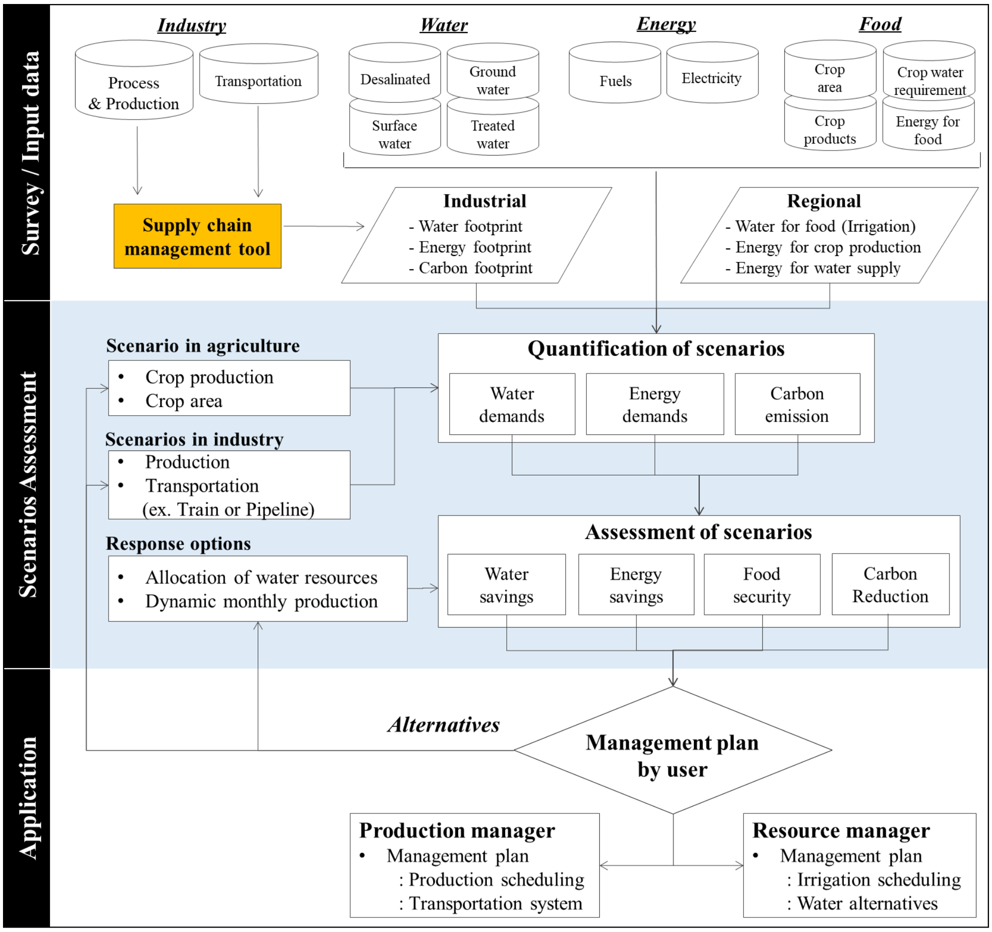

Figure 1 Assessment of holistic impacts of various scenarios relating to phosphate industry, agriculture, and resource management using WEF-P Tool

2.2 Application of Integrated Supply Chains to WEF-P Tool

2.2.1 Site descriptions

Khouribga represents Morocco's primary phosphate mining area and includes three sites from which raw phosphate is excavated and transported for chemical processing and fertilizer production: Sidi Chennane, Merah Lahrach, and Bani Amir. The demand for raw phosphate and the production and export of fertilizer and its products from Jorf Lasfar drives the upstream mining activity of Khouribga. Data collected during visits to the mining fields indicate 1.68 million tons of raw phosphate were excavated and transported to Jorf Lasfar each month during 2015. About 40% of the product was transported via pipeline; as slurry; the remaining 60% was transported by train as rock.

Phosphate is the primary component in the manufacture of phosphorous-fertilizer. The transport of the raw phosphate from Khouribga (mining area) to Jorf Lasfar (industrial production area) is a primary project in Morocco (OCP, 2016a). Plans were to increase phosphate production and phase out transport by train. Tracks were replaced by a 187 km pipeline that ensures the continuous arrival of raw phosphate from the mining area to the industrial area (OCP, 2016a). These plans impact regional water, energy, and food management plans. In particular, shifting from train to pipeline requires additional water to convert dry rock into liquid slurry and reduces the energy otherwise required to dry the phosphate rocks before transport by train.

Shifting from train to pipeline changes the demand for water and energy resources at both the upstream (mining) and the downstream (production) locations.

In accordance with the "Plan Maroc Vert" and the National Water Plan for Morocco, the use of surface water as a substitute for groundwater is encouraged and water withdrawals from the region's aquifers are being phased out since 2010, eventually to be replaced entirely by surface water, supplied to the mining sites from the nearby Ait Messaoud dam, which has a capacity of 13.20 million m³. The plan is to allocate 4.5 million m³ yr^{-1} of water from the dam to the mining site. Additional water comes from the water treatment plant, with a capacity of 5 million m³ yr^{-1} (OCP, 2016b). The phosphate mining area is encircled by cropland, whose water is also supplied from the dam. Both the mining and agricultural activities of the region represent growing enterprises that place added pressure on available water resources and make the sustainable management of the water supply a hotspot to be considered in trade-off analyses.

2.2.2 Application of WEF-P Tool

The WEF-P Tool used the WEF Nexus approach to assess the life cycle of final products supply chain. The water and energy used to produce sub- and final products are calculated by adding the water and energy requirements for the sub-processes through the production supply chain (Figure 2).

In the mining area, the products are phosphate rocks and slurry, which are transported to the manufacturing area. Each product its own resource requirements. Slurry requires flotation and adaptation, thus, is more water-intensive. Phosphate rock is dried using an energy intensive process that consumes most of the energy produced in the mining area. Slurries are transported via pipeline; rock is transported by train. Each mode of transportation has its own resource needs at different stages, and the two transportation systems have distinct processes: the pipeline supply chain includes the washing (water) and adaptation processes that produce slurry; the train supply chain includes the fuel intensive drying process. It is possible to quantify the flow of products according to the transportation system used. When transport changes from train to pipeline, supply lines also change: the drying process is replaced by the adaptation process. High quality phosphate rocks transported by train have undergone mining, screening, and drying. Low and very low-quality phosphate rocks also undergo a washing process in advance of any other processes. If the phosphate is transported by pipeline, it must first be transformed to slurry, adding the adaptation process to the supply chain. Changes in the supply chain impact the water and energy consumed and, consequently, the CO_2 emitted.

The mining and screening processes include extraction from the ground, tone removal, and screening to produce pieces of phosphate rock. Here, the supply chain is determined by the quality and size of the phosphate rock, which in turn, depends on the phosphate content at the moment of extraction, which ranges from very low to high. High quality phosphate rock is transported to a drying process from which it will either be marketed or chemically transformed into fertilizer at the manufacturing site. Low to medium quality phosphate rock goes is washed, dried, ground, and subjected to flotation, intended to increase the phosphate content. Therefore, it is important to combine the supply chains for products and transportation systems.

We considered the supply chain's integrating processes of production and transportation and adapted the water and energy footprints, which indicate the quantity of water or energy consumed in various sub-processes in integrated supply chains (Fig. 2). From the technical (engineering) perspective, footprints are calculated using a regression function, or average value based on survey data, and technical experts in each process can modify this relation function as needed. The WEF-P Tool uses historical data (from 2015) to estimate the average value of the footprint and the relationship between water/energy consumption and phosphate production. First, we analysed the relationship between outputs of each process and water (or energy) consumption. Second, the WEF-P Tool considered transportation of water and consumption of energy by train and pipeline. Transportation by train was only related to fuel, i.e., diesel, consumption. However, the pipeline station consumes electricity for operating the pipeline and freshwater is transported with slurry. The pipeline should be full of materials such as slurry but it is impossible to fill the pipeline with slurry, thus it alternately carries slurry and freshwater. Therefore, total water (or energy) consumption in the mining area includes not only water (or energy) used in processes but also that used in transportation systems and the water consumed at the pipeline station in mining area, which basically indicates the transported water used in the manufacturing area. WEF-Tool could quantify the water and energy consumption of the various processes and at the pipeline station, as shown in equations (Eqs. 1-5).

$$WC_{mining\ area} = \sum_i^n (P_\mathrm{i} \times WFP_i) + WC_{pipleline\ station} \tag{1}$$

$$WC_{pipleline\ station} = P_\mathrm{slurry} \times WC_{pipleline\ station} \tag{2}$$

$$EC_{mining\ area} = \sum_i^n (P_\mathrm{i} \times EFP_i) + EC_{pipleline\ station} + EC_{train} \tag{3}$$

$$EC_{pipleline\ station} = P_\mathrm{slurry} \times EFP_{pipleline\ station} \tag{4}$$

$$EC_{train} = P_\mathrm{phosphate\ rock} \times EFP_{train} \tag{5}$$

where $WCmining\ area$ (m^3) is total water consumption in mining area, $ECmining\ area$ (MWh or L) is total energy consumption in mining area, Pi (ton) is production from each process (i) in mining area such as mining, screening, washing, flotation, and drying. $WFPi$ (m^3 ton^{-1}) and $EFPi$ (MWh ton^{-1} or L ton^{-1}) are water and energy footprints in each process (i). $WCpipeline\ station$ (m^3) is water consumption in pipeline station, $ECpipeline\ station$ (MWh or L) is energy consumption in pipeline station, and $ECtrain$ (MWh or L) is energy consumption by train to transport phosphate rock to manufacturing area. $Pslurry$ and $Pphosphate\ rock$ (ton) are production of slurry and phosphate rock. $WFPpipeline\ station$ (m^3 ton^{-1}) is water footprint at pipeline station in mining area. $EFPpipeline\ station$ and $EFPtrain$ (MWh ton^{-1} or L ton^{-1}) are energy footprints in pipeline station and of transportation by train. It is worth mentioning that the tool distinguishes between two types of water: water transported from mining to manufacturing area by pipeline, and the embedded water in slurry.

CO_2 emissions are relevant when assessing the environmental impact of phosphate production. These emissions are caused by burning the fuels used in the production process and during generation of electricity. Fossil fuels (gasoline, diesel, coal, etc.), when burned, produce direct CO_2 emissions. Indirect CO_2 emission is also related to the source fuel used in generating electricity: indirect emission occurs in the generation of electricity from other (non-fossil) sources, such as hydroelectric, wind power, or solar. According to USEIA(https://www.eia.gov), one litre of gasoline used by machinery or a facility produces 2.6 kg of direct CO_2 emission, and a power plant burning only coal to generate electricity, emits 1,026 tons of CO_2 kWh^{-1}. Renewable (non-fossil) electricity emits only 15.8 tons of CO_2 kWh^{-1}. A survey of sources of electricity generation in Morocco indicates that coal is the main fuel for power generation (43.4% of the national production). Oil and natural gas account for 25.3% and 22.7% respectively: fossil fuels account for 90 % of the electricity produced in Morocco (IEA, 2014). Based on reference data, we calculated direct and indirect CO_2 emission as shown in equations (6-7).

$$DCO_2 = \sum_i^n CFF\_F_i \times FC_i \tag{6}$$

$$InDCO_2 = \sum_j^n CFP\_E_j \times ELC_j \tag{7}$$

where DCO_2 (ton) is direct CO_2 emissions and $InDCO_2$ (ton) is indirect CO_2 emissions. CFF_Fi (ton L^{-1}) is CO_2 footprint by burning fuel, FCi (ton L^{-1}) is fuel consumption by machine excluding fuel use for electricity generation, and i is the types of fuels such as diesel or gasoline. CFP_Ej (ton MWh^{-1}) is CO_2 footprint by generating electricity, $ELCj$ (MWh) is electricity consumption, and j is the source of electricity generation such as coal, petroleum, natural gas, solar, wind, and hydropower.

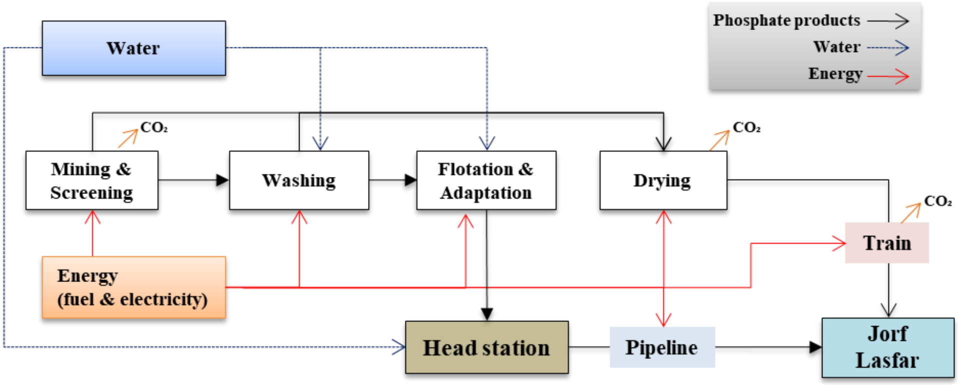

Figure 2 The functional processes and the flow of products in Khouribga (mining) and Jorf Lasfar (manufacturing)

2.3 Water and energy requirement for food production

In this study, "water for food" indicates water that is withdrawn for crop production, generally for irrigation. CROPWAT 8.0 is a decision support tool developed by the Land and Water Development Division of FAO (http://www.fao.org/land-water/databases-and-software/cropwat/en/), and was used to calculate the evapotranspiration, crop water requirements, and irrigation requirements of four crops grown in the region. The climate data (temperature, precipitation, humidity, wind speed, and hours of sunshine) were taken from the climatic database CLIMWAT 2.0, which offers observed agro-climatic data from 5000 stations worldwide and provides long-term, monthly mean values of climatic parameters. The compiled data of CLIMWAT 2.0 generally includes the period 1971-2000 (when this data was not available, series ending after 1975 that include at least 15 years of data were used). CROPWAT 8.0 was used to calculate crop water and irrigation requirements based on soil, climate, and crop data. The calculation procedures used in CROPWAT 8.0 are based on the FAO publication, Irrigation and Drainage Series: No. 56, Crop Evapotranspiration-Guidelines for computing crop water requirements. Irrigation water requirements were calculated by estimating crop evapotranspiration (ETc), determined by multiplying the crop coefficient (Kc) by the reference crop evapotranspiration (ETo), (see Eq. (8)). ETo is calculated using the FAO Penman–Monteith method, as recommended by FAO and described in Eq. (9) (Allen et al., 1998).

$$ET_c = ET_0 \times K_c \tag{8}$$

$$ET_0 = \{0.408\Delta(R_n - G) + \gamma(900/\mathrm{T} + 273)u_2(e_s - e_a)\}/\{\Delta + \gamma(1 + 0.34u_2)\} \tag{9}$$

where ETo is the reference crop evapotranspiration (mm/day); ETc is the crop evapotranspiration (mm d^{-1}); Kc is the crop coefficient; Δ is the slope of the saturated vapor pressure/temperature curve (kPa $°C^{-1}$); γ is the psychrometric constant (kPa $°C^{-1}$); u_2 the wind speed at 2 m height (m s^{-1}); R_n is the total net radiation at crop surface (MJ/m²day); G is the soil heat flux density (MJ/m²day); T is the mean daily air temperature at 2 m height (°C); e_s is the saturation vapor pressure (kPa); and e_a is the actual vapor pressure (kPa). Crop coefficients are influenced by cultivation, local climatic conditions, and seasonal differences in crop growth patterns (Kuo et al., 2006). FAO provides crop coefficients for each stage. The values for Mediterranean countries were applied (Table 1).

Table 1 Crop Information (Allen et al., 1998)

Crop	Plant data	Stage length (Days)					Crop coefficients		
		Init.	Dev.	Mid	Late	Total	Kc init	Kc mid	Kc end
Olives	March	30	90	60	90	270	0.65	0.7	0.7
Wheat	November	30	140	40	30	240	0.7	1.15	0.25
Barley	March	20	25	60	30	135	0.3	1.15	0.25
Potato	Jan	25	30	30	30	115	0.5	1.15	0.75

3 Results and discussion

3.1 Quantification of water and energy consumption and CO_2 emission by production and transport of phosphate

The amount of raw phosphate embedded in slurries and rock is measured in commercial metric tons, thus is the unit of phosphate product used in the study. In 2015, 1.68 million tons of raw phosphate was mined and transported from the mining to the manufacturing area, monthly. Target production was set at 2.45 million tons/month^{-1} for phosphate products, and represents a 50% increase in phosphate exports (Table 2). Water and energy consumption depends on mode of transport (as slurry by pipeline or rock by train). The production processes for slurry and for rock consume different quantities of water and energy, consequently, the mode of transport also becomes a scenario to allow quantification of their respective water and energy requirements.

In the case of phosphate industry, production and transport scenarios were applied and quantified for water, energy, and CO_2 emissions (Table 3). In the mining area, 20.1 million tons of raw phosphate were produced in the 2015; this forms the "business as usual" (BAU) scenario: 40% of the production was in the form of slurry and transported by pipeline; 60% was in the form of rock and transported by train. Scenario BAU indicates that 15.84 million m^3 of water were used in all processing (both rock and slurry). Additional fresh water was transported through the pipeline to maintain slurry consistency in the system. For the BAU scenario, 3.85 million m^3 fresh water were transported to the industrial area by pipeline. Scenario 1 (all raw phosphate transported by pipeline) increases the total water used to 32.14 million m^3 (103% increase over BAU). Fresh water is also used to maintain the good operation of the pipeline, but with the increase in slurry transported by pipeline, the quantity of 'maintenance' fresh water decreased from 3.85 to 2.47 million m^3, leading to a smaller total consumption of fresh water: a 76% increase was shown for total water consumption (for both processing and transport by pipeline).

Using only the pipeline for transport requires an additional 131,832 MWh in electricity for the flotation and adaptation processes used to produce slurry (31% increase in comparison to BAU). However, the consumption of fuel significantly decreases as there is no need to dry phosphate rock. This results in a nearly 86% decrease in fuel consumption over the BAU scenario and a fuels savings of 176.4 million litre, which translates into a 40% decrease in CO_2 emission in Scenario 1. With regard to Scenario 2, there was a 50% increase of raw phosphate export over the BAU scenario and with transport the same as in BAU. Total water consumed, including fresh water transported through the pipeline, increased by 16% over BAU, energy consumption increased by 46 %, and CO_2 emission increased by 39%. Scenario 3 (all raw phosphate is transformed to slurry and total production increased by 50% over BAU) also indicates a total water consumption increase to 46.6 million m^3 (137% over BAU), and electricity consumption increased by 75%. However, transport by pipeline also led to an 80% decrease in fuel consumption (compared to BAU), and consequent 18% decrease in CO_2 emissions.

Table 2 Creation of scenarios relating to production and transportation of phosphate

Name of scenario	Contents of scenario	Production of phosphate (10^6 ton yr^{-1})	Phosphate in a form of slurry transported by pipeline (10^6 ton yr^{-1})	Phosphate in a form of rock transported by train (10^6 ton yr^{-1})
BAU	Production as BAU (2015)	20.1	7.8	12.3
Scenario 1			20.1	-
Scenario 2	Increase of production (50% over BAU)	29.3	11.3	18.0
Scenario 3			29.3	-

Table 3 Water and energy use, and CO_2 emission by scenario of phosphate production and transport

Scenario (Transportation)	Water (10^6 m³ yr^{-1})		Energy		CO_2 emission (10^6 ton yr^{-1})	
	Water used in processes	Transported water	Electricity (MWh yr^{-1})	Fuels (10^6 L yr^{-1})	Direct	Indirect
BAU	15.84	3.85	424,512	204.0	0.53	0.35
Scenario 1	32.14	2.47	556,344	27.6	0.07	0.46
Scenario 2	19.35	3.45	551,495	297.9	0.77	0.45
Scenario 3	45.15	1.45	743,928	40.5	0.11	0.61

3.2 Assessment of the impacts of water allocation and treated water use in the industrial and the agricultural areas

The main challenge of the mining area is sustainable water allocation for both the phosphate industry and the irrigated agricultural areas. Production targets were established for both phosphates and crops. Scenarios were evaluated using the WEF-P Tool. Target crop production rates for Morocco's primary food crops (wheat, olive, barley, and potato), were set as 0.1 % of national production. Table 4 shows that 25.07 million m³ yr^{-1} of irrigation water is required to produce 5,722 ha of crops. In the case of wheat, irrigation requirements were calculated at 313.7 mm yr^{-1}, equivalent to 9.08 million m³ to produce 0.1 % of national production annually.

The main water resource for the mining area is the Ait Messaoud dam. Water allocations from this source affect both phosphate and agricultural areas. Water used for phosphate production increases when the pipeline is used to transport slurry (verses dry rocks transported by train). The impact of water allocation under only the pipeline is calculated using various scenarios for water allocation (Table 5). In the "Alloc. 1" scenario, supply capacity from the dam was set at 80% for the phosphate industry and 20% for the agricultural area. The waste-water treatment plant (capacity 5 million m³ yr^{-1}) operates in the mining area, and for scenario Alloc. 1, all treated water is assigned to the phosphate industry. The "Alloc. 2" scenario focuses on the importance of water for agriculture and assigns the water equally between the phosphate and agricultural areas. Water supplied from the dam plus treated water from the plant may be insufficient for both industries: to address this issue, treated water and ground water were considered as supplementary water sources; treated water quantity of 2.5 million m³ (50 % of current operation) was assigned to the two industries.

When water resources were allocated according to the Alloc. 1 scenario (80% of surface water and 100% of treated water allocated to phosphate mining area), 9.68 million m³ additional water are required for agriculture (Table 6). When water is allocated equally between the two industries (Alloc. 2 scenario), there is a shortfall of 9.61 million m³ in the phosphate industry, but of only 70,000 m³ for agricultural irrigation. In the case of a 50% increase in phosphate production over BAU and using the pipeline as the only mode of transport, the Alloc. 1 scenario indicates intensive water supply to phosphate mining area rather than to agricultural area and causes an annual shortage of 5.59 and 16.07 million m³ water in the phosphate mining and the agricultural area, respectively. To address this shortage, 2.5 million m³ of treated water could be supplied in addition to 19.16 million m³ of ground water.

Additionally, electricity is required to pump ground water and treat wastewater. Thus, the source of water may also affect electricity consumption. Goldstein and Smith (2002) noted that 0.198 kWh is required to supply 1 cubic meter of ground water, and the least electricity required to supplying surface water is 0.079 kWh m^{-3}. Therefore, a 50% increase over BAU is accompanied by 3,794 MWh yr^{-1} electrical consumption for pumping ground water (Table 6). Increasing the use of treated water releases the demand for ground water use, but the costs of building and operating the infrastructure and treatment facility must be considered. In this study, the capacity of treated water was set at 2.5 million m³ yr^{-1}, and ground water requirements were changeable only as scenarios of water allocation.

Table 4 Water use for crop production under Moroccan condition

Crops	Production*	Productivity	Area	Irrigation water requirement	
	ton	ton ha^{-1}	ha	mm yr^{-1}	10^6 m^3 yr^{-1}
Olive	834	1.28	652	622.4	4.06
Wheat	4054	1.40	2895	313.7	9.08
Barely	1840	0.87	2115	562.7	11.90
Potato	1417	23.43	60	48.9	0.03
Total	8146		5722	1547.7	25.07

*Crop production is the amount of 0.1% of national production in Morocco

Table 5 Water allocation and treated water use scenarios

Scenario	Sources	Capacity	Assignment of capacity	
		10^6 m^3 yr^{-1}	Phosphate	Agriculture
Alloc. 1	Dam	45.0	80%	20%
	Treated water	5.0	100%	0%
Alloc. 2	Dam	45.0	50%	50%
	Treated water	5.0	50%	50%
Treated water supply		2.5	1st priority	2nd priority

Table 6 Additional water and energy for solving water shortage by sceansrios of phosphate production

Production (Only pipeline)	Water allocation	Water shortage		Additional water supply		Energy use for water supply	
		Phosphate	Agriculture	Treated water	Ground water	Treated water	Ground water
		10^6 m^3 yr^{-1}	10^6 m^3 yr^{-1}	10^6 m^3 yr^{-1}	10^6 m^3 yr^{-1}	MWh yr^{-1}	MWh yr^{-1}
Production as BAU	Alloc. 1	0.00	9.68	2.50	7.18	1653	1421
	Alloc. 2	9.61	0.07				
50% Increase over BAU	Alloc. 1	5.59	16.07	2.50	19.16	1653	3794
	Alloc. 2	21.59	0.07				

3.3 Assessment of the impact of dynamic management of phosphate production on ground water and energy savings

Water resource availability and water requirements for crop production are seasonal. Rainfall in June and July is less than 10 mm month^{-1} and irrigation water requirements exceed 80 mm month^{-1} (Fig. 3). Thus, there is water scarcity in the agriculture area during June and July. Given that water resources are shared between the phosphate industry and the agriculture industry, static production of phosphate could accelerate water shortage for agriculture. Dynamic production of phosphate is considered as a scenario with greater agricultural production during non-irrigation seasons and less production during irrigation seasons. Using the dynamic phosphate production scenario, the monthly production of phosphate decreases from 1.68 to 0.91 million tons month^{-1} between May and October, representing a 50% decrease in raw phosphate export compared to BAU scenario. Between November and April, phosphate production increases to 2.45 million tons month^{-1}, representing a 50% increase in raw phosphate export in compared to BAU scenario.

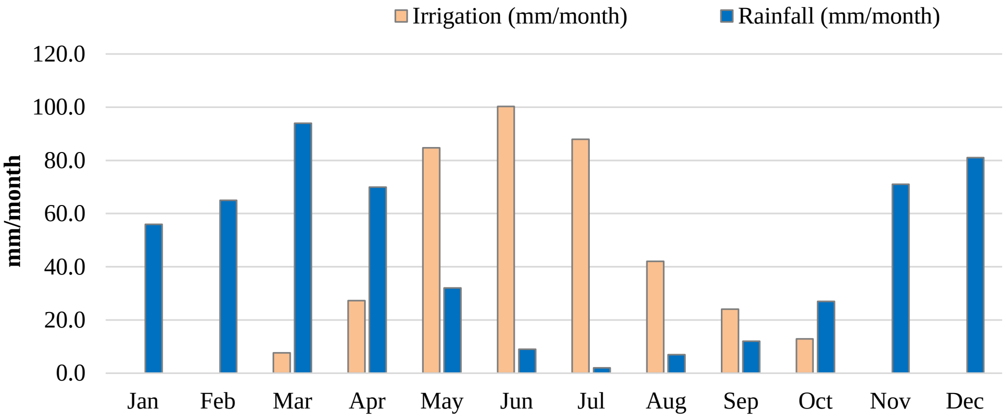

Figure 3 Monthly irrigation water requirement and rainfall in Khouribga

Water availability and irrigation water requirements differ seasonally: dynamic monthly production of phosphate can contribute to sustainable water management. The effect of dynamic phosphate production on water supply becomes obvious when the pipeline is the only mode of transport: slurries are more water intensive than rock. Under static phosphate production, the monthly water demand from the dam in January and February was about 2.5 million m^3, and increased to 7.0 million m^3 $month^{-1}$ in June (Fig. 4). Nevertheless, dynamic phosphate production decreases the water demanded during the water scarce season. Moreover, the lack of water supply is covered by ground water: dynamic production uses less ground water than static production (Fig. 5). During the water scarce season (May to July), total ground water used is 5.77 million m^3 in static phosphate production. This decreases by 10% in dynamic production, potentially saving 0.58 million m^3 of ground water during the water scarce season. Groundwater resources constitute an important aspect of the national hydraulic heritage and represent the only water resource in this hyper arid climate (Tale, 2006). Thus, dynamic phosphate production carries positive impact on sustainable water management and water conservation.

In addition, dynamic phosphate production contributes to electricity savings: supplying water from the dam, ground water, or treatment require electricity for pumping, transporting, and treating (Fig. 6). Total electricity consumed in supplying water to the phosphate and agriculture industries was 9,971 MWh yr^{-1} under the static production scenario (phosphate slurries, no rocks). This number decreased to 9,828 MWh yr^{-1} when phosphate slurries were produced dynamically. About 143 MWh electricity can be saved annually, and is accompanied by a reduction of 117 tons of CO_2 emission.

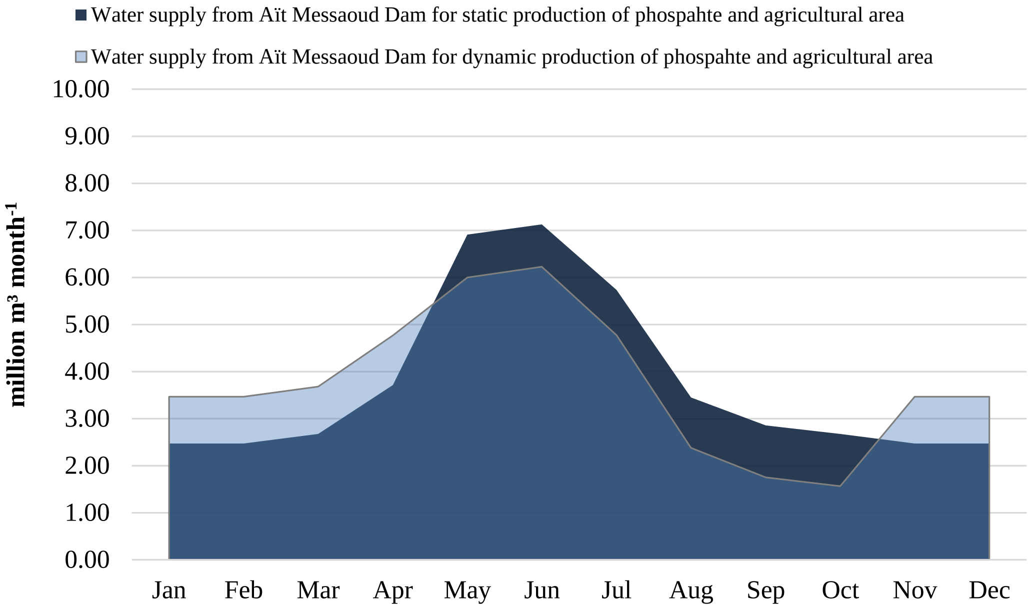

Figure 4 Monthly water supply from Aït Messaoud Dam

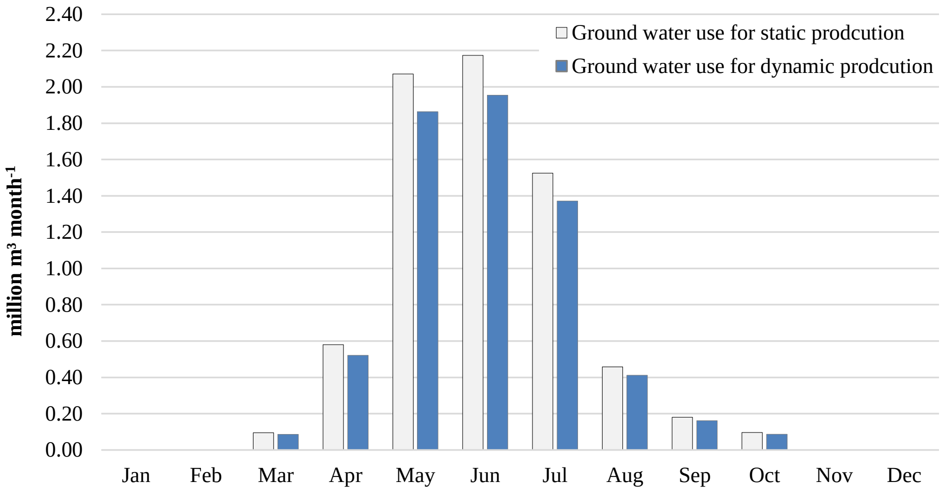

Figure 5 Monthly ground water use by static and dynamic production of phosphate slurries transported by pipeline

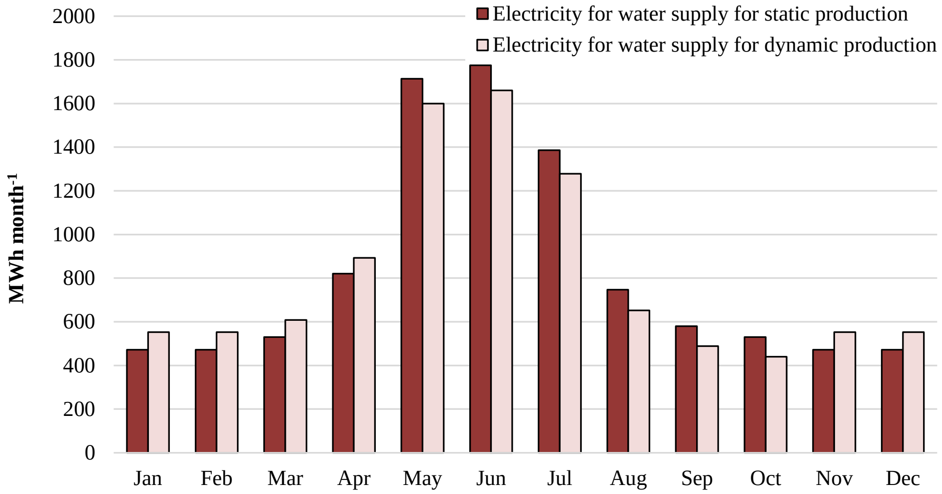

Figure 6 Monthly electricity consumption for supplying water by static and dynamic production of phosphate slurries transported by pipeline

4 Conclusions

As Morocco continues to work toward meeting its projected phosphate production goals, it is important to assess and quantify the potential resource competition between the growing municipal and agricultural sectors. The WEF-P Tool integrates water-energy-food management and supply chain management for phosphate production. The strength of the WEF-P Tool is that it links the resource needs of the phosphate and agricultural areas. Previously, the WEF Nexus approach focused on water and energy used in food production, thus it was mainly related to agriculture. However, Khouribga is also a representative phosphate mining area and a main consumer of water and energy. Sustainable resource management strives for a symbiosis between the phosphate industry and other sectors, endeavouring to create synergy through multiple strategies. This tool considers not only the trade-offs between water, energy, and food, but also a systematic analysis based on the total supply chain management of phosphate production.

As phosphate mining increases, options that contribute to reducing water and energy stress include increased reliance on transport by pipeline and dynamic management of phosphate production. This tool assesses the impacts of various production pathways, including for specific process decisions throughout the phosphate supply chain, such as the choices for transport by pipeline or train and the impacts on regional water and energy use. For example, transport by pipeline instead of train can contribute an energy savings due to elimination of the phosphate drying process (a main consumer of fuels). At the same time, the slurry adaptation processes are main consumers of water, however, because the pipeline also transfers fresh water to Jorf Lasfar where the fertilizers are produced, the water embedded in slurry is a main water resource for Jorf Lasfar. Previous to receiving this source, the main water resource in Jorf Lasfar was desalinated water, which uses some energy in desalination. Transport by pipeline contributes to a savings of desalinated water and energy for desalinating. The dynamic management scenario is assessed for its impacts on regional water and energy savings: dynamic management of phosphate production indicates different production quantities during irrigated and non-irrigated seasons. Less phosphate production during irrigation season can contribute more surface water for agricultural use and is accompanied by a savings of ground water and the energy required to pump ground water.

Nevertheless, there are limitations in the WEF-P Tool. Further consideration of the economics of the phosphate operation is needed: static production may bring stability to operations (meeting local and export demand), but there are benefits from dynamic production that can be attributed to reduced competition with other water consuming sectors. Additional variables, relating to facility operation, labor, economic cost/benefit of static and dynamic production, etc., should be quantified and included for additional trade-off assessments. Supply chain management in the tool is based only on the 2015 dataset, thus it was difficult to validate the tool. Quantification of water and energy for phosphate production is strongly dependent on the relationship between production and resource consumption: this can change in future scenarios. Proper water availability for the right place and time in a changing climate requires analysis of complex scientific, technical, socio-economical, regulatory, and political issues. The WEF-P Tool can assess the various scenarios to offer an effective means of ensuring the sustainable management of limited resources to both agricultural area and phosphate industry.

Author contribution

Sang-Hyun Lee, Amjad T. Assi, and Rabi H. Mohtar conceived and designed the research; Sang-Hyun Lee and Amjad T. Assi analyzed the data; Sang-Hyun Lee, Bassel T. Daher, and Fatima E. Mengoub contributed analysis tools; Sang-Hyun Lee and Amjad T. Assi wrote the paper.

Competing Interests

The authors declare that there are no conflicts of interest regarding this publication.

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References

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, Italy, 300(9), D05109, 1998.

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., ... and Imanari, Y.: Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environmental Science & Policy, 54, 389-397, 2015.

Food and Agriculture Organization of the United Nations (FAO): AQUASTAT, http://www.fao.org/nr/water/aquastat/main/index.stm/, last access 4 September 2019.

Daher, B. T. and Mohtar, R. H.: Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water International, 40(5-6), 748-771, 2015.

Goldstein, R. and Smith, W.: Water & sustainability (volume 4): US electricity consumption for water supply & treatment-the next half century. Electric Power Research Institute, Water & Sustainability, 4, 2002.

Hoff, H.: Understanding the nexus: Background paper for the Bonn 2011 Nexus Conference, 2011.

IEA (International Energy Agency): Energy Policies Beyond IEA Countries: Morocco 2014, OECD/IEA. France. ISBN 9789264211483, 2014

Keulertz, M., Sowers, J., Woertz, E. and Mohtar, R.: The Water-Energy-Food Nexus in Arid Regions: The Politics of Problemsheds, Oxford Handbooks Online, 2016.

Kuo S.F., Ho, S.S. and Liu, C.W.: Estimation irrigation water requirements with derived crop coefficients for upland and paddy crops in ChiaNan Irrigation Association, Taiwan. Agricultural Water Management, 82(3), 433-451, 2006.

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Mohtar, R. H., Assi, A. T. and Daher, B. T.: Bridging the Water and Food Gap: the Role of the Water-energy-food Nexus. United Nations University, Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), 2015.

Mohtar, R. H. and Daher, B.: A platform for trade-off analysis and resource allocation: the water-energy-food nexus tool and its application to Qatar's food security [part of the "Valuing Vital Resources in the Gulf" series]. Chatham House, 2014

Mohtar, R. H. and Daher, B.: Water-Energy-Food Nexus Framework for Facilitating Multi-stakeholder Dialogue, Water International, 41(5), 655-661, 2016.

Office Cherifien des Phosphates (OCP): Activity report, Casablanca, Morocco, 2013.

Office Cherifien des Phosphates (OCP): Slurry Pipeline, Casablanca, Morocco, 2016a.

Office Cherifien des Phosphates (OCP): Water program, Casablanca, Morocco, 2016b.

Ringler, C., Bhaduri, A. and Lawford, R.: The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Current Opinion in Environmental Sustainability, 5(6), 617-624, 2013.

Taleb, H.: Water management in Morocco. Management of Intentional and Accidental Water Pollution, 177-180, 2006.

USEIA: CO_2 emission by burning fuels and generating electricity. U.S. Energy Information Administration, https://www.eia.gov" https://www.eia.gov, last access 4 September 2019.

World Bank: Population in Morocco. The World Bank Group, https://data.worldbank.org" https://data.worldbank.org, last access 10 September 2019.

World Bank: Energy use by oil equivalent per capita and electric power consumption per capita. The World Bank Group, https://data.worldbank.org" https://data.worldbank.org, last access 10 September 2019.