

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

Sang-Hyun Lee^a, Amjad T. Assi^b, Bassel T. Daher^b, Fatima E. Mengoub^{c,d}, Rabi H. Mohtar^{b,e,f,*}

^aResearch Institute for Humanity and Nature, Kyoto, Japan [sanghyunsnu@gmail.com].

^bDepartment of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117, USA [amjad.assi@tamu.edu; basseldaher@gmail.com]

^cPolicy Center for the New South, Suncity Complex, Building C, Angle of Addolb Boulevard and Albortokal Street, Rabat, Morocco [f.mengoub@policycenter.ma]

^dMohammed VI Polytechnic University, Lot 6620, Hay Moulay Rachid 43150, Benguerir, Morocco

^eZachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136, USA.

^fDepartment of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon.

* Correspondence: Rabi H. Mohtar, Professor and Dean, Faculty of Agricultural and Food Sciences, FAFS 101, American University of Beirut, P.O. Box 11-0236, Riad El Solh, Beirut 1107 2020, Lebanon. Tel.: +961-1-350000 ext: 4400, Fax: +961-1-744460, [mohtar@aub.edu.lb; mohtar@tamu.edu].

Abstract

The study's objective was to develop and use the Water-Energy-Food Nexus-Phosphate (WEF-P) Tool to evaluate the impact of Morocco's phosphate industry on water, energy, and food sectors of Khouribga, the representative phosphate mining region of Morocco. The developed WEF-P Tool enabled a trade-off analysis based on integrating the supply chain processes, transportation, and water-energy footprints of the region. Field data from the mining to transportation processes were collected and applied to possible supply chain scenarios in accordance with the type of product (phosphate rock and slurry). The potential impacts of the scenarios were considered in terms of the water supply in the agricultural areas. The analysis of the positive impacts of dynamic management suggests that seasonal management of phosphate production (less during the irrigated season, more during wetter/rainier seasons) is more effective. Additionally, while the transport of raw phosphate slurry through a pipeline increased the total water required to 34.6 million m³, an increase of 76% over the "business as usual scenario" (BAU), it also resulted in an energy savings of nearly 80% over BAU: slurry transport requires only 40.5 million litres of fossil fuel, instead of the 204 million litres required to transport rocks. During the dry or "water scarce" irrigated season (May to July), total ground water use decreased from 5.8 to 5.2 million m³. Dynamic management of the phosphate industry can also save 143 MWh of electricity annually and brings a reduction of 117 tons of CO₂ emissions. 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 by assessing user-created scenarios, thus it is an effective management-decision aid for ensuring more sustainable use 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 offers a roadmap for other industrial application for which trade-offs between the primary resources must be considered.

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

39 1 Introduction

40 Nexus thinking emerged from the understanding that natural resource availability can limit and is limited by, economic growth
41 and other goals associated with human well-being (Hoff, 2011; Keulertz, 2016). The innovative aspect of nexus thinking is its
42 more balanced view of the issues linking resources (Al-Saidi and Elagib, 2017). Thus, nexus frameworks identify key issues
43 in food, water, and energy securities through a lens of sustainability and seek to predict and protect against future risks and
44 resource insecurities (Biggs et al., 2015). The 2015 World Economic Forum identified water, food, and energy shocks as
45 primary future risks, calling for increased efficiency in water use across all sectors and the implementation of integrated water
46 resources management. Various conceptual frameworks relating to the nexus approach were developed: the FAO (2014)
47 emphasized the role of the nexus in food security; the International Renewable Energy Association (IRENA, 2014) applied
48 the nexus approach in transforming conventional energy systems to renewable systems.

49 The demand for water, energy, and food, is expected to increase due to drivers such as population growth, economic
50 development, urbanisation, and changing consumer habits (Terrapon-Pfaff et al., 2018). The interlinkages across key natural
51 resource sectors and improving their production efficiency offer a win-win strategy for environmental sustainability, whether
52 for current or future generations (Ringler et al., 2013). Accordingly, application of the Water-Energy-Food (WEF) nexus
53 concept or approach is expected to make implementation of the Sustainable Development Goals (SDGs) more efficient and
54 robust (Brandi et al., 2014; Yumkella and Yillia, 2015). The SDGs are classic examples of the necessity to acknowledge
55 multidimensional, nexus interlinkages and trade-offs, particularly as governments are challenged to maximize benefits and
56 invest limited resources. Infrastructure and capital are needed to achieve national SDG targets and the nexus concept is now
57 used to highlight interdependencies between resources and the need for integrated, sustainable governance and management
58 of those resources (Pahl-Wostl, 2019).

59 The debate surrounding effectively addressing water and food security challenges stems from questions about whether the
60 water-food crisis is due to a poor understanding of the resources or to their improper management (Mohtar et al., 2015). One
61 long-standing challenge to water management lies in the lack of integration among the multiple sectors that interact with the
62 water sectors across geographical areas or within large, transboundary, basins (Mohtar and Lawford, 2016). Projections about
63 availability and quality of water, food, energy, or soil resources are often alarming. A fundamental shift is needed away from
64 traditional ‘silo’ approaches and toward more integrative, systems approaches (Daher and Mohtar, 2015). Energy and water
65 are crucial for economic growth, especially in industrialized areas (Flörke et al., 2013; Cai et al., 2016), making the rapid
66 increase in demand for these resources a serious issue for both economics and the environment. While technology to reduce
67 industrial demand for water and energy is important, we must also understand the relationship between economic growth,
68 water–energy consumption, the impact of industrial activity on agriculture at the local level. Increase of industrial products
69 can cause steep increases in demand for water and energy, which in turn, leads to issues of downscaling water or energy
70 securities.

71 The nexus framework is dependent on the stakeholders, system boundary, and analytical tools. In considering the application
72 of the nexus as a platform, an integrated modelling approach is essential. These issues manifest in very different ways across
73 each sector, but their impacts are often closely related in terms of trade-offs. In particular, the sub-nexus needs to be effectively
74 conceptualized and a theoretical sub-nexus developed. Private-sector water, energy, and food supply chain players are the key
75 stakeholders to address current contradictions arising as a consequence of attempts to develop a grand nexus approach (Allan
76 et al., 2015). Accordingly, we must consider the “specialized” nexus of multi-stakeholders, such as agriculture, industry and
77 urban areas, for which water, energy and food are treated as subsystems. Current nexus frameworks often focus on macro-
78 level drivers of resource consumption patterns (Biggs et al., 2015), but major nexus challenges are faced at local levels
79 (Terrapon-Pfaff et al., 2018). Thus, ‘larger scale’ extraction and consumption of natural resources may lead to depletion of
80 natural capital stocks and increased climate risk with no equitable share of the benefits (Hoff, 2011; Rockström et al., 2009).
81 Al-Saidi and Elagib (2017) showed the importance of exploring driving forces and interactions at different scales in the

82 conceptual development of the nexus, emphasizing more case-study based recommendations in the reality of institutions,
83 bureaucracies, and environmental stakeholders.

84 Morocco's phosphate and agriculture industries offer an example of increasing resource pressures attributable to near- and
85 medium-term growth across these sectors (Taleb, 2006). A holistic approach that considers the needs of all stakeholders is
86 necessary to resolve resource allocation pressures. Between 1990 and 2016, Morocco's population grew from 25 million to 35
87 million people (World Bank, 2019a). Both crop production and total cultivated land significantly increased since 1971, and
88 half of Morocco's arable land receives less than 350 mm of rainfall annually and nearly 87.3% of Morocco's total water
89 withdrawals are used for agriculture (FAO, 2015). Per capita consumption of electric power increased from 358 kWh (1990)
90 to 901 kWh (2014); energy use by oil equivalent per capita increased from 306 to 553 kg during the same period (World Bank,
91 2019b). Proper management of water, energy, and food resources is critical to economic, social, and environmental well-being.
92 Globally, phosphates lie at the heart of agriculture and soil enhancement. More than 75% of global phosphate reserves,
93 representing 30% of the global market share, are found in Morocco, positioning that country for a leading role in global food
94 security (OCP, 2013). Phosphate mining and its chemical processing require considerable water, energy, land, and other
95 resource inputs. Morocco uses recycling and reverse osmosis desalination to relieve some of the pressure on its fresh water
96 resources and help secure the water necessary for phosphate production processes (OCP, 2016b). Each water source carries a
97 distinct energy tag that must be accounted for, especially in a country that imports nearly 90% of its consumed energy (World
98 Bank, 2019c). Water, energy, land, and financial resources are frequently shared between multiple sectors, especially
99 agriculture (food production) and municipal (growing urbanization): Morocco is no exception. It is critical that potential
100 sectoral competition be understood, quantified, and accounted for when planning for the sustainable progress of all sectors.
101 An integrated approach to resource allocation is needed to minimize inevitable competition for resources: one that quantifies
102 the trade-offs associated with the possible pathways. As Morocco heads toward achieving its phosphate production goals, the
103 ability to account for the resources associated with that achievement should be balanced with the associated (and increasing)
104 agriculture and municipal demand projections: this is key to sustainable resource allocation (OCP, 2013).

105 This study adapted the WEF Nexus Tool linking industry and agriculture to integrate the supply chain for industrial products.
106 Using the Tool, the authors evaluated the impact of Morocco's phosphate production on the water, energy, and food resource
107 systems of its mining region and then addressed the resource elements in the supply chain management of phosphate
108 production. Specifically, they assessed the impact of phosphate mining and transportation by slurry pipeline on potential water
109 and energy savings in the mining area. The results suggest the need for dynamic management of phosphate production, one
110 that adjusts monthly phosphate production in consideration of its potential impacts on water and energy management in
111 agricultural areas. The specific objectives of the study are to quantify the water, food, energy used by the phosphate industry
112 in the Khouribga region of Morocco and to assess the trade-offs of resource allocations between agriculture and industry.

113 **2 Materials and methods**

114 **2.1 Site description**

115 We contacted the managers and engineers working in the Office Cherifien des Phosphates (OCP) group which is that country's
116 leading phosphate producer in Morocco, and had a lot of discussion about the site, data, policy, and goals. OCP group accounts
117 for 3% of the country's gross domestic product and about 20% of national exports in value over the course of the 20th century
118 (Croset, 2012). The OCP group ran three mining fields: in central Morocco, near the city of Khouribga, and on the Gantour
119 site. Khouribga, the largest mining area, includes three main sites from which raw phosphate is excavated and transported for
120 chemical processing and fertilizer production: Sidi Chennane (SC), Merah Lahrach (MEA), and Bani Amir (BA) (Figure 1).
121 The output in Khouribga is raw phosphate produced as either rock or slurry, the main component of manufactured phosphorous
122 fertilizers. The transport of the phosphate (rocks and slurries) from Khouribga (mining area) to Jorf Lasfar (industrial

123 production area) is a primary project in Morocco (OCP, 2016a). The demand for raw phosphate and the production and export
124 of fertilizer and its products from Jorf Lasfar drive the upstream mining activity of Khouribga. In 2015, approximately 20.1
125 million tons of raw phosphate were excavated, which was 58 % of total raw phosphate excavated in Morocco in 2018 (OCP,
126 2020), and transported to Jorf Lasfar; about 40% of this product was transported via pipeline as slurry and the balance via train
127 as rock.

128 The pipeline from Khouribga to Jorf Lasfar is 187 km and ensures the continuous transport of phosphate from the Khouribga
129 to Jorf Lasfar (Figure 1). As the plan was to increase phosphate production and phase out transport by train, tracks were
130 replaced by pipeline that ensures the continuous flow of raw phosphate from the mining to the industrial area (OCP, 2016a).
131 The plans impact regional water, energy, and food management: in particular, shifting from train to pipeline requires additional
132 water to convert dry rock into liquid slurry. Shifting from train to pipeline changes the demand for water and energy resources
133 at both the mining and the production locations.

134 In accordance with the “Green Morocco (Plan Maroc Vert)” (Stührenberg, 2016) and the National Water Plan for Morocco,
135 the use of surface water as a substitute for groundwater is encouraged: water withdrawals from regional aquifers are being
136 phased out since 2010, to be replaced entirely by surface water from the nearby Ait Messaoud dam, which has a capacity of
137 13.20 million m³. The plan is to allocate 4.5 million m³ yr⁻¹ of water from the dam to the mining site. Additionally, OCP
138 launched a plan to complete treatment plants for urban wastewater (capacity 5 million m³ yr⁻¹) to be used for washing phosphate
139 and industrial reuse in the mining area (OCP, 2016b). The phosphate mining area is encircled by cropland, whose water is also
140 supplied from the dam. In this study, the authors consider the allocation of treated water to both the phosphate industry and
141 agricultural irrigation (Tian et al, 2018). Both the mining and the agricultural activities of the region represent growing
142 enterprises that place added pressure on available water resources, making the sustainable management of the water supply a
143 hotspot to be considered in trade-off analyses.



144

145 **Figure 1** Study area: phosphate mining area (Khouribga), fertilizer manufacturing area (Jorf), and transportation system
146 (slurry pipeline) (<http://www.ocpgroup.ma/ocpslurrypipeline/slurry-pipeline>)

147 2.2 Development of Water-Energy-Food-Nexus - Phosphate (WEF-P) Tool

148 2.2.1 Overall Framework of WEF-P Tool

149 The developed WEF-P Tool, adapted from the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015), considers the supply chain of
150 final product in terms of its resource consumption, including the set of processes that pass materials forward (La Londe and
151 Masters, 1994; Mentzer et al., 2001), and various organizations or individuals directly involved in the flow of products
152 (Mentzer et al., 2001). It assesses the impact of various scenarios and possible responses to regional resource management
153 needs. Table 1 shows the differences between WEF Nexus Tool 2.0 and WEF-P Tool in the context of variables, scenarios,
154 analytical tools, and quantitative assessments.

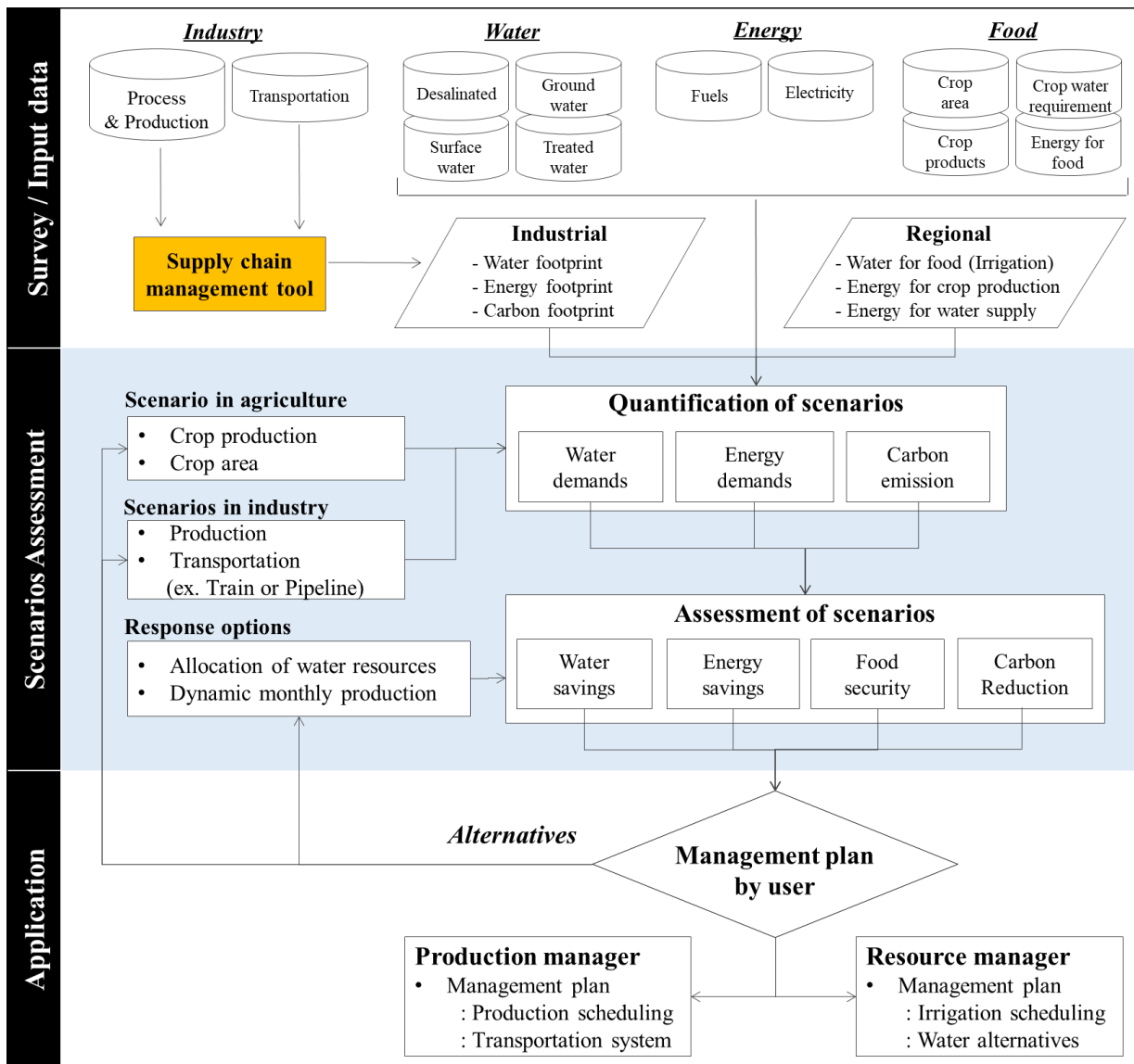
155 Both the Tools offer a platform for development of the analytics necessary to understand the trade-offs and catalyse a
156 stakeholder dialogue (Mohtar and Daher, 2016; Mohtar, R. H. and Daher, 2014). The core of the WEF Nexus is that production,
157 consumption, and distribution of water, energy, and food are inextricably inter-linked: decisions made in one sector impact the

158 other sectors (Hoff 2011, Mohtar and Daher, 2012). The WEF Nexus Tool 2.0 allows holistic quantification of the impact of
159 resource allocation strategies to support informed, and inclusive stakeholder dialogue between policy makers, private sector
160 firms, and civil society (Daher and Mohtar, 2015). Each stakeholder becomes involved at different stages and scales in the
161 decision-making process. In the WEF-P Tool (Figure 2), water resources are shared between the phosphate industry and
162 agricultural interests in the region of study. Sustainable water management must holistically consider the allocation of water
163 resources for both industrial production and agricultural irrigation. New water (treated urban wastewater) has the potential to
164 contribute significantly to bridging water and food gaps (Mohtar et al., 2015). However, it carries an energy footprint that must
165 be considered when increasing local food production. Potentially, agriculture's demand for water competes with those of a
166 growing industry. The Tool quantifies the use of water and energy and the amount of CO₂ emitted for each scenario. It also
167 quantifies the water and energy savings resulting from choices made regarding transportation scenarios. The Tool assesses the
168 effects of decisions of dynamic management of phosphate production as these impact water and energy securities. The WEF-
169 P tool can assess various scenarios and help account for interdependencies between food and industrial production, and
170 between water and energy consumption, thus allowing the trade-offs associated with potential resource allocation pathways to
171 be quantified.

172 Throughout the tool development process, the supply chain was verified with OCP and the OCP Policy Center in various ways:
173 (i) during the data collection phase, through meetings with the OCP steering committee, financial managers, technical
174 managers and engineers; and (ii) through follow ups with OCP Policy Center team (conference calls and email). The OCP
175 Policy Center team shared with WEF Nexus Team their main concerns regarding the tool structure, based on input from the
176 OCP technical team. The WEF Nexus Team used these shared concerns in their considerations of revisions to the tool structure
177 and associated excel spreadsheets of the model. Specifically, the major aggregated processes and lines of productions were
178 revised and identified in a functional supply chain to maximize the abilities and flexibilities of the model and ensure efficacy
179 of the available data base for processes and production lines.

180 However, the WEF-P Tool has limitations in assessing economic impacts such as cost and benefit analysis. This is because
181 cost must include the price of water, which is still under discussion, and the price of products when analysing their benefits.
182 Raw phosphate is transported to the manufacturing area and used in the production of various fertilizers that have different
183 prices: this makes it difficult to set the price of excavating raw phosphate in the mining area. Sustainability assessment also
184 has qualitative aspects in terms of environmental impact. The WEF Nexus Tool 2.0 applied the sustainability index based on
185 resource capacity and availability, however, it is still a quantitative aspect. We should consider the meaning and definition of
186 sustainability, both quantitatively and qualitatively, and then assess the index using the stakeholders' weights for the variables
187 related to sustainability. Additionally, spatial and temporal scales should be included in a sustainability index. For example,
188 the pipeline transportation system requires water, which is transported with products: the pipeline causes greater water use at
189 the origin, but also provides additional water to the destination area. Also, the water requirement differs with temporal season,
190 such as the water intensive agricultural production season. Thus, more research is needed for a sustainability assessment based
191 on economic and environmental impact. However, the quantitative analysis is an essential factor for assessing sustainability,
192 therefore, the WEF-P Tool focuses on quantification of 1) water and requirements for phosphate production and transportation,
193 2) carbon emissions by energy used in product processes, 3) water supply system and transportation, and 4) dynamic production
194 impacts on water and energy savings.

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Figure 2 Assessment of holistic impacts of various scenarios relating to phosphate industry, agriculture, and resource management using WEF-P Tool

200 **Table 1** Comparison between WEF Nexus Tool 2.0 and WEF-P Tool

	WEF Nexus Tool 2.0	WEF-P Tool
Variables and scenarios	<ul style="list-style-type: none"> • Self-sufficiency of produced crops • Type of agricultural production • Sources of water (groundwater, surface water, treated water and so on) • Sources of energy (natural gas, diesel, solar, wind and so on) • Trade portfolio (countries of import and amounts per country) 	<ul style="list-style-type: none"> • Static and dynamic phosphate production • Transportation modes (train and pipeline) • Sources of water (groundwater, surface water, treated water and so on) • Water allocation between industry and agriculture
Analytical tool	<ul style="list-style-type: none"> • Food product base analysis • Food-centric interlinkages among water, energy, and food • Water and energy footprint based on product (ex. water footprint of crops) 	<ul style="list-style-type: none"> • Process base analysis • Phosphate-centric interlinkages among production, transportation, and resource allocation • Water and energy footprint based on processes (ex. water footprint in washing process)
Quantitative assessment	<ul style="list-style-type: none"> • Water requirement for energy and agricultural production • Energy requirement for agricultural and water production • Land footprint for agricultural and energy production • Carbon emissions from energy used for water and food production • Financial cost 	<ul style="list-style-type: none"> • Water and requirement for phosphate production and transportation • Carbon emission by energy used in product processes, water supply system and transportation • Dynamic production impacts on water and energy savings

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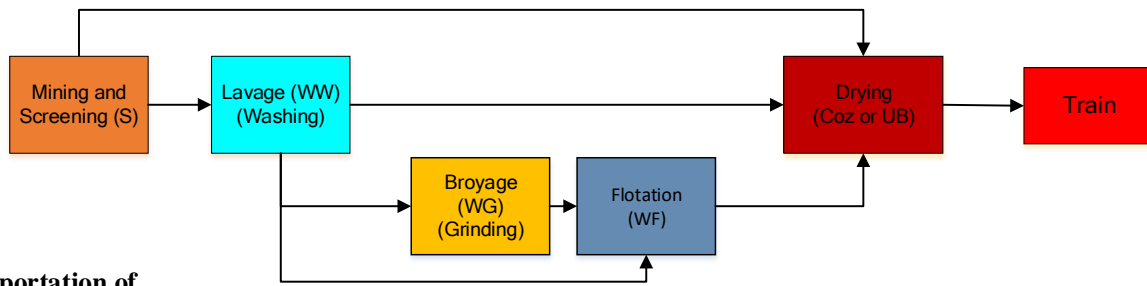
202 *2.2.2 Analysis of integrated supply chains linking sub-processes and transportation modes*

203 The WEF-P Tool used the WEF Nexus approach to assess the life cycle of the final products supply chain. The water and
 204 energy used to produce sub- and final products were calculated by adding the water and energy requirements from the sub-
 205 processes through the production supply chain. In Khouribga, raw phosphate products pass through a sequence of functional
 206 processes: Mining and Screening (S), Washing (WW), Grinding (WG), Flotation (WF), Adaptation including powdering
 207 (WA), and Drying (COZ - Complex Ouad Zem) for SC and (UB) for MEA (Figure 3). The mining and screening processes
 208 include extraction from the ground, tone removal, and screening to produce pieces of phosphate rock. Here, the supply chain
 209 is determined by the quality and size of the phosphate rock, which in turn, depends on the phosphate content at extraction,
 210 ranges from very low to high. High quality phosphate rock is transported to a drying process from which it will either be
 211 marketed or chemically transformed into fertilizer at the manufacturing site. Low to medium quality phosphate rock goes is
 212 washed, dried, ground, and subjected to flotation, intended to increase the phosphate content.

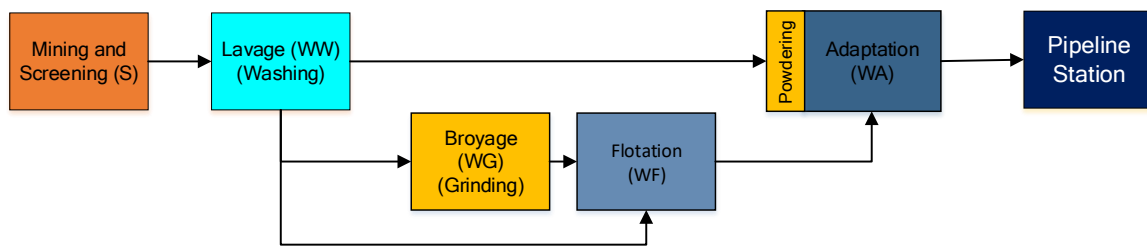
213 The change in transportation system can affect the supply lines (Figure 3). In the mining area, the products are phosphate rocks
 214 and slurry, both of which are transported to the manufacturing area, each with its own resource requirements. Slurry requires
 215 flotation and adaptation, thus is more water intensive; phosphate rock is dried in an energy intensive process that consumes
 216 most of the energy produced in the mining area. Slurries are transported via pipeline and rock by train; each mode has distinct
 217 resource needs at different stages. The two transportation systems are also distinct: the pipeline supply chain includes washing
 218 (water) and adaptation to produce slurry; the train supply chain includes a fuel intensive drying process. It is possible to
 219 quantify the flow of products according to the transportation system used. When transport changes from train to pipeline,
 220 supply lines also change: the drying process is replaced by the adaptation process. If the phosphate is transported by pipeline,
 221 it must first be transformed to slurry, adding the adaptation process to the supply chain. Changes in the supply chain impact

222 the water and energy consumed and, consequently, the CO₂ emitted. The mining and screening processes include extraction
 223 from the ground, tone removal, and screening to produce pieces of phosphate rock.

Transportation of phosphate rock by Train



Transportation of phosphate slurry by pipeline



224
 225 **Figure 3** The functional processes and flows of products in Khouribga (mining) by transportation method.

226 2.2.3 Adaptation of process-base water, energy, and CO₂ footprints

227 The main function of the WEF-P Tool is identification of the relationship between resources and production, and the
 228 quantification of the resources consumed in phosphate production. The methodology is based on life cycle assessment. The
 229 water and energy footprints were analysed, indicating the quantity of water or energy consumed in various sub-processes in
 230 the supply chain's integration of production and transportation. The technical details of each process are specific and
 231 aggregated into functional processes. The main component is the footprint, which indicates the water and energy requirements
 232 for phosphate products, and the CO₂ emitted through energy consumption. Each process has a specific footprint based on field
 233 data and fed into the tool monthly, or when a significant change in capacity of the functional processes has occurred. For all
 234 footprint processes in Khouribga, the amount of raw phosphate is measured in commercial metric tons embedded in slurries
 235 and rock. Even if the phosphate rock changes to slurry through several processes, the amount of raw phosphate embedded in
 236 products is not changed. Thus, the tons of phosphate in water and energy footprints indicate the raw phosphate embedded in
 237 the products in each process and is constant through entire supply chains.

238 From the technical (engineering) perspective, footprints are calculated using a regression function, or average value based on
 239 survey data; technical experts in each process can modify this relation function as needed. The WEF-P Tool uses historical
 240 data (from 2015) to estimate the average value of the footprint and the relationship between water/energy consumption and
 241 phosphate production. First, the relationship between outputs of each process and water (or energy) consumption was analysed.
 242 Second, the WEF-P Tool considered transportation of water and consumption of energy by train and pipeline. Transportation
 243 by train was only related to fuel, i.e., diesel, consumption. However, the pipeline station consumes electricity for operating the
 244 pipeline and freshwater is transported with slurry. The pipeline should be full, but as it is impossible to fill the pipeline with
 245 slurry, it alternately carries slurry and freshwater. Therefore, total water (or energy) consumption in the mining area includes
 246 not only water (or energy) used in processes but also that used in transportation systems and the water consumed at the pipeline
 247 station in mining area, which basically indicates the transported water used in the manufacturing area. WEF-Tool could
 248 quantify water and energy consumption of the various processes and at the pipeline station, as shown in equations (Eqs. 1-5).

$$WC_{mining\ area} = \sum_i^n (P_i \times WFP_i) + WC_{pipeline\ station} \quad (1)$$

$$WC_{pipeline\ station} = P_{slurry} \times WC_{pipeline\ station} \quad (2)$$

$$EC_{mining\ area} = \sum_i^n (P_i \times EFP_i) + EC_{pipeline\ station} + EC_{train} \quad (3)$$

$$EC_{pipeline\ station} = P_{slurry} \times EFP_{pipeline\ station} \quad (4)$$

$$EC_{train} = P_{phosphate\ rock} \times EFP_{train} \quad (5)$$

where $WC_{mining\ area}$ (m^3) is total water consumption in mining area, $EC_{mining\ area}$ (MWh or L) is total energy consumption in mining area, P_i (ton) is production from each process (i) in mining area such as mining, screening, washing, flotation, and drying. WFP_i ($m^3\ ton^{-1}$) and EFP_i (MWh ton^{-1} or L ton^{-1}) are water and energy footprints in each process (i). $WC_{pipeline\ station}$ (m^3) is water consumption in pipeline station, $EC_{pipeline\ station}$ (MWh or L) is energy consumption in pipeline station, and EC_{train} (MWh or L) is energy consumption by train to transport phosphate rock to manufacturing area. P_{slurry} and $P_{phosphate\ rock}$ (ton) are production of slurry and phosphate rock. $WFP_{pipeline\ station}$ ($m^3\ ton^{-1}$) is water footprint at pipeline station in mining area. $EFP_{pipeline\ station}$ and EFP_{train} (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.

CO₂ emissions are relevant when assessing the environmental impact of phosphate production. Although real emission in each process in supply chain should be measured, this study is limited measuring CO₂ emission in mining area. In addition, CO₂ emission in crop area is related to soil and crops, and it is another level of research. Thus, we limited CO₂ emission to that emitted by fuel energy use by machinery (direct emission) and electricity generation in power plants (indirect emission), and the reference CO₂ footprints were applied (Table 2). Fossil fuels (gasoline, diesel, coal, etc.), when burned, produce direct CO₂ emissions. Indirect CO₂ 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 (2019), one litre of gasoline used by machinery or a facility produces 2.6 kg of direct CO₂ emission; a power plant burning only coal emits 1,026 tons of CO₂ kWh⁻¹. Renewable (non-fossil) electricity emits only 15.8 tons of CO₂ 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, direct and indirect CO₂ emission is calculated as shown in equations (6-7).

$$DCO_2 = \sum_i^n CFF_{Fi} \times FC_i \quad (6)$$

$$InDCO_2 = \sum_j^n CFP_{Ej} \times ELC_j \quad (7)$$

where DCO_2 (ton) is direct CO₂ emissions and $InDCO_2$ (ton) is indirect CO₂ emissions. CFF_{Fi} (ton L⁻¹) is CO₂ footprint by burning fuel, FC_i (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 CO₂ footprint by generating electricity, ELC_j (MWh) is electricity consumption, and j is the source of electricity generation such as coal, petroleum, natural gas, solar, wind, and hydropower.

Table 2 CO₂ emission by burning fuels and generating electricity

CO ₂ emission by burning fuel		CO ₂ emission by generating electricity			
Sources	CO ₂ emission ¹ (kg of CO ₂ L ⁻¹)	Sources	CO ₂ emission by sources ¹ (ton of CO ₂ 10 ⁻⁶ kWh)	Proportion of sources in Morocco ² (%)	CO ₂ emission (ton of CO ₂ 10 ⁻⁶ kWh)
Gasoline	2.59	Coal	1,026	43.4%	820.9
Diesel	2.96	Petroleum	1,026	25.3%	
		Natural gas	504	22.7%	
		Hydroelectricity	19.7	6.9%	
		Renewables	15.8	1.7%	

¹ U.S. Energy Information Administration (USEIA) ² International Energy Agency (IEA)

284 **2.3 Agricultural water requirement for food production**

285 In this study, “water for food” indicates water withdrawn for crop production, generally irrigation. CROPWAT 8.0 is a decision
 286 support tool developed by the Land and Water Development Division of FAO (Smith, 1992), and used to calculate the
 287 evapotranspiration, crop water requirements, and irrigation requirements of four crops grown in the region. The climate data
 288 (temperature, precipitation, humidity, wind speed, and hours of sunshine) were taken from the climatic database CLIMWAT
 289 2.0, which offers observed agro-climatic data from 5000 stations worldwide and provides long-term, monthly mean values of
 290 climatic parameters. The compiled data of CLIMWAT 2.0 generally includes the period 1971-2000 (when this data was not
 291 available, series ending after 1975 that include at least 15 years of data were used). Table 3 showed the average climate data
 292 in Khouribga area provided from CLIMWAT 2.0.

293 CROPWAT 8.0 was used to calculate crop water and irrigation requirements based on soil, climate, and crop data. The
 294 calculation procedures used in CROPWAT 8.0 are based on the FAO publication, Irrigation and Drainage Series: No. 44 and
 295 56, Crop Evapotranspiration-Guidelines for computing crop water requirements (Allen et al, 1998; Smith, 1992). Irrigation
 296 water requirements were calculated by estimating crop evapotranspiration (ET_c), determined by multiplying the crop
 297 coefficient (K_c) by the reference crop evapotranspiration (ET₀), (see Eq. (8)). ET₀ is calculated using the FAO Penman–
 298 Monteith method, as recommended by FAO and described in Eq. (9) (Allen et al., 1998).

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

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

301 where ET₀ is the reference crop evapotranspiration (mm day⁻¹); ET_c is the crop evapotranspiration (mm d⁻¹); K_c is the crop
 302 coefficient; Δ is the slope of the saturated vapor pressure/temperature curve (kPa °C⁻¹); γ is the psychrometric constant (kPa
 303 °C⁻¹); u₂ the wind speed at 2 m height (m s⁻¹); R_n is the total net radiation at crop surface (MJ m⁻² day⁻¹); G is the soil heat flux
 304 density (MJ m⁻² day⁻¹); T is the mean daily air temperature at 2 m height (°C); e_s is the saturation vapor pressure (kPa); and e_a
 305 is the actual vapor pressure (kPa). Crop coefficients are influenced by cultivation, local climatic conditions, and seasonal
 306 differences in crop growth patterns (Kuo et al., 2006). FAO provides crop coefficients for each stage. The values for
 307 Mediterranean countries were applied, as shown in Table 4 (Allen et al., 1998). Irrigation water requirement was calculated
 308 by ET_c and effective precipitation, as shown in Eq. (10). The effective precipitation indicated the precipitation except for
 309 runoff, and was calculated using the USDA Soil Conservation Service method (Eq. 11) (Smith, 1992).

$$IRReq = ET_c - P_{eff} \tag{10}$$

$$P_{eff} = P_{tot} (125 - 0.2 P_{tot}) / 125 \quad \text{for } P_{tot} < 250 \text{ mm} \tag{11}$$

$$P_{eff} = 125 + 0.1 P_{tot} \quad \text{for } P_{tot} > 250 \text{ mm}$$

313 where *IRReq* is irrigation water requirement, ET_c is the crop evapotranspiration, *P_{eff}* is effective precipitation, and *P_{tot}* is
 314 total precipitation.

315 **Table 3** Climate information in Khouribga

Month	Precipitation (mm m ⁻¹)	Temperature		Relative humidity (%)	Sunshine hours (h d ⁻¹)
		min. (°C).	max. (°C)		
Jan	56	3.8	17.3	72	5.6
Feb	65	5	19	76	5.7
Mar	94	7.2	21.8	69	6.4
Apr	70	9.5	25.3	67	7.4
May	32	12.5	29.3	55	8.8
Jun	9	16.6	34.5	48	9.8
Jul	2	19.8	39.7	39	10.9
Aug	7	20	39.6	37	10.3
Sep	12	17.5	34.5	47	9.1
Oct	27	13.5	29	58	7.6
Nov	71	8.8	22	70	5.2
Dec	81	5.1	18.6	71	5.5

317 **Table 4** Crop planting and harvesting seasons, stage length and crop coefficients

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

* Next year

318 **3 Results and discussion**319 **3.1 Application of scenarios**

320 Increasing the exportable phosphate products and changing the transportation system from train to pipeline are considered top
321 priorities for OCP group. Therefore, we assessed the impact of increased production by applying the scenarios (Table 5). Until
322 recently, dried phosphate was transported by train from mining to manufacturing site, but, in the near future OCP group will
323 use only pipeline transport. The change of from train to pipeline can affect not only direct energy or water consumption by
324 transportation system but also that of the total supply chain in the mining site. Consequently, the production processes for
325 slurry and for rock consume different quantities of water and energy, so that the mode of transport also becomes a scenario to
326 allow quantification of their respective water and energy requirements.

327 Therefore, we applied the scenario about transportation system which indicates the only usage of pipeline. Table 4 showed the
328 scenarios combining production and transportation. The first two scenarios are related to the ‘business as usual (BAU)’
329 scenario for production in 2015 but changing the transportation system from Khouribga to the terminal station at Jorf Lasfar.
330 The other scenarios are related to the increase in the production.

331

332 **Table 5** Scenarios through combination of production and transportation system

Scenario	Phosphate production	Transportation of phosphate products	
		by pipeline	by train
BAU	Production in 2015	40 % of total phosphate	60 % of total phosphate
Scenario 01		100% of total phosphate	None
Scenario 02	50% increase of phosphate export	40 % of total phosphate	60 % of total phosphate
Scenario 03		100% of total phosphate	None

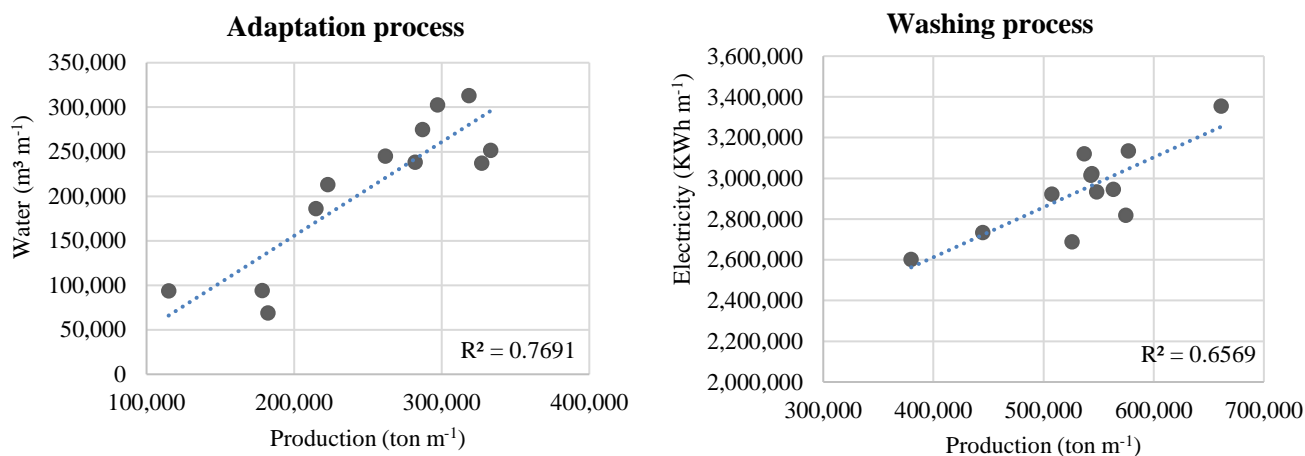
333

334 **3.2 Quantification of water and energy consumption and CO₂ emission by production and transport of phosphate**

335 To quantify the water, energy, and CO₂ emissions, water and energy footprints of each process in each mining site were
336 analysed based on survey data. For example, the adaptation process is essential for pipeline transportation and large amounts
337 water are needed in comparison to other processes, thus the relationship between the amounts of phosphate and water used in
338 adaptation process were analysed (Figure 4 (a)). In addition, energy footprint includes electricity and fuel consumption;
339 analysed through the linear relationship (Figure 4 (b)).

340 Production and transport scenarios were applied and quantified for water, energy, and CO₂ emissions in each scenario (Table
341 6). In the mining area, 20.1 million tons of raw phosphate were produced in the 2015, the “business as usual” (BAU) scenario.
342 40% of the production was in the form of slurry and transported by pipeline; 60% was in the form of rock and transported by
343 train. Scenario BAU indicates that 15.84 million m³ of water were used in all processing (both rock and slurry). Additional
344 fresh water was transported through the pipeline to maintain slurry consistency in the system. For the BAU scenario, 3.85
345 million m³ of fresh water were transported by pipeline to the industrial area. Scenario 1 (all raw phosphate transported by
346 pipeline) increases the total water used to 32.14 million m³ (103% increase over BAU). Fresh water is also used to maintain

347 the good operation of the pipeline, but with the increase in slurry transported by pipeline, the quantity of ‘maintenance’ fresh
 348 water decreased from 3.85 to 2.47 million m³, leading to a smaller total consumption of fresh water: a 76% increase was shown
 349 for total water consumption (for both processing and transport by pipeline).
 350 Using only the pipeline for transport requires an additional 131,832 MWh in electricity for the flotation and adaptation
 351 processes used to produce slurry (31% increase in comparison to BAU). However, the consumption of fuel significantly
 352 decreases as there is no need to dry phosphate rock. This results in a nearly 86% decrease in fuel consumption over the BAU
 353 scenario and a fuels savings of 176.4 million litre, which translates into a 40% decrease in CO₂ emission in Scenario 1. In
 354 Scenario 2, there was a 50% increase of raw phosphate export over the BAU scenario, with transport the same as in BAU.
 355 Total water consumed, including fresh water transported through the pipeline, increased by 16% over BAU, energy
 356 consumption increased by 46 %, and CO₂ emission increased by 39%. Scenarios 3 and 4 represent a 50% increase in phosphate
 357 exports, thus target production was set at 2.45 million tons month⁻¹ for raw phosphate, in total, 29.3 million tons yr⁻¹. Scenario
 358 3 indicates a total water consumption increase to 46.6 million m³ (137% over BAU), and electricity consumption increase of
 359 75%. However, transport by pipeline also led to an 80% decrease in fuel consumption (compared to BAU), and consequent
 360 18% decrease in CO₂ emissions.
 361 In summary, the comparison between BAU and scenario 1 showed the trade-off between water and energy by the change in
 362 transportation method. Pipeline transportation can save energy use and reduce CO₂ emission, but more water is required due
 363 to additional processes, such as adaptation and water used to operate the pipeline. However, since the water used to operate
 364 the pipeline is actually transported to Jorf Lasfar and re-used in fertilizer factories, it could be considered non-consumptive
 365 water in terms of the supply chain integrating Khouribga and Jorf Lasfar, even though it is still real water withdrawn from
 366 Khouribga.



(a) Water footprint in an adaptation process in MEA

(b) Energy footprint in a washing process in MEA

367 **Figure 4.** Water and energy footprints in MEA based on the BAU data-base

368

369 **Table 6** Water and energy use, and CO₂ emission by scenario of phosphate production and transport

Scenario (Transportation)	Water (10 ⁶ m ³ 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

370 3.2 Assessment of the impacts of water allocation and treated water use in the industrial and the agricultural areas

371 The main challenge of the mining area is sustainable water allocation for both the phosphate industry and irrigated agricultural
 372 areas. Thus, production targets were established for both phosphates and crops, and scenarios evaluated using the WEF-P Tool.
 373 Target crop production rates for Morocco’s primary food crops (wheat, olive, barley, and potato), were set as 0.1 % of national
 374 production. Table 7 shows that 25.07 million m³ yr⁻¹ of irrigation water is required to produce 5,722 ha of crops. In the case
 375 of wheat, irrigation requirements were calculated at 313.7 mm yr⁻¹, equivalent to 9.08 million m³ to produce 0.1 % of national
 376 production annually.

377 The main water resource for the mining area is the Ait Messaoud dam. Water allocations from this source affect both phosphate
 378 and agricultural areas. Water used for phosphate production increases when the pipeline is used to transport slurry (verses dry
 379 rocks transported by train). The impact of water allocation under only the pipeline is calculated using various scenarios for
 380 water allocation (Table 8) and the treated wastewater from urban area was considered as a water resource for both the phosphate
 381 industry and agriculture.

382 In the “Alloc 1” scenario, supply capacity from the dam was set at 80% for the phosphate industry and 20% for the agricultural
 383 area. The waste-water treatment plant operates in the mining area. For scenario Alloc 1, all treated water was assigned to the
 384 phosphate industry. The “Alloc 2” scenario focuses on the importance of water for agriculture and assigns the water equally
 385 between the phosphate and agricultural areas. Water supplied from the dam, plus treated water from the plant may be
 386 insufficient for both industries. To address this issue, treated water and ground water were considered as supplementary water
 387 sources and a treated water quantity of 2.5 million m³ yr⁻¹ (50 % of current operation) was assigned to the two industries.

388 When water resources were allocated according to the Alloc 1 scenario (80% of surface water and 100% of treated water
 389 allocated to phosphate mining area), 9.68 million m³ additional water are required for agriculture (Table 9). When water is
 390 allocated equally between the two industries (Alloc 2 scenario), there is a shortfall of 9.61 million m³ in the phosphate industry,
 391 but of only 70,000 m³ for agricultural irrigation. In the case of a 50% increase in phosphate production over BAU and using
 392 the pipeline as the only mode of transport, the Alloc 1 scenario indicates intensive water supply to phosphate mining area
 393 rather than to agricultural area and causes an annual shortage of 5.59 and 16.07 million m³ water in the phosphate mining and
 394 the agricultural area, respectively. To address this shortage, 2.5 million m³ of treated water could be supplied in addition to
 395 19.16 million m³ of ground water.

396 Additionally, electricity is required to pump ground water and treat wastewater. Thus, the source of water may also affect
 397 electricity consumption. Goldstein and Smith (2002) noted that 0.198 kWh is required to supply 1 cubic meter of ground water,
 398 and the least electricity required to supplying surface water is 0.079 kWh m⁻³. Therefore, a 50% increase over BAU is
 399 accompanied by 3,794 MWh yr⁻¹ electrical consumption for pumping ground water (Table 9). Increasing the use of treated
 400 water releases the demand for ground water use, but the costs of building and operating the infrastructure and treatment facility
 401 must be considered. In this study, the capacity of treated water was set at 2.5 million m³ yr⁻¹, and ground water requirements
 402 were changeable only as scenarios of water allocation.

403
 404 **Table 7** 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

405

406 **Table 8** 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	1 st priority	2 nd priority

407

408 **Table 9** Additional water and energy for solving water shortage by sceansrios of phosphate production

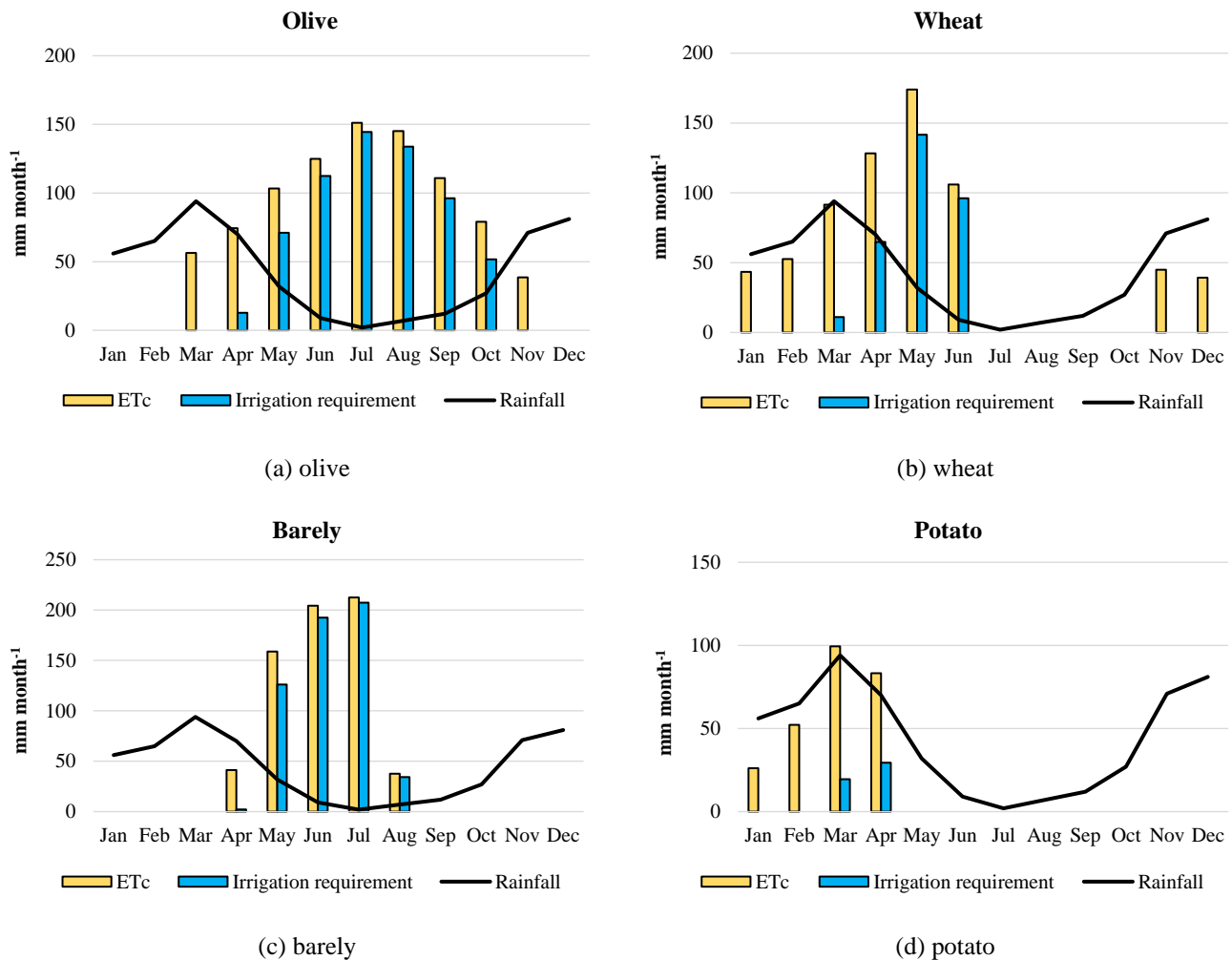
Production (Only pipeline)	Water allocation	Water shortage		Additional water supply		Energy use for water supply	
		Phosphate	Agriculture	Treated water	Ground water	Treated water	Ground water
		10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	MWh yr ⁻¹	MWh yr ⁻¹
Production as BAU	Alloc 1	0.00	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				

409 **3.3 Assessment of the impact of dynamic management of phosphate production on ground water and energy savings**

410 Water resource availability and water requirements for crop production are seasonal. Rainfall in June and July is less than 10
411 mm month⁻¹ and irrigation water requirements exceed 80 mm month⁻¹ (Figure 5). Thus, there is water scarcity in the agriculture
412 area during June and July. Given that water resources are shared between the phosphate industry and the agriculture industry,
413 static production of phosphate could accelerate water shortage for agriculture. Dynamic production of phosphate is a scenario
414 with greater agricultural production during non-irrigation seasons and less production during irrigation seasons. Using the
415 dynamic phosphate production scenario, the monthly production of phosphate decreases from 1.68 to 0.91 million tons month⁻¹
416 ¹ between May and October, representing a 50% decrease in raw phosphate export compared to BAU scenario. Between
417 November and April, phosphate production increases to 2.45 million tons month⁻¹, representing a 50% increase in raw
418 phosphate export in compared to BAU scenario.

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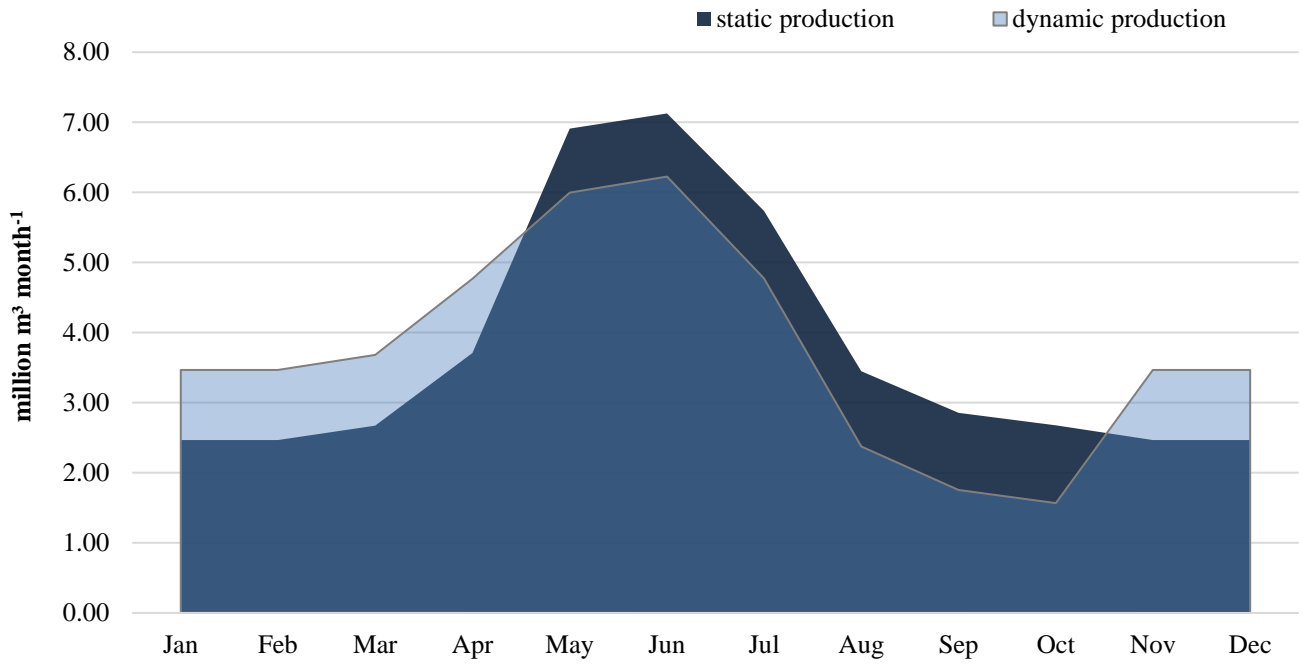


422 **Figure 5** Monthly irrigation water requirement and rainfall in Khouribga

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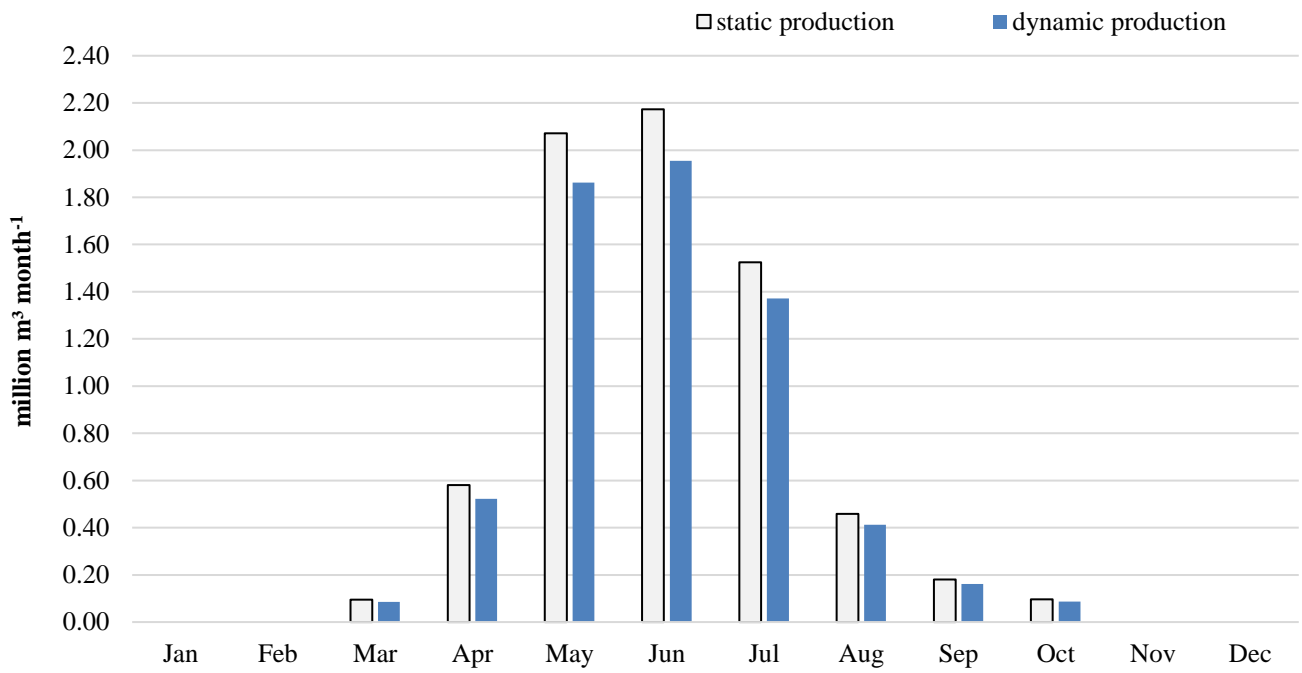
424 Water availability and irrigation water requirements differ seasonally: dynamic monthly production of phosphate can
 425 contribute to sustainable water management. The effect of dynamic phosphate production on water supply becomes obvious
 426 when the pipeline is the only mode of transport: slurries are more water intensive than rock. Under static phosphate production,
 427 the monthly demand for water from the dam in January and February was about 2.5 million m³, increasing to 7.0 million m³
 428 month⁻¹ in June (Figure 6). Nevertheless, dynamic phosphate production decreases the water demanded during the water scarce
 429 season. Moreover, the lack of water supply is covered by ground water: dynamic production uses less ground water than static
 430 production (Figure 7). During the water scarce season (May to July), total ground water used is 5.77 million m³ in static
 431 phosphate production. This decreases by 10% in dynamic production, potentially saving 0.58 million m³ of ground water
 432 during the water scarce season. Groundwater resources constitute an important aspect of the national hydraulic heritage and
 433 represent the only water resource in this hyper arid climate (Tale, 2006). Thus, dynamic phosphate production carries positive
 434 impact on sustainable water management and water conservation.

435 Dynamic phosphate production also contributes to electricity savings: supplying water from the dam, ground, or treatment
 436 require electricity for pumping, transporting, and treating (Figure 8). Total electricity consumed in supplying water to the
 437 phosphate and agriculture industries was 9,971 MWh yr⁻¹ under the static production scenario (phosphate slurries, no rocks).
 438 This number decreased to 9,828 MWh yr⁻¹ when phosphate slurries were produced dynamically. About 143 MWh electricity
 439 can be saved annually, accompanied by a reduction of 117 tons of CO₂ emission.



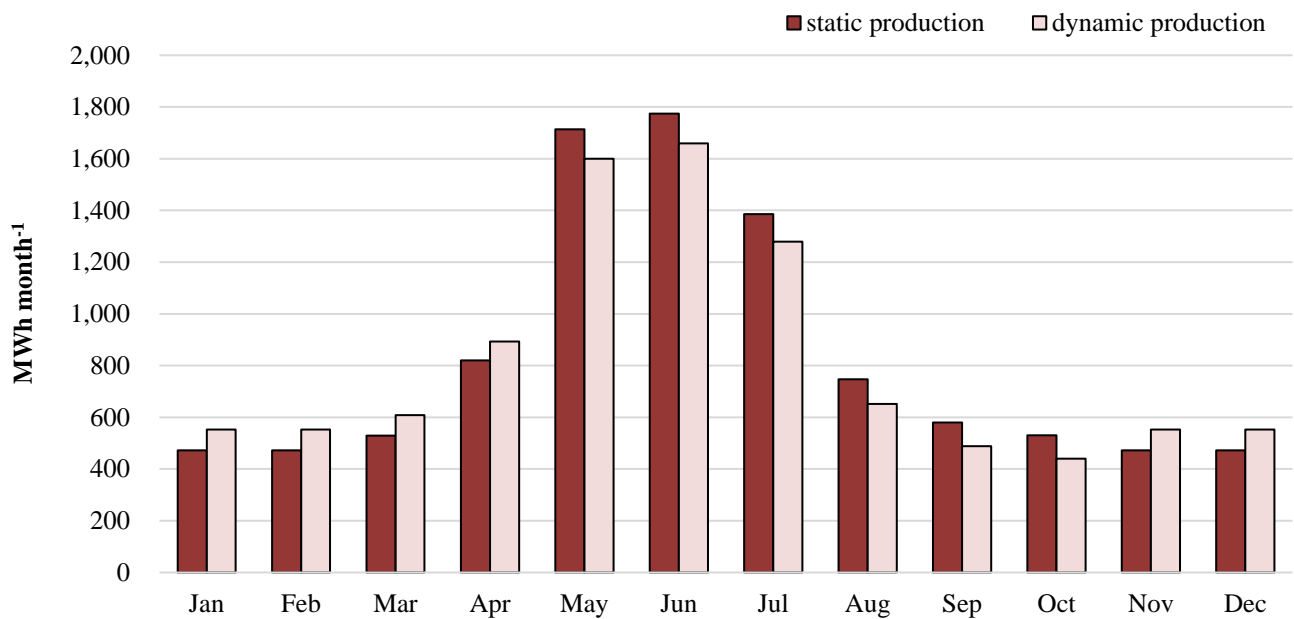
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441 **Figure 6** Monthly water supply from Ait Messaoud Dam

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445 **Figure 7** Monthly ground water use by static and dynamic production of phosphate slurries transported by pipeline

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Figure 8 Monthly electricity consumption for supplying water by static and dynamic production of phosphate slurries transported by pipeline

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4 Conclusions

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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. Sustainable resource management strives for symbiosis between the phosphate industry and other sectors, and endeavours to create synergy through multiple strategies. The WEF-P Tool integrates water-energy-food management and supply chain management for phosphate production, considering the trade-offs between water, energy, and food, as well as a systematic analysis based on the total supply chain management of phosphate production. In other words, the WEF-P Tool offers a decision support system to provide quantifiable trade-off analyses for management decisions such as increasing production, transportation systems, and water allocation. The developed WEF-P Tool enables users to:

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- understand and identify the associated footprints of the primary functional production processes and existing flows in production lines;
- identify the main sources of data to be gathered and fed into the model on a specific temporal basis;
- identify the techniques employed to conserve or produce water and energy and minimize the impacts of phosphate production;
- form a translational platform between sectors and stakeholders to evaluate proposed scenarios and their associated resource requirements

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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 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 to energy savings due to the elimination of the phosphate drying process (a main consumer of fuels). At the same time, the slurry adaptation processes are main consumers of water, though 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. Previously, the main water resource in Jorf Lasfar was desalinated water, which consumes energy in desalination. Transport by pipeline

477 contributes to a savings of desalinated water and energy for desalinating. The dynamic management scenario is assessed for
478 its impacts on regional water and energy savings: dynamic management of phosphate production indicates different production
479 quantities during irrigated and non-irrigated seasons. Less phosphate production during irrigation season can contribute more
480 surface water for agricultural use and is accompanied by a savings of ground water and the energy required to pump ground
481 water.

482 Further consideration of the economics of the phosphate operation is needed: static production may bring stability to operations
483 (meeting local and export demand), but there are benefits from dynamic production that can be attributed to reduced
484 competition with other water consuming sectors. Additional variables, such as facility operation, labour, economic cost/benefit
485 of static and dynamic production, etc., should be quantified and included for additional trade-off assessments. Quantification
486 of water and energy for phosphate production is strongly dependent on the relationship between production and resource
487 consumption: this can change in future scenarios. Proper water availability for the right place and time in a changing climate
488 requires analysis of complex scientific, technical, socio-economical, regulatory, and political issues.

489 Beyond the limitations, the deliverables from this study include a conceptual and analytical model of the phosphate supply
490 chain in Morocco, the WEF-P Tool. The Tool can assess the various scenarios to offer an effective means of ensuring the
491 sustainable management of limited resources to both agricultural area and phosphate industry. It quantifies the products
492 (phosphate) and resource footprints (water, energy) across the supply chain; identifies the interlinkages between water and
493 energy in phosphate production and transport, and establishes reference values for comparison of outcomes and performance.
494 The WEF-P Tool enables the user to evaluate trade-offs between water resource allocations and the impact of the Moroccan
495 phosphate industry with agricultural water use.

496 **Author contribution**

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

500 **Competing Interests**

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

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507

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

Sang-Hyun Lee^a, Amjad T. Assi^b, Bassel T. Daher^b, Fatima E. Mengoub^{c,d}, Rabi H. Mohtar^{b,e,f,*}

^a Research Institute for Humanity and Nature, Kyoto, Japan [sanghyunsnu@gmail.com].

^b Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117, USA [amjad.assi@tamu.edu; basseldaher@gmail.com]

^c Policy Center for the New South, Suncity Complex, Building C, Angle of Addolb Boulevard and Albortokal Street, Rabat, Morocco [f.mengoub@policycenter.ma]

^d Mohammed VI Polytechnic University, Lot 6620, Hay Moulay Rachid 43150, Benguerir, Morocco

^e Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136, USA.

^f Department of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon.

* Correspondence: Rabi H. Mohtar, Professor and Dean, Faculty of Agricultural and Food Sciences, FAFS 101, American University of Beirut, P.O. Box 11-0236, Riad El Solh, Beirut 1107 2020, Lebanon. Tel.: +961-1-350000 ext: 4400, Fax: +961-1-744460, [mohtar@aub.edu.lb; mohtar@tamu.edu].

Abstract

The study's objective was to develop and use the Water-Energy-Food Nexus-Phosphate (WEF-P) Tool to evaluate the impact of Morocco's phosphate industry on regional water, energy, and food sectors of ~~in~~ Khouribga, the representative phosphate mining area of Morocco, using the developed WEF-P Tool. 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~~ enabled a trade-off analysis, based on integrating the supply chain processes, transportation, and water-energy footprints of the region. Field data from the mining to transportation processes were collected and applied to possible supply chain scenarios in accordance with the type of product (phosphate rock and slurry). 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 of the scenarios were considered in terms of ~~on~~ the water supply in the 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). The analysis of the positive impacts of dynamic management suggests that seasonal management of phosphate production (allows less phosphate production during the irrigation-irrigated season, thereby increasing water available for agriculture) and greater phosphate production during wetter/rainier seasons is more effective. (when less water is demanded for agricultural production). Additionally, while the transport of raw phosphate slurry through a pipeline increased the total water required to 34.6 million m³, an increase of 76% over the "business as usual scenario" (BAU), but it also resulted in an energy savings of nearly 80% over BAU, as slurry transport requires only 40.5 million litres of fossil fuel, compared instead of the with 204 million litres required to transport for rocks transport. During the dry or "water scarce" irrigated season (May to July), when irrigation is needed, total ground water use decreased from 5.8 to 5.2 million m³. Dynamic management of the phosphate industry can also save 143 MWh of electricity annually and is brought accompanied by a reduction of 117 tons of CO₂ 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 by assessing user-created scenarios, thus becomes it is an effective management-decision aid for effectively ensuring more sustainable management use 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 offer a roadmap for other industrial application where-for which trade-offs between the primary resources must be considered exist.

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

47 1 Introduction

48 Nexus thinking emerged from the understanding that natural resource availability can limit and is limited by, ~~and can limit,~~
49 economic growth and other the goals associated with human well-being (Hoff, 2011; Keulertz, 2016). The innovative aspect
50 of the nexus thinking is its e look at a more balanced view of the issues linking the resources (Al-Saidi and Elagib, 2017). T;
51 thus, the nexus frameworks identify key issues in food, water, and energy securities through thea lens of sustainability and ;
52 seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The 2015 World Economic
53 Forum identified water, food, and energy shocks as primary future risks, ~~and calling ed~~ for increased efficiency in water use
54 across all sectors and the implementation of integrated water resources management. Various conceptual frameworks relating
55 to the nexus approach were have been developed: For example, the FAO (2014) emphasized the role of the nexus for in food
56 security; and the International Renewable Energy Association (IRENA, 2014) applied the nexus approach in for transforming
57 conventional energy systems to renewable waysystems.

58 The demand for resources including water, energy, and food, -is expected to further increase due to drivers such as population
59 growth, economic development, urbanisation, and changing consumer habits (Terrapon-Pfaff et al., 2018). The interlinkages
60 across key natural resource sectors and improving edtheir production efficiency offer a win-win strategy for environmental
61 sustainability, whether for current or future generations (Ringler et al., 2013). Accordingly, applicatioy in of g the Water-
62 Energy-Food (WEF) nexus concept or approach is expected to make the implementation of the Sustainable Development Goals
63 (SDGs) more efficient and robust (Brandi et al., 2014; Yumkella and Yillia, 2015). The SDGs are classica examples of the
64 necessity to acknowledge -multidimensional, nexus of interlinkages and trade-offs, particularly a. As governments are
65 challenged with ways to maximize the benefits and of invest ing their limited resources of human. Infrastructure and capital
66 are needed in the SDGs to achieve national SDG targets and increasing popularity in recent years, and more and more
67 publications do not focus on security in the nexus but the concept is now used in broader terms to highlight interdependencies
68 between resources and the need for integrated, ion for sustainable governance and management of those resources (Pahl-Wostl,
69 2019).

70 The debate surrounding effectively addressing water and food security challenges stems from questions about whether the
71 water-food crisis is due to a poor understanding of these resources ~~and/~~ or to their improper management (Mohtar et al., 2015).
72 One long-standing challenge to water management lies in the lack of integration between among the multiple sectors that
73 interacting with the water sectors across geographical areas or within large, transboundary, basins (Mohtar and Lawford, 2016).
74 Projections about availability and quality of le-water, food, energy, or soil (~~quality~~)-resources are often alarming. A
75 fundamental shift is needed away from traditional 'silo' approaches and toward more integrative, systems approaches (Daher
76 and Mohtar, 2015). Energy and water are crucial resources for economic growth, especially in industrialized areas (Flörke et
77 al., 2013; Cai et al., 2016), making and thus the rapid fast-increase in demand for these resources is a serious issue for in terms
78 of both economics and the environmental impacts. While developing technology to reduce industrial demand for water and
79 energy intensities in industry is important, we must also understand the relationship between economic growth, water-energy
80 consumption, the impact of industrial activity on agriculture at the local level. Increase of industrial products can cause steep
81 increases in demand for water and energy, which in turn, leads to issues of downscaling water or energy securities.

82 The nexus framework is dependent on the stakeholders, system boundary, and analytical tools. In considering the application
83 of the nexus as a platform, an integrated modelling approach is essential. These issues manifest in very different ways across
84 each sector, but their impacts are often closely related in terms of trade-offs. In particular, the sub-nexus needs to be effectively
85 conceptualized and a theoretical sub-nexus developed. Private-sector water, energy, and food supply chain players are the key
86 stakeholders to address current contradictions arising as a consequence of attempts to develop a grand nexus approach (Allan
87 et al., 2015). Accordingly, we must consider the "specialized" nexus of multi-stakeholders, such as agriculture, industry and
88 urban areas, for which water, energy and food are treated as subsystems. Current nexus frameworks often focus on macro-
89 level drivers of resource consumption patterns (Biggs et al., 2015), but major nexus challenges are faced at local levels

(Terrapon-Pfaff et al., 2018). Thus, 'larger scale' extraction and consumption of natural resources may lead to depletion of natural capital stocks and increased climate risk with no equitable share of the benefits (Hoff, 2011; Rockström et al., 2009). Al-Saidi and Elagib (2017) showed the importance of exploring driving forces and interactions at different scales in the conceptual development of the nexus, emphasizing more case-study based recommendations in the reality of institutions, bureaucracies, and environmental stakeholders.

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 necessary to resolve the resource allocation pressures. Between 1990 and 2016, Morocco's population grew from 25 million to 35 million people (World Bank, 2019a)(<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 (FAO, 2015)(<http://www.fao.org/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 (World Bank, 2019b)(<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 relieve some of the pressure on its fresh water resources and help secure the water necessary for phosphate production processes (OCP, 2016b) 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 its consumed energy it consumes (World Bank, 2019c). 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. An integrated approach to resource allocation is needed to minimize inevitable competition for resources; an integrated approach to resource allocation is needed, one approach that quantifies the trade-offs associated with the possible pathways. As Morocco heads toward achieving its phosphate production goals, its the 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 (OCP, 2013).

This study adapted the WEF Nexus Tool linking industry and agriculture to to also integrate the supply chain for industrial products. Using the Tool, we the authors evaluated the impacts of Morocco's phosphate production on the water, energy, and food resource systems of its mining region, and then addressed the resource elements in in the supply chain management of phosphate production. Specifically, we they 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 are to quantify the water, energy, food, energy used by the of phosphate industry in the Khouribga region of Morocco and to assess the trade-offs of water and resource s allocations between agriculture and industrial use.

2 Materials and methods

2.1 Site description

131 We contacted the managers and engineers working in the Office Cherifien des Phosphates (OCP) group which is that country's
 132 leading phosphate producer in Morocco, and had a lot of discussion about the site, data, policy, and goals. OCP group accounts
 133 for 3% of the country's gross domestic product and about 20% of national exports in value over the course of the 20th century
 134 (Croset, 2012). The OCP group ran three mining fields: in central Morocco, near the city of Khouribga, and on the Gantour
 135 site. Khouribga, the largest mining area, includes three main sites from which raw phosphate is excavated and transported for
 136 chemical processing and fertilizer production: Sidi Chennane (SC), Merah Lahrach (MEA), and Bani Amir (BA) (Figure 1).
 137 The output in Khouribga is raw phosphate produced as either rock or slurry, the main component of manufactured phosphorous
 138 fertilizers. The transport of the phosphate (rocks and slurries) from Khouribga (mining area) to Jorf Lasfar (industrial
 139 production area) is a primary project in Morocco (OCP, 2016a). The demand for raw phosphate and the production and export
 140 of fertilizer and its products from Jorf Lasfar drive the upstream mining activity of Khouribga. In 2015, approximately 20.1
 141 million tons of raw phosphate were excavated, which was 58 % of total raw phosphate excavated in Morocco in 2018 (OCP,
 142 2020), and transported to Jorf Lasfar; about 40% of this product was transported via pipeline as slurry and the balance via train
 143 as rock.

144 The pipeline from Khouribga to Jorf Lasfar is 187 km and ensures the continuous transport of phosphate from the Khouribga
 145 to Jorf Lasfar (Figure 1). As the plan was to increase phosphate production and phase out transport by train, tracks were
 146 replaced by pipeline that ensures the continuous flow of raw phosphate from the mining to the industrial area (OCP, 2016a).
 147 The plans impact regional water, energy, and food management: in particular, shifting from train to pipeline requires additional
 148 water to convert dry rock into liquid slurry. Shifting from train to pipeline changes the demand for water and energy resources
 149 at both the mining and the production locations.

150 In accordance with the “Green Morocco (Plan Maroc Vert)” (Stührenberg, 2016) and the National Water Plan for Morocco,
 151 the use of surface water as a substitute for groundwater is encouraged: ~~and~~ water withdrawals from ~~the regional~~ ~~'s~~ aquifers
 152 are being phased out since 2010, ~~eventually~~ to be replaced entirely by surface water ~~from~~ ~~supplied to the mining sites from~~
 153 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
 154 from the dam to the mining site. Additionally, OCP launched a plan to complete treatment plants for urban wastewater
 155 (capacity 5 million m³ yr⁻¹) to be used for washing phosphate and industrial reuse in the mining area (OCP, 2016b). The
 156 phosphate mining area is encircled by cropland, whose water is also supplied from the dam. In this study, the authors consider
 157 the allocation of treated water to both the phosphate industry and agricultural irrigation (Tian et al, 2018). Both the mining and
 158 the agricultural activities of the region represent growing enterprises that place added pressure on available water resources,
 159 ~~and~~ making the sustainable management of the water supply a hotspot to be considered in trade-off analyses.



160
 161 **Figure 1** Study area: ~~including~~ phosphate mining area (Khouribga), fertilizer manufacturing area (Jorf), and transportation
 162 system (slurry pipeline) (<http://www.ocpgroup.ma/ocpslurrypipeline/slurry-pipeline>)

163 **2.12.2 Overall Framework Development of Water-Energy-Food-Nexus - Phosphate (WEF-P) Tool**

164 **2.2.1 Overall Framework of WEF-P Tool**

165 The developed WEF-P Tool, adapted from the WEF Nexus Tool 2.0 (Daher and Mohtar, 2015), considers the supply chain of
166 final product in terms of its resource consumption, including the set of processes that pass materials forward (La Londe and
167 Masters, 1994; Mentzer et al., 2001), and various organizations or individuals directly involved in the flow of products
168 (Mentzer et al., 2001). It assesses the impact of various scenarios and possible responses to regional resource management
169 needs. Table 1 shows the differences between WEF Nexus Tool 2.0 and WEF-P Tool in the context of variables, scenarios,
170 analytical tools, and quantitative assessments.

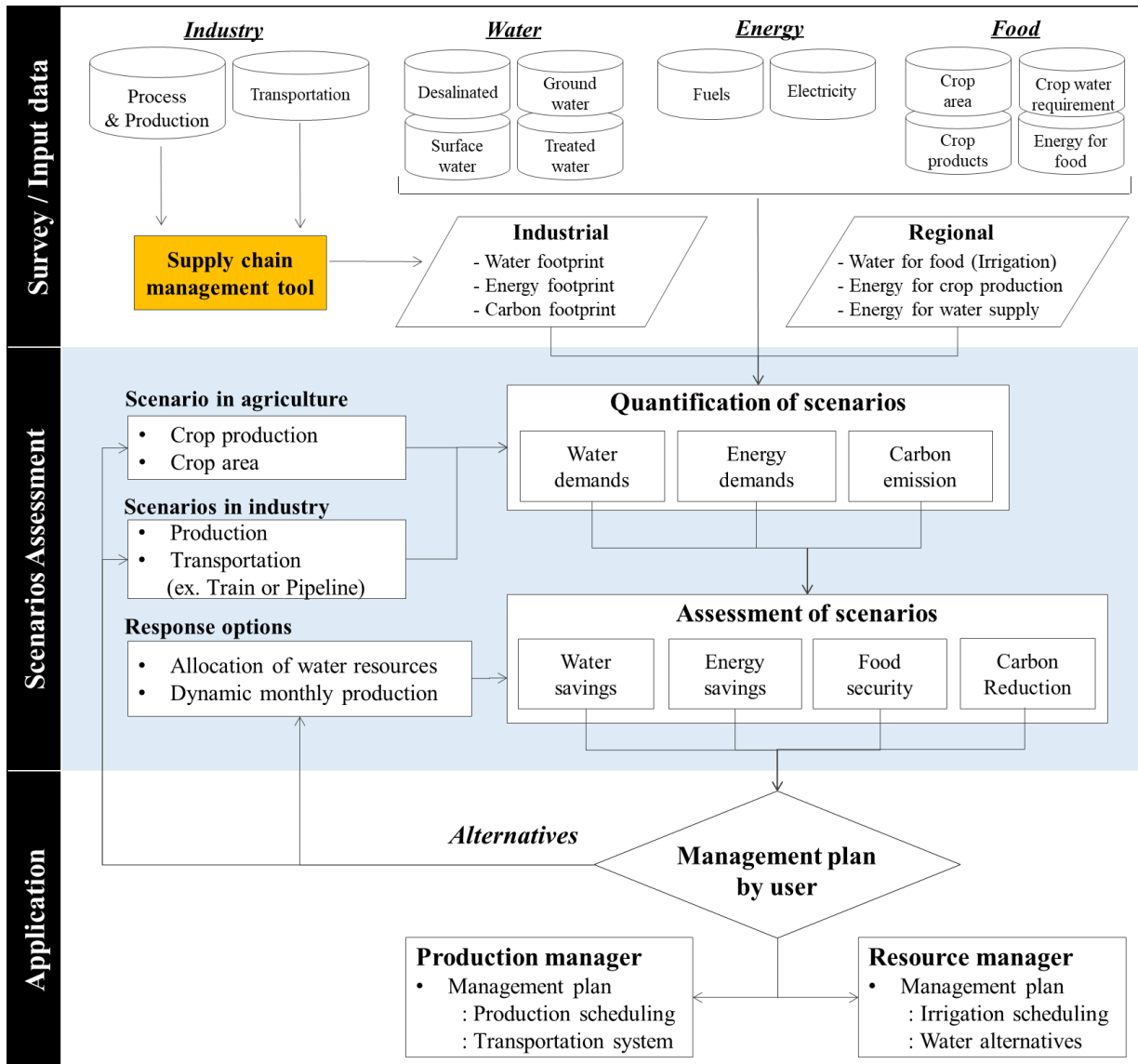
171 Both the Tools offer a platform for development of the analytics necessary to understand the trade-offs and catalyse a
172 stakeholder dialogue (Mohtar and Daher, 2016; Mohtar, R. H. and Daher, 2014). The core of the WEF Nexus is that production,
173 consumption, and distribution of water, energy, and food are inextricably inter-linked: decisions made in one sector impact the
174 other sectors (Hoff 2011, Mohtar and Daher, 2012). The WEF Nexus Tool 2.0 allows holistic quantification of the impact of
175 resource allocation strategies to support informed, and inclusive stakeholder dialogue between policy makers, private sector
176 firms, and civil society (Daher and Mohtar, 2015). Each stakeholder becomes involved at different stages and scales in the
177 decision-making process. In the WEF-P Tool (Figure 2), water resources are shared ~~betweeny~~ the phosphate industry and ~~the~~
178 agricultural interests in the region of study. Sustainable water management must holistically consider the allocation of water
179 resources for both industrial production and ~~the agricultural irrigation of agricultural crops~~. New water (~~grey, produced,~~
180 ~~brackish, and treated urban~~ ~~wastewater from urban area~~) ~~ha~~ is a resource with the potential to ~~contribute~~ significantly ~~contribute~~
181 to bridging water and food gaps (Mohtar et al., 2015). ~~H;~~ however, ~~it new water also~~ carries an energy footprint that must be
182 considered when increasing local food production. ~~Potentially, a~~ Agriculture's demand for water ~~potentially~~ competes with
183 ~~those of e~~ ~~demands of~~ a growing industry. The Tool quantifies the use of water and energy and the amount of CO₂ emitted for
184 each scenario. It also quantifies the water and energy savings resulting from choices made regarding transportation scenarios.
185 The Tool assesses the effects of decisions of dynamic management of phosphate production as these impact water and energy
186 securities. The WEF-P tool can assess various scenarios and help account for ~~the~~ interdependencies between food and industrial
187 production, ~~and~~ between water and energy consumption. ~~Only~~ thus ~~allowing ean~~ the trade-offs associated with potential
188 resource allocation pathways ~~to~~ be quantified.

189 Throughout the tool development process, the supply chain was verified with OCP and the OCP Policy Center in various ways:
190 (i) during the data collection phase, through meetings with the OCP steering committee, financial managers, technical
191 managers and engineers; and (ii) through follow ups with OCP Policy Center team (conference calls and email). The OCP
192 Policy Center team shared with WEF Nexus Team their main concerns regarding the tool structure, based on input from the
193 OCP technical team. The WEF Nexus Team used these shared concerns in their considerations of revisions to the tool structure
194 and associated excel spreadsheets of the model. Specifically, the major aggregated processes and lines of productions were
195 revised and identified in a functional supply chain to maximize the abilities and flexibilities of the model and ensure efficacy
196 of the available data base for processes and production lines.

197 However, the WEF-P Tool has limitations in assessing economic impacts such as cost and benefit analysis. This is because
198 cost must include the price of water, which is still under discussion, and the price of products when analysing their benefits.
199 Raw phosphate is transported to the manufacturing area and used in the production of various fertilizers that have different
200 prices: this makes it difficult to set the price of excavating raw phosphate in the mining area. Sustainability assessment also
201 has qualitative aspects in terms of environmental impact. The WEF Nexus Tool 2.0 applied the sustainability index based on
202 resource capacity and availability, however, it is still a quantitative aspect. We should consider the meaning and definition of
203 sustainability, both quantitatively and qualitatively, and then assess the index using the stakeholders' weights for the variables
204 related to sustainability. Additionally, spatial and temporal scales should be included in a sustainability index. For example,
205 the pipeline transportation system requires water, which is transported with products: the pipeline causes greater water use at
206 the origin, but also provides additional water to the destination area. Also, the water requirement differs with temporal season,
207 such as the water intensive agricultural production season. Thus, more research is needed for a sustainability assessment based

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on economic and environmental impact. However, the quantitative analysis is an essential factor for assessing sustainability, therefore, the WEF-P Tool focuses on quantification of 1) water and requirements for phosphate production and transportation, 2) carbon emissions by energy used in product processes, 3) water supply system and transportation, and 4) dynamic production impacts on water and energy savings.



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Figure 1-2 Assessment of holistic impacts of various scenarios relating to phosphate industry, agriculture, and resource management using WEF-P Tool

The Tool quantifies the use of water and energy and the amount of CO₂ 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.

Table 1 Comparison between WEF Nexus Tool 2.0 and WEF-P Tool

	<u>WEF Nexus Tool 2.0</u>	<u>WEF-P Tool</u>
<u>Variables and scenarios</u>	<ul style="list-style-type: none"> • <u>Self-sufficiency of produced crops</u> • <u>Type of agricultural production</u> • <u>Sources of water (groundwater, surface water, treated water and so on)</u> • <u>Sources of energy (natural gas, diesel, solar, wind and so on)</u> • <u>Trade portfolio (countries of import and amounts per country)</u> 	<ul style="list-style-type: none"> • <u>Static and dynamic phosphate production</u> • <u>Transportation modes (train and pipeline)</u> • <u>Sources of water (groundwater, surface water, treated water and so on)</u> • <u>Water allocation between industry and agriculture</u>
<u>Analytical tool</u>	<ul style="list-style-type: none"> • <u>Food product base analysis</u> • <u>Food-centric interlinkages among water, energy, and food</u> • <u>Water and energy footprint based on product (ex. water footprint of crops)</u> 	<ul style="list-style-type: none"> • <u>Process base analysis</u> • <u>Phosphate-centric interlinkages among production, transportation, and resource allocation</u> • <u>Water and energy footprint based on processes (ex. water footprint in washing process)</u>
<u>Quantitative assessment</u>	<ul style="list-style-type: none"> • <u>Water requirement for energy and agricultural production</u> • <u>Energy requirement for agricultural and water production</u> • <u>Land footprint for agricultural and energy production</u> • <u>Carbon emissions from energy used for water and food production</u> • <u>Financial cost</u> 	<ul style="list-style-type: none"> • <u>Water and requirement for phosphate production and transportation</u> • <u>Carbon emission by energy used in product processes, water supply system and transportation</u> • <u>Dynamic production impacts on water and energy savings</u>

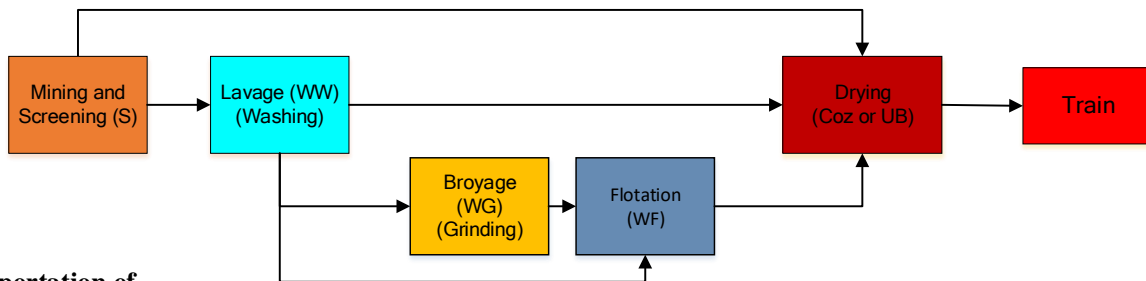
2.2.2 Analysis of integrated supply chains linking sub-processes and transportation modes ~~WEF-P Tool~~

The WEF-P Tool used the WEF Nexus approach to assess the life cycle of the final products supply chain. The water and energy used to produce sub- and final products ~~are~~ were calculated by adding the water and energy requirements from ~~of~~ the sub-processes through the production supply chain ~~(Figure 2)~~. In Khouribga, raw phosphate products pass through a sequence of functional processes: Mining and Screening (S), Washing (WW), Grinding (WG), Flotation (WF), Adaptation including powdering (WA), and Drying (COZ - Complex Ouad Zem) for SC and (UB) for MEA (Figure 3). 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 extraction, 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.

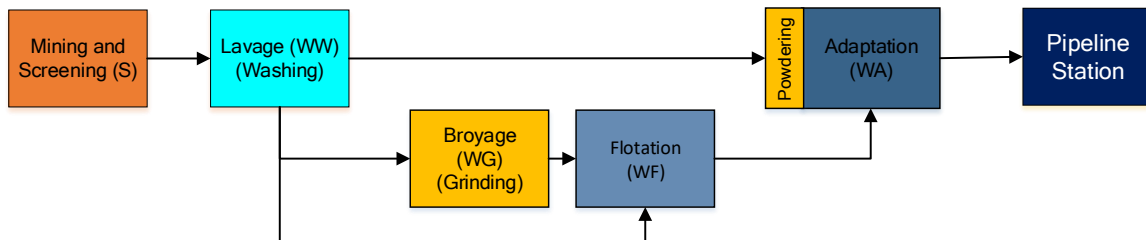
The change in transportation system can affect the supply lines (Figure 3). In the mining area, the products are phosphate rocks and slurry, both of which are transported to the manufacturing area, e. ~~Each product with~~ its own resource requirements. Slurry requires flotation and adaptation, thus, is more water-intensive; p. ~~Phosphate rock is dried in using~~ an energy intensive process that consumes most of the energy produced in the mining area. Slurries are transported via pipeline and; ~~rock is transported by~~ train; e. ~~Each mode of transportation has its distinct own~~ resource needs at different stages. T, ~~and~~ the two transportation systems are also have distinct ~~processes~~: the pipeline supply chain includes ~~the~~ washing (water) and adaptation ~~processes to that~~

239 produce slurry; the train supply chain includes ~~the a~~ fuel intensive drying process. It is possible to quantify the flow of products
 240 according to the transportation system used. When transport changes from train to pipeline, supply lines also change: the
 241 drying process is replaced by the adaptation process. ~~High quality phosphate rocks transported by train have undergone mining,~~
 242 ~~screening, and drying. Low and very low quality phosphate rocks also undergo a washing process in advance of any other~~
 243 ~~processes.~~ If the phosphate is transported by pipeline, it must first be transformed to slurry, adding the adaptation process to
 244 the supply chain. Changes in the supply chain impact the water and energy consumed and, consequently, the CO₂ emitted. The
 245 mining and screening processes include extraction from the ground, tone removal, and screening to produce pieces of
 246 phosphate rock. ~~Here, the supply chain is determined by the quality and size of the phosphate rock, which in turn, depends on~~
 247 ~~the phosphate content at the moment of extraction, which ranges from very low to high. High quality phosphate rock is~~
 248 ~~transported to a drying process from which it will either be marketed or chemically transformed into fertilizer at the~~
 249 ~~manufacturing site. Low to medium quality phosphate rock goes is washed, dried, ground, and subjected to flotation, intended~~
 250 ~~to increase the phosphate content. Therefore, it is important to combine the supply chains for products and transportation~~
 251 ~~systems.~~

Transportation of phosphate rock by Train



Transportation of phosphate slurry by pipeline



252
 253 **Figure 3** The functional processes and flows of products in Khouribga (mining) by transportation method.s

254 2.2.3 Adaptation of process-base water, energy, and CO₂ footprints

255 ~~We considered the supply chain's integrating processes of production and transportation and adapted the water and energy~~
 256 ~~footprints, which indicate the quantity of water or energy consumed in various sub processes in integrated supply chains (Fig-~~
 257 ~~2). The main function of the WEF-P Tool is identification of the relationship between resources and production, and the~~
 258 ~~quantification of the resources consumed in phosphate production. The methodology is based on life cycle assessment. The~~
 259 ~~water and energy footprints were analysed, indicating the quantity of water or energy consumed in various sub-processes in~~
 260 ~~the supply chain's integration of production and transportation. The technical details of each process are specific and~~
 261 ~~aggregated into functional processes. The main component is the footprint, which indicates the water and energy requirements~~
 262 ~~for phosphate products, and the CO₂ emitted through energy consumption. Each process has a specific footprint based on field~~
 263 ~~data and fed into the tool monthly, or when a significant change in capacity of the functional processes has occurred. For all~~
 264 ~~footprint processes in Khouribga, the amount of raw phosphate is measured in commercial metric tons embedded in slurries~~
 265 ~~and rock. Even if the phosphate rock changes to slurry through several processes, the amount of raw phosphate embedded in~~

products is not changed. Thus, the tons of phosphate in water and energy footprints indicate the raw phosphate embedded in the products in each process and is constant through entire supply chains.

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 was analyzed. 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, but 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).

$$WC_{mining\ area} = \sum_i^n (P_i \times WFP_i) + WC_{pipeline\ station} \quad (1)$$

$$WC_{pipeline\ station} = P_{slurry} \times WC_{pipeline\ station} \quad (2)$$

$$EC_{mining\ area} = \sum_i^n (P_i \times EFP_i) + EC_{pipeline\ station} + EC_{train} \quad (3)$$

$$EC_{pipeline\ station} = P_{slurry} \times EFP_{pipeline\ station} \quad (4)$$

$$EC_{train} = P_{phosphate\ rock} \times EFP_{train} \quad (5)$$

where $WC_{mining\ area}$ (m^3) is total water consumption in mining area, $EC_{mining\ area}$ (MWh or L) is total energy consumption in mining area, P_i (ton) is production from each process (i) in mining area such as mining, screening, washing, flotation, and drying. WFP_i ($m^3\ ton^{-1}$) and EFP_i (MWh ton^{-1} or L ton^{-1}) are water and energy footprints in each process (i). $WC_{pipeline\ station}$ (m^3) is water consumption in pipeline station, $EC_{pipeline\ station}$ (MWh or L) is energy consumption in pipeline station, and EC_{train} (MWh or L) is energy consumption by train to transport phosphate rock to manufacturing area. P_{slurry} and $P_{phosphate\ rock}$ (ton) are production of slurry and phosphate rock. $WFP_{pipeline\ station}$ ($m^3\ ton^{-1}$) is water footprint at pipeline station in mining area. $EFP_{pipeline\ station}$ and EFP_{train} (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.

CO₂ emissions are relevant when assessing the environmental impact of phosphate production. Although real emission in each process in supply chain should be measured, this study is limited measuring CO₂ emission in mining area. In addition, CO₂ emission in crop area is related to soil and crops, and it is another level of research. Thus, we limited CO₂ emission to that emitted by fuel energy use by machinery (direct emission) and electricity generation in power plants (indirect emission), and the reference CO₂ footprints were applied (Table 2). 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 CO₂ emissions. Indirect CO₂ 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 (2019) (<https://www.eia.gov>), one litre of gasoline used by machinery or a facility produces 2.6 kg of direct CO₂ emission, and a power plant burning only coal to generate electricity, emits 1,026 tons of CO₂ kWh⁻¹. Renewable (non-fossil) electricity emits only 15.8 tons of CO₂ 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 CO₂ emission is calculated as shown in equations (6-7).

$$DCO_2 = \sum_i^n CFF_{F_i} \times FC_i \quad (6)$$

$$InDCO_2 = \sum_j^n CFP_{E_j} \times ELC_j \quad (7)$$

where DCO_2 (ton) is direct CO_2 emissions and $InDCO_2$ (ton) is indirect CO_2 emissions. CFP_{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.

Table 2 CO_2 emission by burning fuels and generating electricity

<u>CO₂ emission by burning fuel</u>		<u>CO₂ emission by generating electricity</u>			
<u>Sources</u>	<u>CO₂ emission¹</u> <u>(kg of CO₂ L⁻¹)</u>	<u>Sources</u>	<u>CO₂ emission</u> <u>by sources¹</u> <u>(ton of CO₂ 10⁻⁶ kWh)</u>	<u>Proportion of sources</u> <u>in Morocco²</u> <u>(%)</u>	<u>CO₂ emission</u> <u>(ton of CO₂ 10⁻⁶ kWh)</u>
<u>Gasoline</u>	<u>2.59</u>	<u>Coal</u>	<u>1,026</u>	<u>43.4%</u>	
<u>Diesel</u>	<u>2.96</u>	<u>Petroleum</u>	<u>1,026</u>	<u>25.3%</u>	
		<u>Natural gas</u>	<u>504</u>	<u>22.7%</u>	<u>820.9</u>
		<u>Hydroelectricity</u>	<u>19.7</u>	<u>6.9%</u>	
		<u>Renewables</u>	<u>15.8</u>	<u>1.7%</u>	

¹ U.S. Energy Information Administration (USEIA) (<https://www.eia.gov>)

² International Energy Agency (IEA)

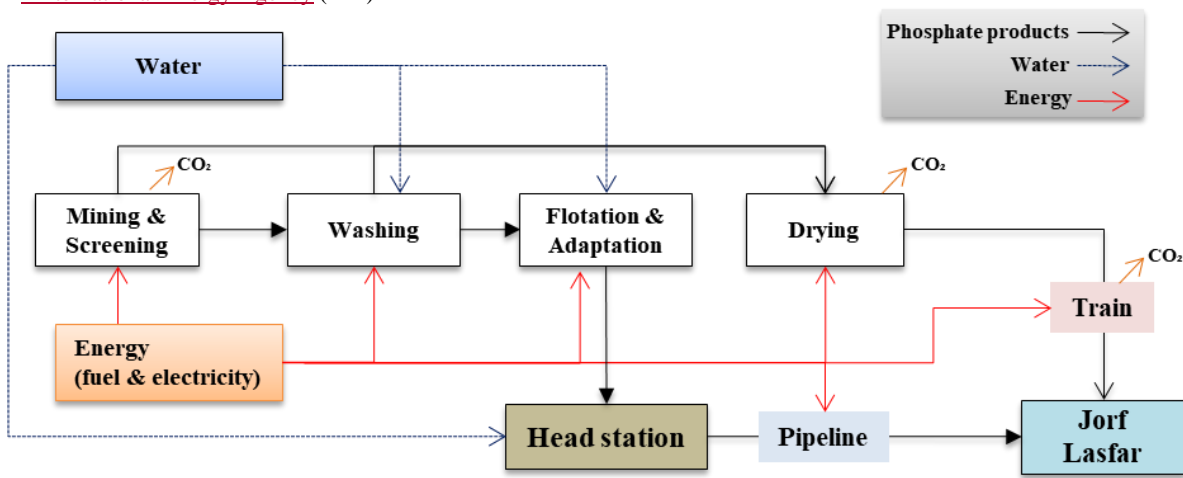


Figure 2 The functional processes and the flow of products in Khouribga (mining) and Jorf Lasfar (manufacturing)

2.3 Agricultural 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 (Smith, 1992) (<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). Table 3 showed the average climate data in Khouribga area provided from CLIMWAT 2.0.

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. 44 and 56, Crop Evapotranspiration-Guidelines for computing crop water requirements (Allen et al., 1998; Smith, 1992). 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).

$$ET_c = ET_0 \times K_c \quad (8)$$

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

where ET_0 is the reference crop evapotranspiration (mm d^{-1}); ET_c is the crop evapotranspiration (mm d^{-1}); K_c is the crop coefficient; Δ is the slope of the saturated vapor pressure/temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$); γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$); u_2 the wind speed at 2 m height (m s^{-1}); R_n is the total net radiation at crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$); G is the soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$); T is the mean daily air temperature at 2 m height ($^\circ\text{C}$); 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, as shown in Table 4 (Allen et al., 1998).

Irrigation water requirement was calculated by ET_c and effective precipitation, as shown in Eq. (10). The effective precipitation indicated the precipitation except for runoff, and it was calculated using by the USDA Soil Conservation Service method (Eq. 11) (Smith, 1992).

$$IRReq = ET_c - P_{eff} \quad (10)$$

$$P_{eff} = P_{tot} (125 - 0.2 P_{tot}) / 125 \quad \text{for } P_{tot} < 250 \text{ mm} \quad (11)$$

$$P_{eff} = 125 + 0.1 P_{tot} \quad \text{for } P_{tot} > 250 \text{ mm}$$

where $IRReq$ is irrigation water requirement, ET_c is the crop evapotranspiration, P_{eff} is effective precipitation, and P_{tot} is total precipitation.

Table 3 Climate information in Khouribga

Month	Precipitation (mm m ⁻¹)	Temperature		Relative humidity (%)	Sunshine hours (h d ⁻¹)
		min. (°C)	max. (°C)		
Jan	56	3.8	17.3	72	5.6
Feb	65	5	19	76	5.7
Mar	94	7.2	21.8	69	6.4
Apr	70	9.5	25.3	67	7.4
May	32	12.5	29.3	55	8.8
Jun	9	16.6	34.5	48	9.8
Jul	2	19.8	39.7	39	10.9
Aug	7	20	39.6	37	10.3
Sep	12	17.5	34.5	47	9.1
Oct	27	13.5	29	58	7.6
Nov	71	8.8	22	70	5.2
Dec	81	5.1	18.6	71	5.5

Table 4 Crop planting and harvesting seasons, stage length and crop coefficients Information (Allen et al., 1998)

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

* Next year

3 Results and discussion

3.1 Application of scenarios

Increasing the exportable phosphate products and changing the transportation system from train to pipeline are considered top priorities for OCP group. Therefore, we assessed the impact of increased production by applying the scenarios (Table 5). Until recently, dried phosphate was transported by train from mining to manufacturing site, but, in the near future OCP group will use only pipeline transport. The change of from train to pipeline can affect not only direct energy or water consumption by

transportation system but also that of the total supply chain in the mining site. Consequently, the production processes for slurry and for rock consume different quantities of water and energy, so that the mode of transport also becomes a scenario to allow quantification of their respective water and energy requirements. Therefore, we applied the scenario about transportation system which indicates the only usage of pipeline. Table 4 showed the scenarios combining production and transportation. The first two scenarios are related to the ‘business as usual (BAU)’ scenario for production in 2015 but changing the transportation system from Khouribga to the terminal station at Jorf Lasfar. The other scenarios are related to the increase in the production.

Table 5 Scenarios through combination of production and transportation system

Scenario	Phosphate production	Transportation of phosphate products	
		by pipeline	by train
BAU	Production in 2015	40 % of total phosphate	60 % of total phosphate
Scenario 01		100% of total phosphate	None
Scenario 02	50% increase of phosphate	40 % of total phosphate	60 % of total phosphate
Scenario 03	export	100% of total phosphate	None

3.1.2 Quantification of water and energy consumption and CO₂ emission by production and transport of phosphate

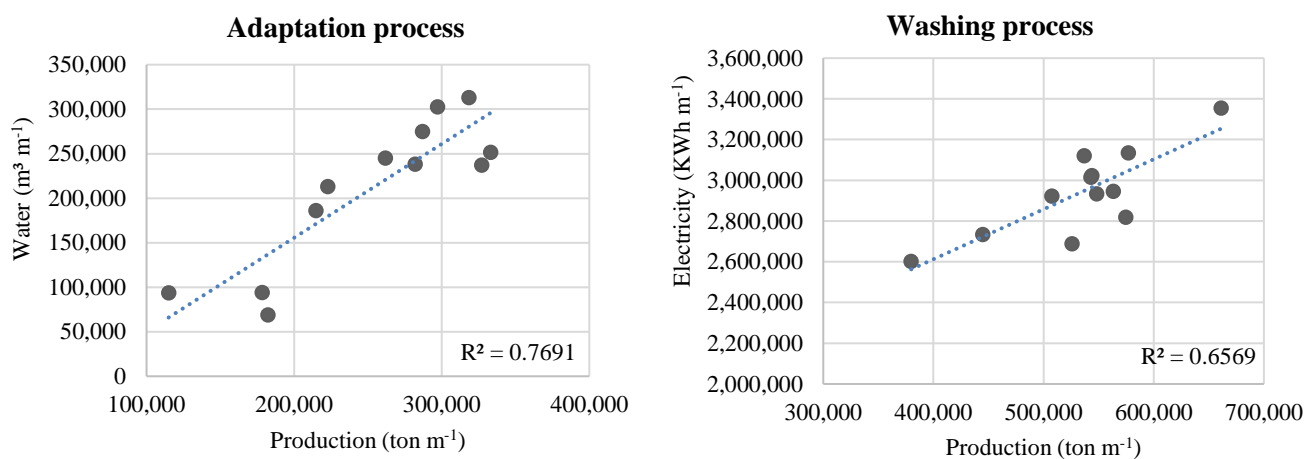
To quantify the water, energy, and CO₂ emissions, water and energy footprints of each process in each mining site were analysed based on survey data. For example, the adaptation process is essential for pipeline transportation and large amounts water are needed in comparison to other processes, thus the relationship between the amounts of phosphate and water used in adaptation process were analysed (Figure 4 (a)). In addition, energy footprint includes electricity and fuel consumption; analysed through the linear relationship (Figure 4 (b)).

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 CO₂ emissions in each scenario (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 m³ 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 m³ of fresh water were transported by pipeline to the industrial area by pipeline. Scenario 1 (all raw phosphate transported by pipeline) increases the total water used to 32.14 million m³ (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 m³, 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

396 decreases as there is no need to dry phosphate rock. This results in a nearly 86% decrease in fuel consumption over the BAU
 397 scenario and a fuels savings of 176.4 million litre, which translates into a 40% decrease in CO₂ emission in Scenario 1. In With
 398 regard to Scenario 2, there was a 50% increase of raw phosphate export over the BAU scenario, and with transport the same
 399 as in BAU. Total water consumed, including fresh water transported through the pipeline, increased by 16% over BAU, energy
 400 consumption increased by 46 %, and CO₂ emission increased by 39%. Scenarios 3 and 4 represent a 50% increase in phosphate
 401 exports, thus target production was set at 2.45 million tons month⁻¹ for raw phosphate, in total, 29.3 million tons yr⁻¹. Scenario
 402 3 (all raw phosphate is transformed to slurry and total production increased by 50% over BAU) also indicates a total water
 403 consumption increase to 46.6 million m³ (137% over BAU), and electricity consumption increase of by 75%. However,
 404 transport by pipeline also led to an 80% decrease in fuel consumption (compared to BAU), and consequent 18% decrease in
 405 CO₂ emissions.
 406 In summary, the comparison between BAU and scenario 1 showed the trade-off between water and energy by the change in
 407 transportation method. Pipeline transportation can save energy use and reduce CO₂ emission, but more water is required due
 408 to additional processes, such as adaptation and water used to operate the pipeline. However, since the water used to operate
 409 the pipeline is actually transported to Jorf Lasfar and re-used in fertilizer factories, it could be considered non-consumptive
 410 water in terms of the supply chain integrating Khouribga and Jorf Lasfar, even though it is still real water withdrawn form
 411 Khouribga.



(a) Water footprint in an adaptation process in MEA

(b) Energy footprint in a washing process in MEA

412 **Figure 4.** Water and energy footprints in MEA based on the BAU data-base

413 **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	Increase of production (50% over BAU)	29.3	20.1	-
Scenario 2			11.3	18.0
Scenario 3			29.3	-

415 **Table 3-6** Water and energy use, and CO₂ emission by scenario of phosphate production and transport

Scenario (Transportation)	Water (10 ⁶ m ³ 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. Thus, production targets were established for both phosphates and crops, and 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 4-7 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 58) and the treated wastewater from urban area was considered as a water resource for both the phosphate industry and agriculture.

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. For scenario Alloc-1, all treated water was 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 and a treated water quantity of 2.5 million m³ yr⁻¹ (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 69). 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 69). 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 4-7 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

453

454 **Table 5-8** 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	1 st priority	2 nd priority

455

456 **Table 6-9** Additional water and energy for solving water shortage by scenarios of phosphate production

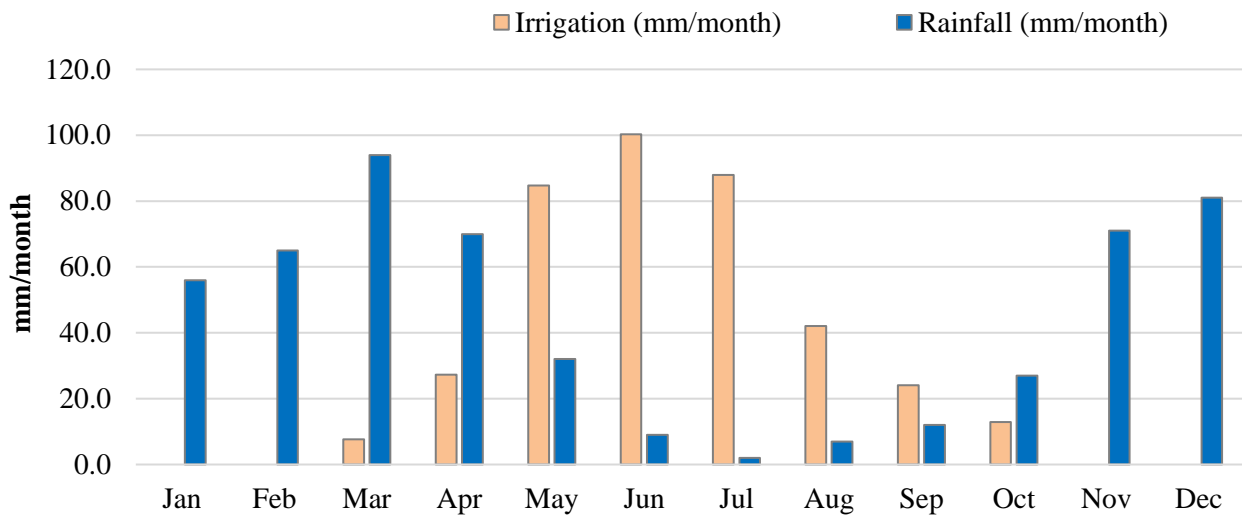
Production (Only pipeline)	Water allocation	Water shortage		Additional water supply		Energy use for water supply	
		Phosphate	Agriculture	Treated water	Ground water	Treated water	Ground water
		10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	10 ⁶ m ³ yr ⁻¹	MWh yr ⁻¹	MWh yr ⁻¹
Production as BAU	Alloc 1	0.00	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				

457 3.3 Assessment of the impact of dynamic management of phosphate production on ground water and energy savings

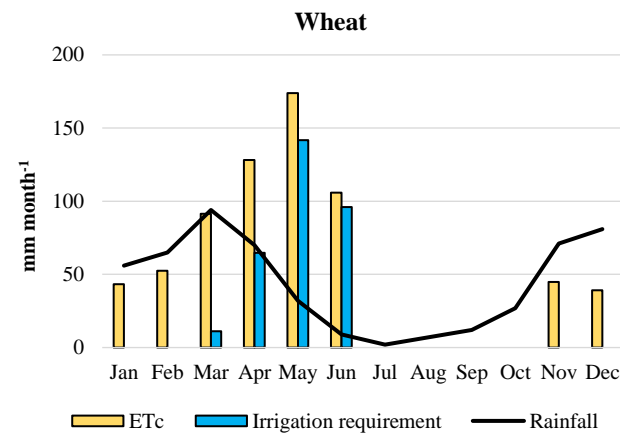
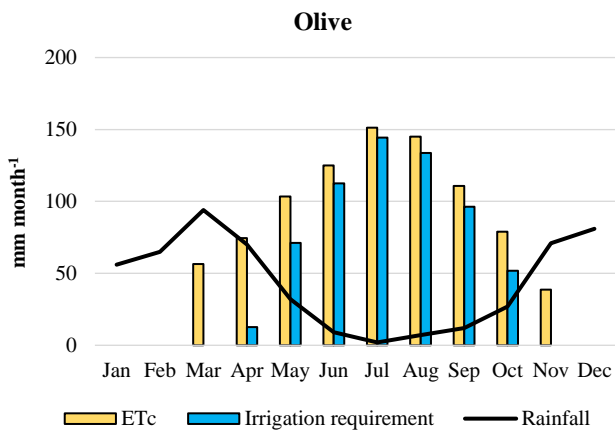
458 Water resource availability and water requirements for crop production are seasonal. Rainfall in June and July is less than 10
459 mm month⁻¹ and irrigation water requirements exceed 80 mm month⁻¹ (Figure- 35). Thus, there is water scarcity in the
460 agriculture area during June and July. Given that water resources are shared between the phosphate industry and the agriculture
461 industry, static production of phosphate could accelerate water shortage for agriculture. Dynamic production of phosphate is
462 ~~considered as~~ a scenario with greater agricultural production during non-irrigation seasons and less production during irrigation
463 seasons. Using the dynamic phosphate production scenario, the monthly production of phosphate decreases from 1.68 to 0.91
464 million tons month⁻¹ between May and October, representing a 50% decrease in raw phosphate export compared to BAU
465 scenario. Between November and April, phosphate production increases to 2.45 million tons month⁻¹, representing a 50%
466 increase in raw phosphate export in compared to BAU scenario.

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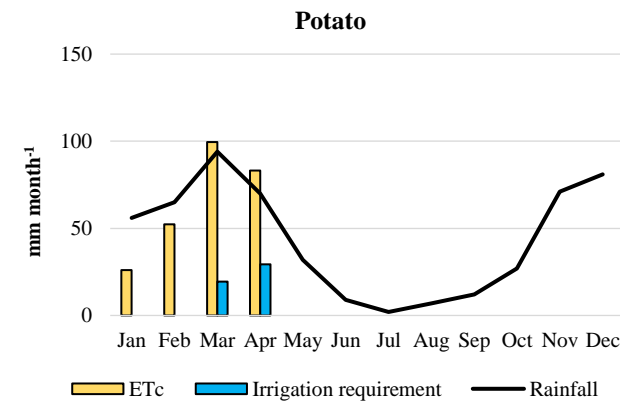
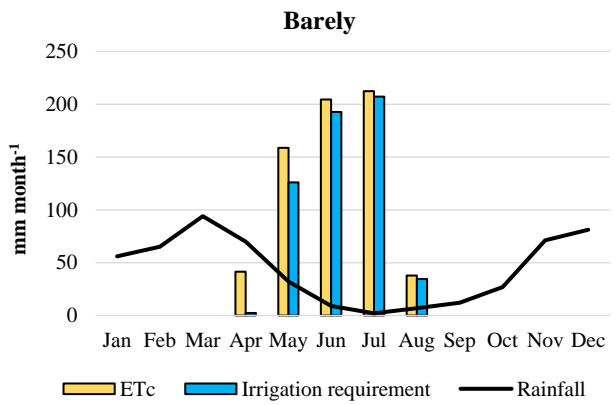


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(a) olive

(b) wheat



(c) barely

(d) potato

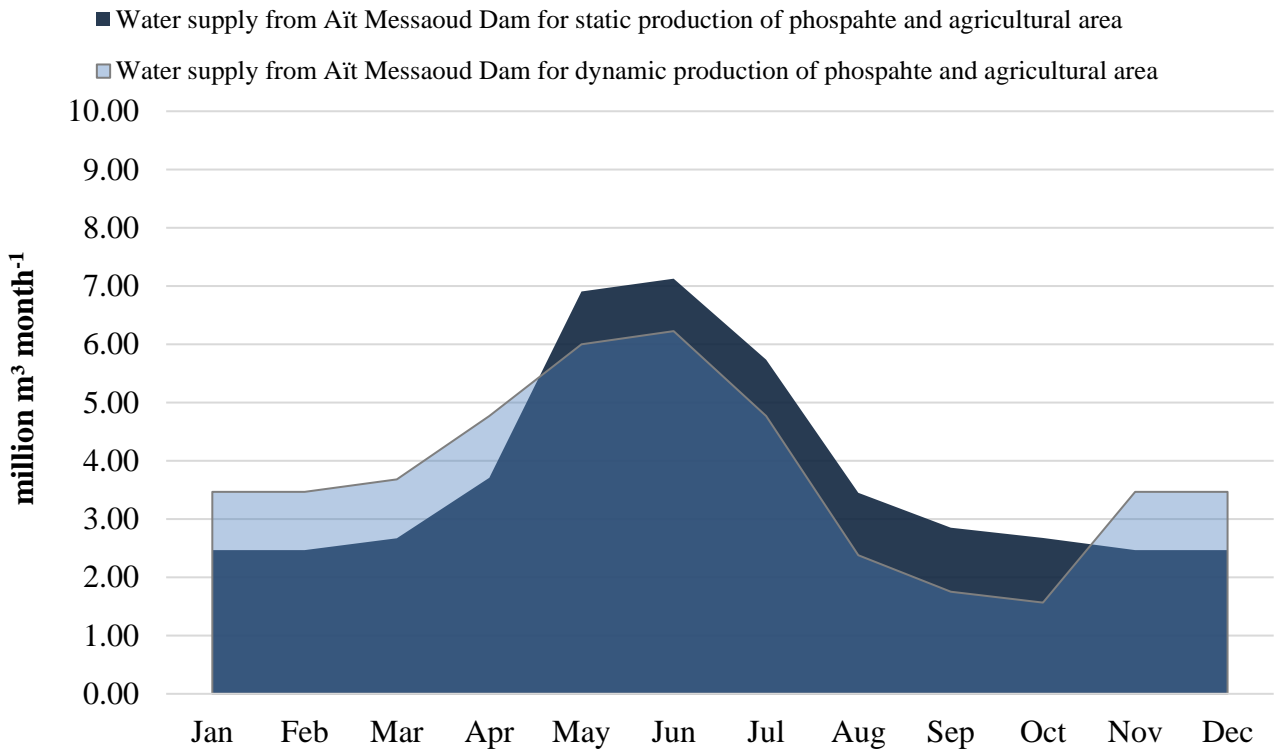
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Figure 5 Monthly irrigation water requirement and rainfall in Khouribga

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 for water from the dam in January and February was about 2.5 million m³, ~~and increasing ed~~ to 7.0 million m³ month⁻¹ in June (Figure- 46). 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

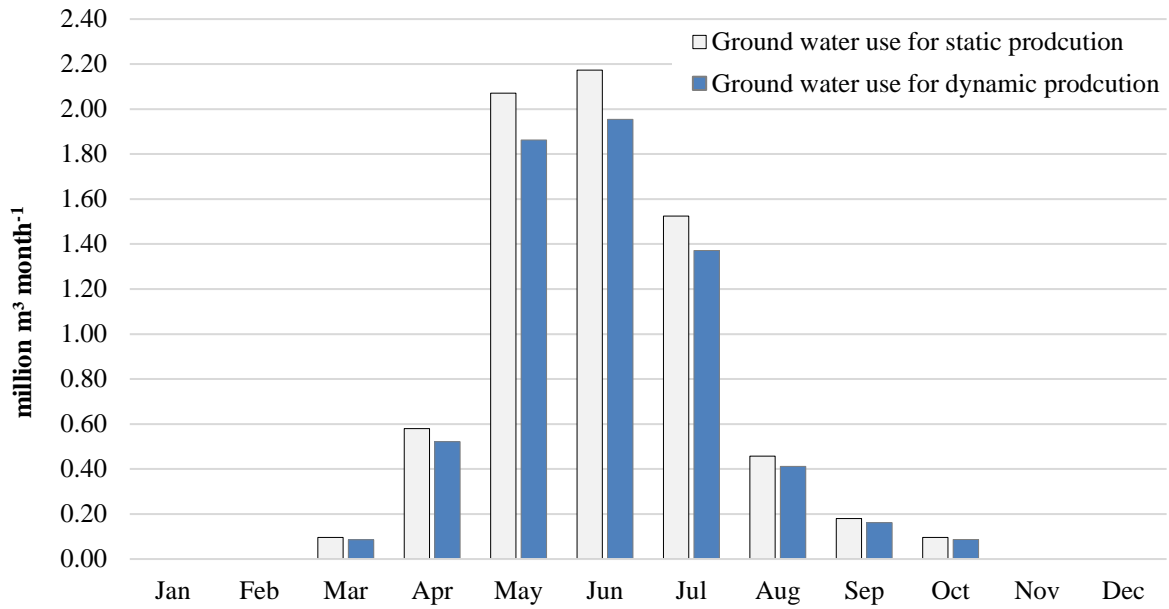
479 water than static production (Figure- 57). During the water scarce season (May to July), total ground water used is 5.77 million
 480 m³ in static phosphate production. This decreases by 10% in dynamic production, potentially saving 0.58 million m³ of ground
 481 water during the water scarce season. Groundwater resources constitute an important aspect of the national hydraulic heritage
 482 and represent the only water resource in this hyper arid climate (Tale, 2006). Thus, dynamic phosphate production carries
 483 positive impact on sustainable water management and water conservation.

484 ~~In addition, d~~Dynamic phosphate production also contributes to electricity savings: supplying water from the dam, ground
 485 ~~water,~~ or treatment require electricity for pumping, transporting, and treating (Figure- 68). Total electricity consumed in
 486 supplying water to the phosphate and agriculture industries was 9,971 MWh yr⁻¹ under the static production scenario
 487 (phosphate slurries, no rocks). This number decreased to 9,828 MWh yr⁻¹ when phosphate slurries were produced dynamically.
 488 About 143 MWh electricity can be saved annually, ~~and is~~ accompanied by a reduction of 117 tons of CO₂ emission.

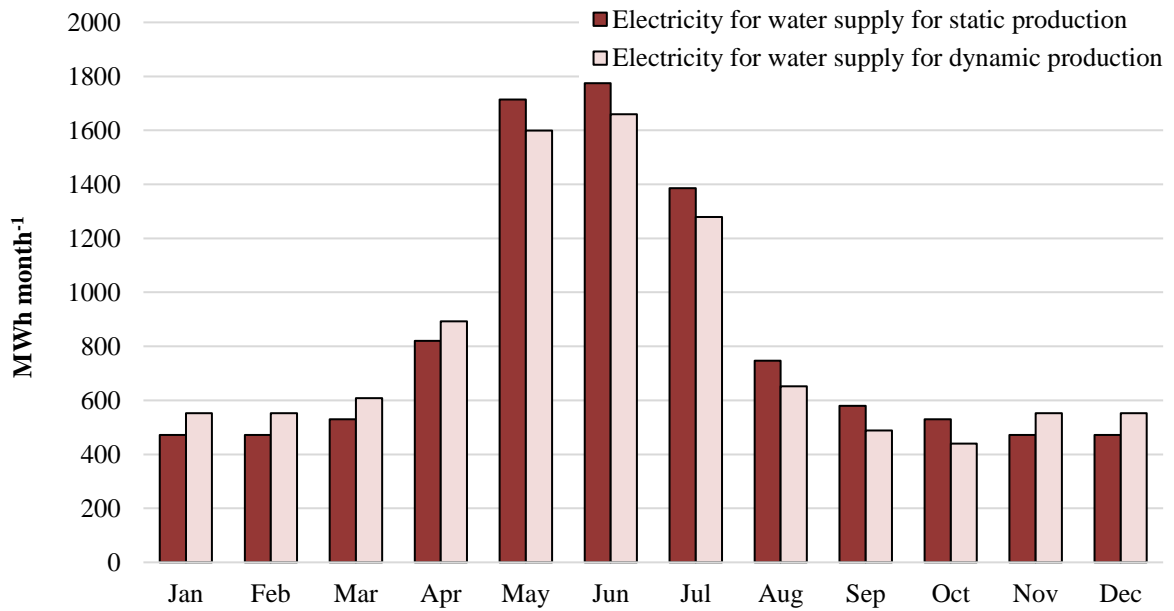


489 **Figure 4 Monthly water supply from Ait Messaoud Dam**

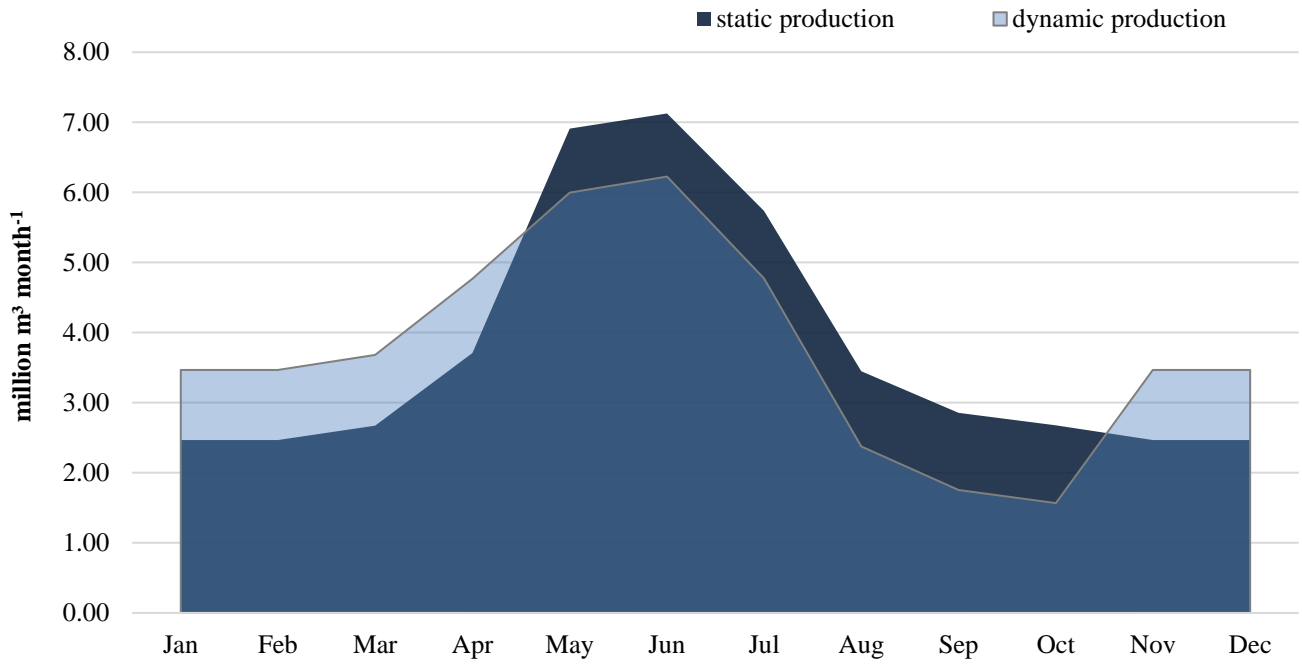
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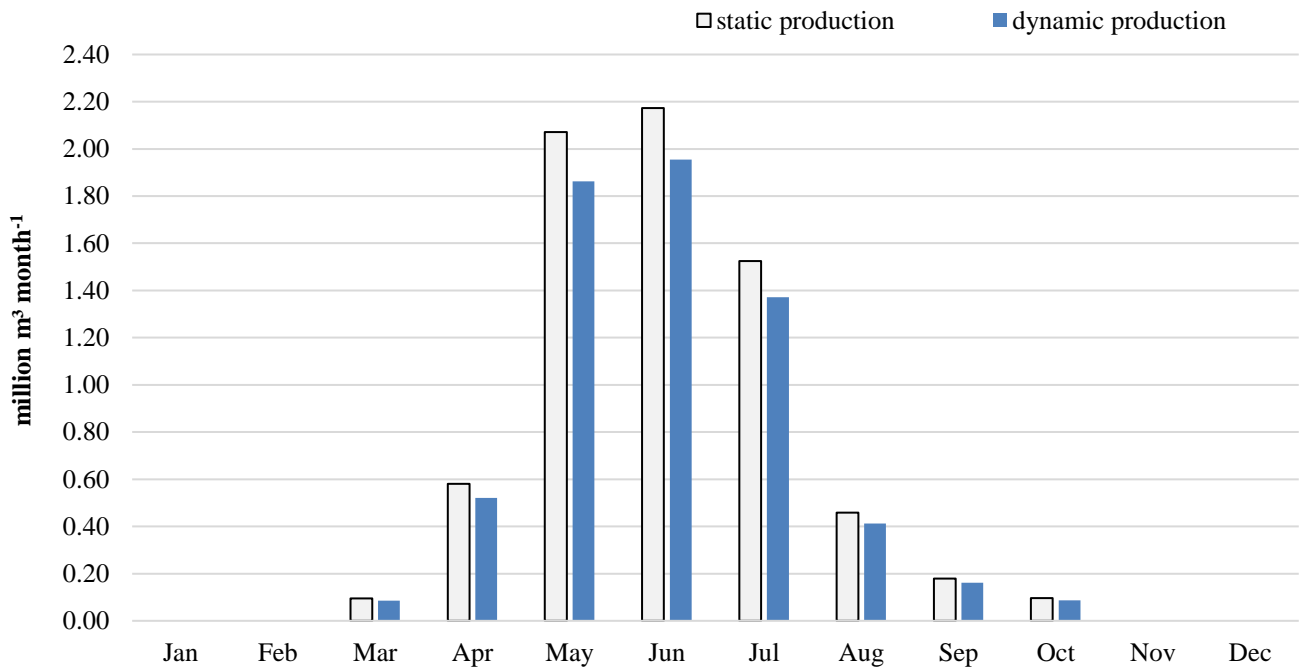
492
493 **Figure 5 Monthly ground water use by static and dynamic production of phosphate slurries transported by pipeline**



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

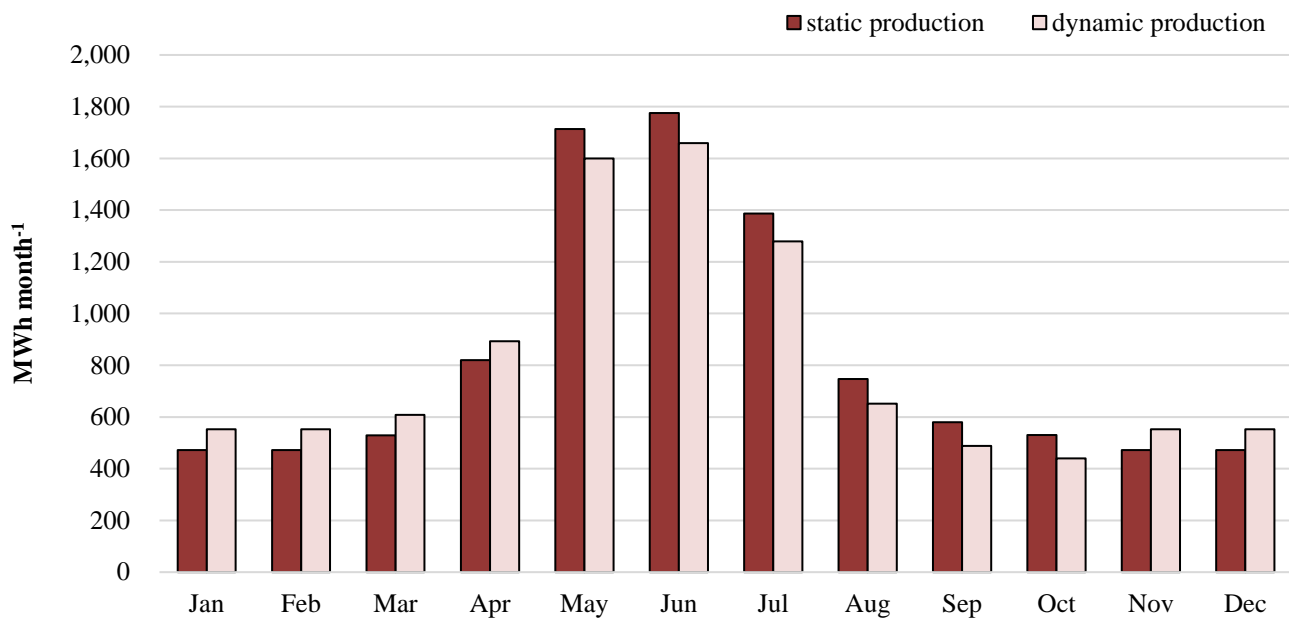


499
500 **Figure 6** Monthly water supply from Ait Messaoud Dam



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504 **Figure 7** Monthly ground water use by static and dynamic production of phosphate slurries transported by pipeline

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Figure 8 Monthly electricity consumption for supplying water by static and dynamic production of phosphate slurries transported by pipeline

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4 Conclusions

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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. Therefore, Ss~~ Sustainable resource management strives for a symbiosis between the phosphate industry and other sectors, and endeavours ~~ring~~ to create synergy through multiple strategies. ~~The WEF-P Tool integrates water-energy-food management and supply chain management for phosphate production. This tool considering s not only~~ the trade-offs between water, energy, and food, ~~as well as but also~~ a systematic analysis based on the total supply chain management of phosphate production. ~~In other words, the WEF-P Tool offers a decision support system to provide quantifiable trade-off analyses for management decisions such as increasing production, transportation systems, and water allocation. The developed WEF-P Tool enables users to:~~

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- ~~understand and identify the associated footprints of the primary functional production processes and existing flows in production lines;~~
- ~~identify the main sources of data to be gathered and fed into the model on a specific temporal basis;~~
- ~~identify the techniques employed to conserve or produce water and energy and minimize the impacts of phosphate production;~~
- ~~form a translational platform between sectors and stakeholders to evaluate proposed scenarios and their associated resource requirements~~

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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

536 pipeline or train and the impacts on regional water and energy use. For example, transport by pipeline instead of train can
537 contribute ~~an-to~~ energy savings due to ~~the~~ elimination of the phosphate drying process (a main consumer of fuels). At the same
538 time, the slurry adaptation processes are main consumers of water, ~~howeverthough~~, because the pipeline also transfers fresh
539 water to Jorf Lasfar where the fertilizers are produced, the water embedded in slurry is a main water resource for Jorf Lasfar.
540 Previously, ~~to-receiving this source~~, the main water resource in Jorf Lasfar was desalinated water, which ~~uses-consumessome~~
541 energy in desalination. Transport by pipeline contributes to a savings of desalinated water and energy for desalinating. The
542 dynamic management scenario is assessed for its impacts on regional water and energy savings: dynamic management of
543 phosphate production indicates different production quantities during irrigated and non-irrigated seasons. Less phosphate
544 production during irrigation season can contribute more surface water for agricultural use and is accompanied by a savings of
545 ground water and the energy required to pump ground water.

546 ~~Nevertheless, there are limitations in the WEF-P Tool. However,~~ Further consideration of the economics of the phosphate
547 operation is needed: static production may bring stability to operations (meeting local and export demand), but there are
548 benefits from dynamic production that can be attributed to reduced competition with other water consuming sectors. Additional
549 variables, ~~such as relating to~~ facility operation, ~~laborlabour~~, economic cost/benefit of static and dynamic production, etc.,
550 should be quantified and included for additional trade-off assessments. ~~Supply chain management in the tool is based only on~~
551 ~~the 2015 dataset, thus it was difficult to validate the tool.~~ Quantification of water and energy for phosphate production is
552 strongly dependent on the relationship between production and resource consumption: this can change in future scenarios.
553 Proper water availability for the right place and time in a changing climate requires analysis of complex scientific, technical,
554 socio-economical, regulatory, and political issues.

555 Beyond the limitations, the deliverables from this study include a conceptual and analytical model of the phosphate supply
556 chain in Morocco, the WEF-P Tool. The Tool can assess the various scenarios to offer an effective means of ensuring the
557 sustainable management of limited resources to both agricultural area and phosphate industry. It quantifies the products
558 (phosphate) and resource footprints (water, energy) across the supply chain; identifies the interlinkages between water and
559 energy in phosphate production and transport, and establishes reference values for comparison of outcomes and performance.
560 The WEF-P Tool enables the user to evaluate trade-offs between water resource allocations and the impact of the Moroccan
561 phosphate industry with agricultural water use.

562 **Author contribution**

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

566 **Competing Interests**

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

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