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Critical Review

Integrated Technological and Management Solutions for Wastewater Treatment and Efficient Agricultural Reuse in Egypt, Morocco, and Tunisia

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ABSTRACT

Mediterranean-African countries (MACs) face a major water crisis. The annual renewable water resources are close to the 500 m^3/capita threshold of absolute water scarcity, and water withdrawals exceed total renewable water resources by 30%. Such a low water availability curbs economic development in agriculture, which accounts for 86% of freshwater consumption. The analysis of the current situation of wastewater treatment, irrigation, and water management in MACs and of the research projects targeted to these countries indicates the need for 1) an enhanced capacity to analyze water stress, 2) the development of water management strategies capable of including wastewater reuse, and 3) development of locally adapted water treatment and irrigation technologies. This analysis shaped the MADFORWATER project (www.madforwater.eu), whose goal is to develop a set of integrated technological and management solutions to enhance wastewater treatment, wastewater reuse for irrigation, and water efficiency in agriculture in Egypt, Morocco, and Tunisia. MADFORWATER develops and adapts technologies for the production of irrigation-quality water from drainage canals and municipal, agro-industrial, and industrial wastewaters and technologies for water efficiency and reuse in agriculture, initially validated at laboratory scale, to 3 hydrological basins in the selected MACs. Selected technologies will be further adapted and validated in 4 demonstration plants of integrated wastewater treatment and reuse. Integrated strategies for wastewater treatment and reuse targeted to the selected basins are developed, and guidelines for the development of integrated water management strategies in other basins of the 3 target MACs will be produced. The social and technical suitability of the developed technologies and nontechnological tools in relation to the local context is evaluated with the participation of MAC stakeholders and partners. Guidelines on economic instruments and policies for the effective implementation of the proposed water management solutions in the target MACs will be developed. *Integr Environ Assess Manag* 2018;14:447–462. © 2018 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION

Two and a half billion people still lack access to water sanitation facilities; 3 billion people are expected to suffer from water scarcity by 2050, and by 2030 a 40% gap is projected to develop between sustainable water supplies and water withdrawals (WWAP 2015; Qadir et al. 2007). An estimated 20% of the world's aquifers are over-exploited (Gleeson et al. 2012). The limit of sustainability in water abstraction has been exceeded for about one-third of the human population (WWAP 2012). Eutrophication is expected to increase almost everywhere until 2030 (UNDESA 2012). Climate change will exacerbate the water crisis, as a result of variations in the distribution and availability of water resources (WWAP 2015). Agriculture is highly sensitive to water availability and quality, as it accounts for 70% of the world's freshwater withdrawals (Pfister et al. 2011; UNESCO–UNWWAP 2003). Agriculture faces the challenge of producing 100% more food by 2050 (OECD 2010; Pfister et al. 2011), but at the same time the bio-economy will require an increased production of nonfood agroproducts (Water JPI 2014).

The consequences of water scarcity and poor quality are particularly relevant in the Middle East and North Africa (MENA) region. According to the Global Risk 2015 Report of the World Economic Forum (2015), the water crisis represents by far the greatest risk in the MENA region, where the expected population growth combined with economic growth is projected to result in a 47% increase in water demand by 2035 (McKinsey & Company 2012). MENA is the driest region of the world, with water withdrawals exceeding renewable water resources by 30% (Antonelli and Tamea 2015; Qadir et al. 2010). The region is significantly affected by desertification, groundwater overexploitation, seawater intrusion into aquifers, and water quality deterioration (Varis and Abu-Zeid 2009). In 2010, the annual renewable water resources in MENA countries (525 m^3/capita, as an average) were about half the 1000 m^3/capita threshold for water scarcity and just above the 500 m^3/capita threshold for absolute water scarcity (Qadir et al. 2010). Water scarcity curbs socioeconomic development, particularly in agriculture, which utilizes 86% of water withdrawals in the MENA region (Qadir et al. 2010). The extent of wastewater (WW) treatment is still low in this region (43%, as an average). In addition, treated WW is typically characterized by insufficient removal of the main pollutants, due to lack of tertiary treatments, poor maintenance and monitoring, frequent power outages, low qualification of personnel, and undersizing of treatment plants (Qadir et al. 2010; Nikiema et al. 2013; Wang et al. 2014).

In the MENA region, climate change is expected to decrease precipitation and soil moisture and increase evaporation from surface waters and crop water requirement (IPCC 2014). These changes, combined with population growth, are expected to decrease annual renewable water resources to 414 m^3/capita by 2025 (Bird et al. 2016; Qadir et al. 2010).

Among several possible strategies to fight the water crisis, the reuse of treated WW represents a promising and widely studied one (Aziz and Farissi 2014; Winpenny et al. 2010; Hanjra et al. 2012): it provides a reliable supply of water during regional shortages, it enhances local economic growth, it reduces water withdrawal from aquifers and rivers, it decreases fertilizer consumption in agriculture, and it reduces eutrophication (National Research Council of the National Academies 2012). Unfortunately, few MENA countries implemented substantial WW reuse programs (Dare et al. 2013; Jeuland 2015).

Several international research projects aim to decrease water stress in the Mediterranean-African region. This paper focuses on the MADFORWATER project (www.madforwater.eu; MADFORWATER 2018), which aims to developing an integrated set of technological and management instruments for the enhancement of wastewater treatment, treated wastewater reuse for irrigation, and water efficiency in agriculture. MADFORWATER focuses its activities on selected hydrological basins located in 3 Mediterranean-African countries (MACs): Egypt, Morocco, and Tunisia. These countries are representative of the Mediterranean-African region in relation to their population (74% of the region's inhabitants), GDP (64%), produced WW (88%), rate of WW treatment (50%), and hydrological characteristics (Sato et al. 2013; World Bank 2017). The selected countries are characterized by a relevant water scarcity: the annual renewable water resources are equal to 60% of the of 1000 m^3/y threshold for water-stressed areas, and just 7% of produced WW is currently reused (Sato et al. 2013; FAO 2017).

The first part of this work consists in an analysis of 1) the current situation of WW treatment, treated WW reuse, irrigation, and water management in Egypt, Morocco, and Tunisia; and 2) the main international water-related research projects in which these countries are involved. The second part of the work illustrates how MADFORWATER is trying to the tackle the current water-related challenges in these countries, taking into account the research gaps that emerge from the analysis of the examined research projects.

CURRENT SITUATION OF WASTEWATER TREATMENT, WASTEWATER REUSE, IRRIGATION, AND WATER MANAGEMENT IN EGYPT, MOROCCO, AND TUNISIA

In terms of WW treatment, the ratio of treated WW to produced WW is equal to 57% in Egypt and 24% in

Morocco, whereas a relatively advanced situation is observed in Tunisia, with a 79% ratio (FAO 2017). In all 3 countries, a large fraction of the treated WW (75%–90%) undergoes secondary treatment for biological oxygen demand (BOD) removal, whereas the remaining fraction is subjected only to primary treatment. Tertiary treatments are rarely implemented. The main technologies utilized for secondary treatment are activated sludge in Tunisia and Egypt and lagoons in Morocco. The main operational problems associated with WW treatment in these countries include the following: 1) insufficient aeration in the secondary treatment, due to power outages or excessive cost of energy; 2) strong delays and high costs for the purchase of components for repairing equipment; 3) failures of the secondary process due to the presence of toxic compounds carried by untreated industrial WWs; 4) WW treatment plants operating above their capacity, due to rapid population growth; and 5) insufficient monitoring of treated WW quality due to legal or technical constraints (A. Abdel-Motaleb, National Water Research Center, personal communication; A Jaouani, Université de Tunis El Manar, personal communication; Nikiema et al. 2013).

The type and diffusion of irrigation technologies are quite diverse in the 3 examined countries: in Egypt 98% of the cultivated area is equipped with irrigation, whereas in Morocco and Tunisia this fraction is equal to just 16% and 10%, respectively (FAO 2017). Surface irrigation systems, such as furrow, border strip, and basin irrigation, represent the most common irrigation technology, with an average efficiency equal to 60%. Conversely, localized irrigation systems are not commonly used in these countries: drip irrigation (90% field efficiency) is used in 20% of the irrigated area (average of the 3 countries), and sprinkler irrigation (75% efficiency) is used in just 14% of the irrigated surface (Brower et al. 1989; FAO 2017). Both Morocco and Tunisia have significantly subsidized the supply of drip irrigation systems. However, because of poor maintenance and low equipment quality, most of these systems were clogged or inefficient after 1 to 2 y, and the farmers switched back to surface irrigation (L. Primard, Rolland Arousers Sprinklers, personal communication).

The treated WW reused for irrigation is equal to 0.3% of WW produced in Morocco, 4% in Egypt, and 24% in Tunisia (FAO 2017). The fraction of the total irrigation area equipped for irrigation with treated WW varies between 1% and 2%. The constraints leading to these poor levels of WW reuse are lack of social acceptance due to inadequate information on the benefits of this practice and to the poor monitoring of treated WW, incomplete economic analysis of WW reuse options, mismatch between water pricing and water scarcity, and lack of economic incentives for treated WW reuse (Choukr-Allah 2011; Jeuland 2015; Qadir et al. 2010).

Each of the 3 target MACs made significant progress in the field of sustainable water management in the last 2 decades. However, further advancement is needed to develop water management strategies capable of 1) guiding local governments, basin authorities, WWTP managers, and farmers in the selection of the most effective water treatment and irrigation technologies, and 2) defining economic instruments aimed at enhancing the adoption of effective water treatment and irrigation technologies and the reuse of treated WW.

In all 3 countries, the national legislation imposes limits for the agricultural reuse of treated WW, focusing on BOD, chemical O demand (COD), total suspended solids, total or fecal coliforms, and intestinal nematodes. The Moroccan and Tunisian legislations set limits for several additional parameters: electrical conductivity, total dissolved solids, pH, and the main heavy metals.

RECENT AND ONGOING RESEARCH PROJECTS ON WATER STRESS ANALYSIS, WATER TREATMENT AND REUSE, AND WATER MANAGEMENT IN EGYPT, MOROCCO, AND TUNISIA

One of the elements that shaped the general goal of MADFORWATER has been an analysis of the recently closed and ongoing research projects that focused on water stress analysis, water treatment and reuse, and water management in Egypt, Morocco, and Tunisia to identify the main research gaps. The search for these projects was mainly based on the Cordis database (the European Commission database of all the EC-funded research projects: http://cordis.europa.eu/) and it was conducted with Matchpoint, an innovative search engine that uses the latest semantic techniques for in-depth searches for research and innovation processes. Geographically, the search included not only the projects that include Egypt, Morocco, or Tunisia in their abstract or partner list but also the projects focusing on the entire African continent or on African regions characterized by elements of similarity with Egypt, Morocco, or Tunisia.

The identified projects, presented in Table 1, were divided into the following categories: analysis of water quantity and quality, sustainable water management including climate change effects, technologies for drinking water production, technologies for WW treatment and reuse, and sustainable agriculture. The analysis of these projects indicated that:

- Only 3 projects focus on the analysis of water quantity and quality, and in none of these is the analysis specifically oriented toward the definition and assessment of water management strategies.
- The concept of water vulnerability, which extends the analysis of water stress to the evaluation of water quality and to the institutional, political, and social aspects of the water crisis, has generally been neglected.
- Even though a relatively large number of projects (11) focus on sustainable water management, most of these

Table 1. Overview of the ongoing and recently completed research projects on water stress analysis, water treatment, and water management in Egypt, Morocco, and Tunisia[ab]

Macroarea	Acronym	Title	Short description	Project type	Start y	End y
Analysis of water quantity and quality	Ground Truth 2.0	Ground Truth 2.0—Environmental Knowledge Discovery of Human Sensed Data	Demonstration and validation of 6 citizen observatories in real operational conditions in the EU and in Africa, with a specific focus on flora, fauna, water availability, and water quality.	Innovation action	2016	2019
	AEGOS	African-European Georesources Observation System	Preparatory work aimed at designing the African-European Georesource Observation System (AEGOS), capable of hosting and providing access to Africa's geological resources, including groundwater, energy, raw materials and mineral resources.	Support action	2008	2011
	GLOWASIS	A collaborative project aimed at prevalidation of a GMES Global Water Scarcity Information Service	Prevalidation of a Global Service for Water Scarcity Information in European and African pilots on the scale of river catchments. Combination of in situ and satellite-derived water cycle information and statistical water demand data in order to create an information portal on water scarcity.	Collaborative project	2011	2013
Sustainable water management, including climate change effects	SWIM	Sustainable Water Integrated Management (SWIM)	Regional Technical Assistance Programme launched by the European Commission to contribute to the extensive dissemination and effective implementation of sustainable water management policies and practices in the southern Mediterranean region.	Support mechanism and demonstration project	2010	2014
	AfriAlliance	Africa-EU Innovation Alliance for Water and Climate	Enhancement of the cooperation between African and European stakeholders in the areas of water innovation, research, policy, and capacity development to prepare Africa for future Climate Change challenges.	Coordination and support action	2016	2021
Sustainable water management, including climate change effects	DAFNE	DAFNE: Use of a decision-analytic framework to explore the water-energy-food nexus in complex and transboundary water resources systems of fast growing developing countries	Development of an integrated and adaptive water resources planning and management approach that explicitly addresses the water-energy-food nexus from a novel participatory and multidisciplinary perspective. Application of the proposed approach in cross-boundary case studies in Africa.	Research and innovation action	2016	2020
	TWIN2GO	Coordinating twinning partnerships toward more adaptive governance in river basins	Review, assessment, and consolidation of several EU-funded projects on specific	Coordination action	2009	2011

			integrated water resources management in Latin America, Africa, and Asia in order to make them transferable and applicable to other basins and to disseminate the project results effectively to relevant authorities, stakeholders, and end users.			
	WASSERMED	Water Availability and Security in Southern Europe and the Mediterranean	Analysis of climate-induced changes in hydrological budgets in southern Europe, North Africa, and the Middle East.	Cooperation action dedicated to international cooperation partner countries (SICA)	2010	2013
Sustainable water management, including climate change effects	TRUST	Transitions to the Urban Water Services of Tomorrow	Production of knowledge and guidance to support transition to urban water services of tomorrow, enabling communities to achieve sustainable, low-carbon water futures without compromising service quality. Collaboration with problem owners in 10 participating pilot city regions under changing and challenging conditions in Europe and Africa.	Large-scale integrating project	2011	2015
	IMPACT2C	Quantifying projected impacts under 2 °C warming	Enhancement of knowledge and quantification of climate change impacts, climate change modeling, assessment of vulnerabilities, risks and economic costs, as well as potential responses. Evaluation of climate change effects on water, energy, infrastructure, coasts, tourism, forestry, agriculture, ecosystems services. Specific focus on some of the world's most vulnerable regions: Bangladesh, Africa (Nile and Niger basins), and the Maldives.	Large-scale integrating project	2011	2015
	IMPALA	Improving Model Processes for African cLimAte	Delivery of a step change in global model climate prediction for Africa on the 5- to 40-y timescale by delivering reductions in model systematic errors, resulting in reduced uncertainty in predictions of African climate and enabling improved assessment of the robustness of multimodel projections for the continent.	Research project funded by the UK government as part of the Future Climate for Africa (FCFA) program	2015	2019
	SIRRIMED	Sustainable Use of Irrigation Water in the Mediterranean Region	Addressment of issues related to sustainable use of water in Mediterranean irrigated agricultural systems, with the overall aim of optimizing irrigation water use. Approach based on an integrated water irrigation management and on the evaluation of the improvement of water use efficiency at farm, irrigation district, and watershed scales.	Cooperation action dedicated to international cooperation partner countries (SICA)	2010	2014
	DECOE	Developing and Expanding Certification to Cover Business Management, and	The purpose is to help the Arab Countries Water Utilities Association (ACWUA) meet	USAID project	2016	2018

(*Continued*)

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Table 1. (*Continued*)

Macroarea	Acronym	Title	Short description	Project type	Start y	End y
		Operational Excellence in Water Management	the objectives of its business plan (2015–2019) in the following areas: expand ACWUA's reach regionally and internationally, support the Arab water utilities in providing their customers with the best services possible, attain financial sustainability.			
	ENTIRE	Empowering regional Civil Society Networks to take an active role in Integrated Water Resources Management (IWRM) in the Southern Mediterranean Region	Project aimed at empowering regional civil society networks to take an active role in integrated water resources management in the southern Mediterranean region working in Algeria, Egypt, Jordan, Lebanon, Morocco, West Bank, the Gaza Strip, Syria and Tunisia.	EU Nonstate Actors and Local Authorities Program	2014	2017
Technologies for drinking water production	WATERSPOUTT	Water-Sustainable Point-Of-Use Treatment Technologies	Design, development, pilot-test and field-test sustainable point-of-use solar disinfection technologies to provide affordable access to safe water to remote and vulnerable communities in Africa	Research and Innovation action	2016	2020
	REvivED water	Low-Energy Solution for Drinking Water Production by a Revival of Electrodialysis Systems	Development of an electrodialysis process to produce safe, affordable, and cost-competitive drinking water, using less than half the energy required by state-of-the-art reverse osmosis plants. Testing of the technology in several developing countries in Africa, Asia, and Latin America.	Innovation action	2016	2020
	NATIOMEM	Nano-structured TiON Photocatalytic Membranes for Water Treatment	Development of a novel technology for producing drinking water from surface and wastewater, based on membranes functionalized with a photocatalytic material. Field test of the technology in the Middle East and North Africa.	Small- or medium-scale focused research project	2010	2013
Technologies for wastewater treatment and reuse	SafeWaterAfrica	Self-Sustaining Cleaning Technology for Safe Water Supply and Management in Rural African Areas	Development of an autonomous and decentralized water treatment system for rural and peri-urban areas, highly efficient in the degradation of harmful pollutants and in killing microbiological contaminants, to be applied in rural African areas	Research and innovation action	2016	2019
	WATERBIOTECH	Biotechnology for Africa's Sustainable Water Supply	Development of low-cost biological wastewater treatment systems suitable for African conditions: lagooning, land treatment, phytodepuration, constructed wetlands systems, biofiltration, membrane bioreactors.	Coordination (or networking) actions	2011	2014

	CB-WR-MED	Capacity Building for Direct Water Reuse in the Mediterranean Area	Reinforcement of Tunisian research and cooperation capacities in the field of wastewater treatment and reuse.	Support actions	2010	2013
	WATEREUS-MED	Water Reuse in Mediterranean Countries	Support and strengthening of the different existing collaboration actions between Europe and Mediterranean Partner Countries (MCP) for research and research training in the field of water reuse through staff exchange opportunities.	International research staff exchange scheme (IRSES)	2012	2016
Technologies for drinking water production and wastewater treatment	WETWIN	Enhancing the role of wetlands in integrated water resources management for twinned river basins in EU, Africa, and South America in support of EU Water Initiatives	Enhancement of the role of wetlands in basin-scale integrated water resources management, with the aim of improving the community service functions, conserving good ecological status, and utilizing the drinking water supply and sanitation potentials of wetlands.	Cooperation action dedicated to international cooperation partner countries (SICA)	2008	2011
	CLARA	Capacity-Linked water supply and sanitation improvement for Africa's peri-urban and Rural Areas	Assessment and adaptation to African conditions of existing low-cost technologies for decentralized water supply and sanitation, to provide demand-oriented water quality. Development of a simplified planning tool for integrated water supply and sanitation systems for small communities and peri-urban areas.	Cooperation action dedicated to international cooperation partner countries (SICA)	2011	2014
Sustainable agriculture	BIODESERT	Biotechnology from desert microbial extremophiles for supporting agriculture research potential in Tunisia and southern Europe	Consolidation of a microbial ecology research platform in Tunisia, to develop strategies of microbial resource management for agriculture in arid environments.	Support action	2010	2012
	WAHARA	Water Harvesting for Rainfed Africa: investing in dryland agriculture for growth and resilience	Development of innovative, locally adapted water-harvesting solutions for rainfed Africa. Focus on 4 geographically dispersed study sites in Tunisia, Burkina Faso, Ethiopia, and Zambia, covering diverse socioeconomic conditions and a range from arid to subhumid climates.	Cooperation action dedicated to international cooperation partner countries (SICA)	2011	2016
	SWUP-MED	Sustainable water use securing food production in dry areas of the Mediterranean region	Improvement of food crop production in dry areas of the Mediterranean region, by modernizing farming systems, strengthening a diversified crop rotation, and using marginal-quality water for supplemental irrigation.	Cooperation action dedicated to international cooperation partner countries (SICA)	2008	2013

[a]The search was extended to projects that started in 2008 at the earliest.
[b]The search was extended not only to the projects that include Egypt, Morocco, or Tunisia (or hydrological basins located in these countries) in their abstract or partner list but also to the projects aimed at developing water treatment technologies or water management tools with a focus either on the entire African continent or on African regions characterized by elements of similarity with Egypt, Morocco, or Tunisia.

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projects do not include a link between locally adapted water treatment/irrigation technologies and water management plans.
- Only 6 projects focus on WW treatment, and 2 of these are staff exchange schemes or support actions not aimed at the development or adaptation of specific technologies; the studied technologies are not integrated into water management strategies, and the reuse of treated WW is not significantly addressed.
- Few projects are aimed at the development or adaptation of irrigation technologies.

This analysis led to the identification of the research gaps in the field of water treatment and management in Egypt, Morocco, and Tunisia briefly listed in Table 2, which illustrated

1. Enhancement of the capacity to analyze water stress, including both water quantity and quality, in order to identify the basins or regions where resources should be addressed with priority; the analysis of water stress should be aimed at the definition and assessment of water management plans for the identified water-stressed basins.
2. Development of locally adapted WW treatment and irrigation technologies.
3. Enhancement of the integration between WW treatment and irrigation technologies and water management strategies; indeed, the development of water-related technologies in developing countries needs to be integrated by the definition of water management strategies and economic instruments aimed at favoring the actual use of such technologies (e.g., UNECA et al. 2003).

Table 2. Research gaps in the field of wastewater treatment and water management in Egypt, Morocco, and Tunisia and corresponding MADFORWATER expected results

Research gaps	Expected results
• Enhancement of the capacity to analyze water stress, in order to identify the basins or regions where resources should be prioritized	• Report on the needs in the target Mediterranean-African countries for novel holistic water management strategies to be proposed for future international cooperation agreements • Freely available country-wide geographic information system maps describing water stress, water vulnerability, and water reuse potential in the target countries and at a 20-y projection on a business basis • Technical description of the effects of water vulnerabilities on food security and socioeconomic development in Egypt, Tunisia, and Morocco • Basin-scale water vulnerability assessment framework for the evaluation of the effectiveness of integrated water management strategies
• Development of locally adapted wastewater treatment and irrigation technologies • Enhanced treated wastewater reuse	• 14 wastewater treatment technologies, tailored to the local conditions of 3 selected basins in the target Mediterranean-African countries and validated at laboratory scale • 6 technologies for increasing water efficiency and reuse in agriculture, tailored to 3 selected basins and validated at laboratory scale • 4 field pilot plants of integrated wastewater treatment and water reuse in agriculture, operated in the 3 selected basins • Stakeholder consultation workshops, capacity-building workshops, train-the-trainer courses, on-field trainings at the project pilots, exchange of scientists, field visits, technical and dissemination videos, technical booklets on the project's technologies, 1 final project conference
• Enhanced integration between wastewater treatment, irrigation technologies and water management strategies • Enhanced treated wastewater reuse	• Two decision support tools for the integration of project technologies for wastewater treatment and management of agricultural water and land • Integrated strategies for wastewater treatment and agricultural water management, with the associated economic instruments, targeted to the 3 selected basins • Policy recommendations for the effective implementation of the proposed water management solutions in the 3 target Mediterranean-African countries • Guidelines and training packages for the adaptation of water vulnerability tools, technologies, and water management strategies to other basins in the target Mediterranean-African countries and in other North African countries of the MADFORWATER

4. Enhancement of treated WW reuse, through (i) a closer integration between WW treatment technologies and irrigation technologies suitable for the use of treated WW, and (ii) the inclusion of treated WW reuse in water management plans.

THE MADFORWATER GOALS AND CONCEPT

The MADFORWATER general goal, defined on the basis of the current situation of water treatment and management in Egypt, Morocco, and Tunisia and of the research gaps illustrated in section *Recent and Ongoing Research Projects on Water Stress Analysis, Water Treatment and Reuse, and Water Management in Egypt, Morocco, and Tunisia*, is to develop integrated technological and management solutions to boost wastewater treatment, treated wastewater reuse for irrigation, and water efficiency in agriculture in selected hydrological basins in Egypt, Morocco, and Tunisia, described in Table 3. This overall goal was translated into the following specific objectives:

1) Improving the identification of vulnerabilities in terms of water quantity and quality in Egypt, Morocco, and Tunisia and developing a locally adapted water vulnerability assessment tool to be used for the evaluation of the potential effectiveness of basin-scale water management strategies.
2) Developing and/or adapting to the local context technologies for WW treatment, treated WW reuse for irrigation, and efficient water use in agriculture.
3) Developing basin-scale water and land management strategies, closely related to the project's technologies.
4) Increasing the level of capacity building in the target countries in relation to the proposed solutions and the social acceptance of treated WW reuse in agriculture.

As shown in Figure 1, the achievement of these MADFORWATER goals is based on 2 pillars: WW treatment, selected as a valuable water source for agriculture, and irrigation, which represents the primary source of water demand in MACs. While the first pillar aims to increase the amount of available irrigation-quality water, the second aims to enhance WW reuse for irrigation and the efficiency of water consumption in agriculture while also ensuring an adequate soil health. These 2 pillars are transversally characterized by 2 key concepts: adaptation and integration. A rigorous adaptation approach is applied to the development of technologies and management strategies for water and land in order to make them technically and culturally suitable for the environmental and socioeconomic context of the target MACs. Such an approach includes the strong involvement of relevant MAC stakeholders who regularly provide feedback

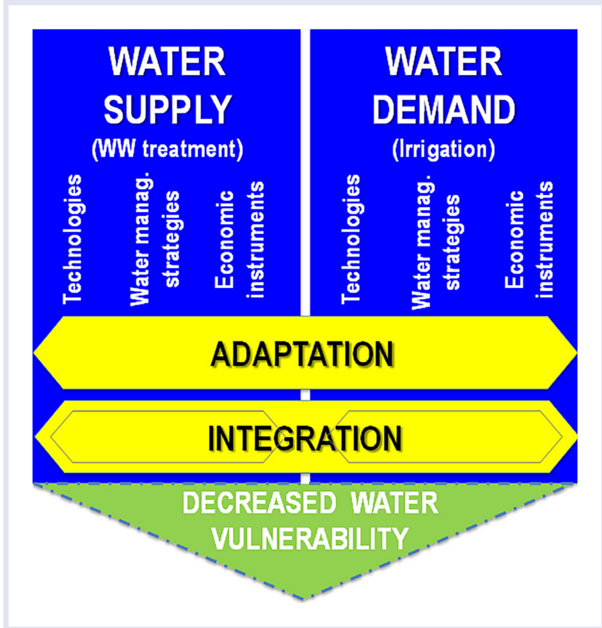

Figure 1. The MADFORWATER concept.

Table 3. Water-stressed basins and subbasins specifically targeted by MADFORWATER

Country	Morocco	Tunisia	Egypt[a]
Basin name	Souss-Massa	Cap-Bon and Miliane	Northeastern Nile Delta
Basin surface (km^2)	28 000	8 300	2500
Basin population	2 300 000	3 600 000	900 000
Basin description	Its economy is based on agriculture (95% of freshwater catchments) and tourism. It is characterized by a strong water deficit (250 million m^3/y), which results in a lowering of the water table by 4 m/y and by a diffuse pollution of water bodies.	It is the largest industrial zone of Tunisia and has intense irrigated agricultural activities (citrus, grapes, tomatoes). It is one of the most water-stressed regions in Tunisia, with a 194% overexploitation of the water resources.	Agriculture (80% of freshwater catchments) is irrigated by a dense canal network heavily polluted with municipal and industrial wastewaters. Surface irrigation is the predominant system and determines a further pollution of the drainage canals with agrochemicals. The Northeastern Delta is characterized by several water vulnerabilities: lack of sufficient water delivery, poor water quality, strong sea water intrusion, and consequent soil salinization.

[a]For Egypt, given the huge extension of the Nile basin, the activities will focus on the Northeastern Delta subbasin.

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on the adaptation measures undertaken and on the social acceptance of the proposed solutions. In addition, integration is applied in the first place between the 2 pillars illustrated in Figure 1 by means of a series of demonstration plants where different WW types are treated with MADFORWATER technologies and reused for the irrigation of crops typical of the 3 target countries, using irrigation technologies adapted to the use of treated WW. The integration approach is applied also within each MADFORWATER pillar, with an integrated development of technologies, decision support tools, and management strategies for water and land.

THE MADFORWATER CONSORTIUM

The MADFORWATER consortium consists of 18 partners geographically distributed mainly around the Mediterranean Sea, in 7 European countries, 3 MACs, and China. It comprises 9 universities, 4 research centers, 1 international nonprofit organization (FAO), 1 consultant company with expertise in marketing and business plan development, and 3 WW treatment and irrigation companies that will design and construct the MADFORWATER demonstration plants. The expertise of the MADFORWATER partners are listed in Table 4.

THE MADFORWATER STRATEGY TO ENHANCE WASTEWATER TREATMENT, WASTEWATER REUSE AND INTEGRATED WATER MANAGEMENT

MADFORWATER is articulated into 3 phases, or blocks of activities, graphically represented in Figure 2: the analytical phase, dedicated to the analysis of water vulnerabilities; the technological phase, dedicated to the development and adaptation of technologies for WW treatment and agricultural reuse; and the implementation phase, which includes activities to maximize the project's long-term impact, such as water and land management strategies, policy recommendations, capacity building, and industrial exploitation. These 3 phases were designed in response to the identified research gaps. MADFORWATER, which started in June 2016, is currently in its 18th month of activity, out of an overall duration of 48 months. Figure 2 also reports the expected duration and the current level of development of each phase.

Table 4. Partners and expertise of the MADFORWATER project

Partner	Expertise
Alma Mater Studiorum, University of Bologna (Italy)	Project coordination; wastewater treatment
University of Manouba (Tunisia)	Wastewater treatment; demonstrator pilot operation
Technical University of Crete (Greece)	Wastewater treatment
University of Tunis El Manar (Tunisia)	Wastewater treatment; demonstrator pilot operation
Wageningen Environmental Research (Netherlands)	Water vulnerability analysis; stakeholder involvement
University of Applied Sciences and Arts of Northwestern Switzerland (Switzerland)	Wastewater treatment; water vulnerability analysis; integrated water management, including policies and economic instruments, life cycle analysis of technologies
Agronomic and Veterinary Institute Hassan II (Morocco)	Wastewater treatment; irrigation; demonstrator pilot operation
University of Milan (Italy)	Wastewater treatment; irrigation
FAO Regional Office for Near East and North Africa (International)	Water vulnerability analysis; capacity building
Polytechnic University of Madrid (Spain)	Water vulnerability analysis; integrated water management, including policies and economic instruments
Mediterranean Agronomic Institute of Bari (Italy)	Irrigation; integrated water management, including policies and economic instruments
National Water Research Center, Ministry of Water Resources and Irrigation (Egypt)	Wastewater treatment; demonstrator pilot construction and operation
National Research Institute of Science and Technology for Environment and Agriculture (France)	Irrigation
PNO Innovatieadvies (Netherlands)	Cost–benefit analysis of technologies; business plans development; coordination of exploitation and dissemination activities
SK Euromarket Ltd (Cyprus)	Wastewater treatment; demonstrator pilot construction
Krofta Waters International (Switzerland)	Wastewater treatment; demonstrator pilot construction
Nanjing University (China)	Wastewater treatment
ROLLAND Arroseurs Sprinklers (France)	Irrigation; demonstrator pilot construction

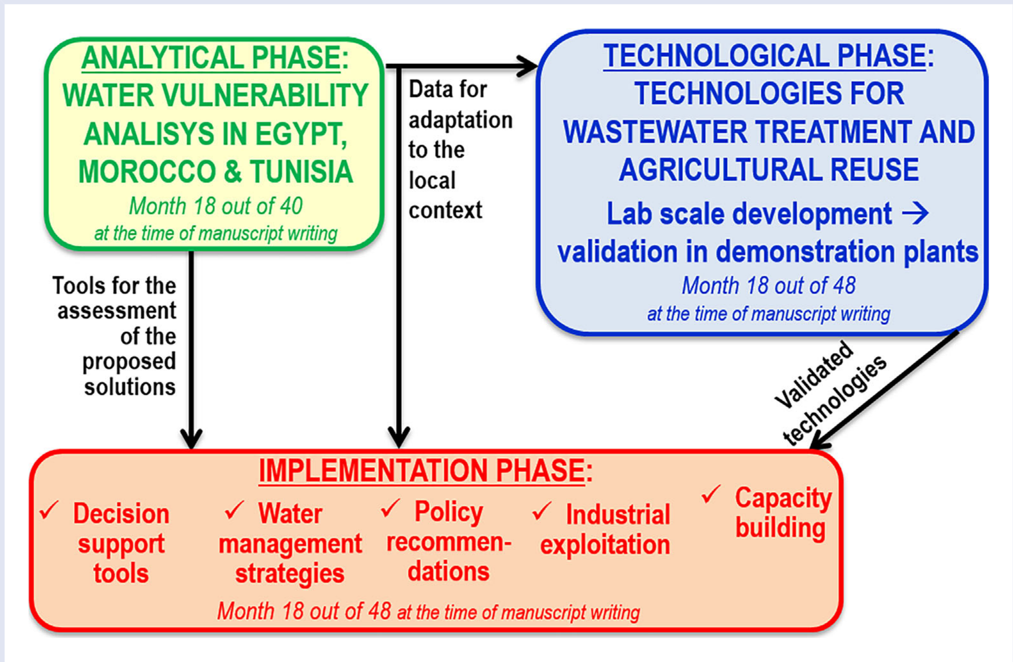

Figure 2. The 3 MADFORWATER phases. The expected duration and current level of development of each phase are indicated.

Analytical phase

This phase first includes a country-scale analysis of water stress and water vulnerability. MADFORWATER aims to define innovative indicators of water stress and vulnerability, adapted to the local context of Egypt, Morocco, and Tunisia and capable of considering the current level and future potential of treated WW reuse, an aspect generally neglected by previous water stress indicators (Gassert et al. 2015). For each selected indicator, a water stress geographic information system map is produced for each target country to help local decision-makers in the identification of those regions where resources should be primarily addressed and in the definition of basin-scale water management plans. A first series of maps refers to the situation at the onset of the project (June 2016). As an example, the map of the water vulnerability index relative to Tunisia is shown in Figure S1 in Supplemental File 1. A second series of maps includes a 20-y projection considering a business-as-usual baseline as well as different socioeconomic and climate change scenarios. Several combinations of shared socioeconomic pathways and representative concentration pathways are adapted to the target MACs. The effects of the identified water stress and vulnerabilities on different dimensions of food security and socioeconomic development are examined. To this purpose, food security indicators developed by FAO for monitoring progress toward the sustainable development goals are used.

The second part of the analytical phase consists in a more detailed investigation of water vulnerability in 3 selected basins or subbasins in the target MACs, described in Table 3. For each basin, the following activities are performed: 1) analysis of the causes and consequences of water vulnerability and obstacles to be overcome, and 2) development of a locally adapted framework for a comprehensive assessment of water vulnerability (Stathatou et al. 2015) to be used to evaluate the effectiveness of the basin-scale integrated water management strategies developed in the framework of the implementation phase.

Technological phase

This phase is dedicated to the development and adaptation of technologies for WW treatment and water efficiency in agriculture to the local context of the 3 MACs. To maximize the impact of MADFORWATER, 4 water categories are taken into consideration:

- Municipal WW (MWW), which represents 82%–92% of the total WW produced; only 50% of MWW produced is currently treated in the target MACs.
- Textile WW (TWW), a relevant type of industrial WW in the 3 MACs (textile production provides 6% of GDP in Egypt, 7% in Morocco and Tunisia).
- Agro-industrial WWs, in particular olive mill WW (OMWW) and fruit and vegetable packaging WW (FVPWW), due to their quantitative and qualitative relevance in all 3 MACs and to the lack of cost-effective, industrial-scale processes for their treatment (Frascari et al. 2016).
- Drainage canal water (DCW) of the Nile Delta (Egypt), a mixture of freshwater from the Nile river and water from irrigation drains, with minor contributions from untreated or partially treated municipal and industrial WWs; DCW is extensively used for irrigation (11×10^9 m^3/y; FAO 2017).

On the basis of the main problems associated with WW treatment in Egypt, Morocco, and Tunisia, listed in the

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section *Current Situation of Wastewater Treatment, Wastewater Reuse, and Irrigation in Egypt, Morocco, and Tunisia*, the following criteria were used to select the MADFORWATER WW treatment technologies: 1) low energy consumption, so the entire power requirement or just the energy needed during power outages could be covered with locally produced photovoltaic energy; 2) technological robustness and simplicity to minimize the need to purchase expensive spare components unavailable in the local market; 3) use of biofilm processes to reduce sludge bulking problems; 4) modularity, so the process could be easily adjusted to the progressive increase of the number of people connected to the sewer system; and 5) inclusion of tertiary treatment technologies aimed at removing pharmaceuticals, dyes, fungicides, and pathogens.

These criteria led to the selection of the WW treatment technologies reported in Figure 3. As shown in this figure, the WW technologies are articulated into several possible treatment trains. In 2 cases, an irrigation-quality treated WW may be achieved with just one technology (aerobic biological treatment in sequencing batch reactors for OMWW, canalized aerobic/anoxic lagoons for DCW), whereas in other cases 2 or even 3 technologies in series are considered necessary for this purpose. The identification of the optimal treatment train for each WW type is currently in progress. The target pollutants of each technology are reported parenthetically. Most of the proposed WW treatment technologies are already marketable, but they are poorly applied in MACs; therefore, innovative features need to be developed to adapt these technologies to the local MAC context and to the production of irrigation-quality water. Conversely, some of the proposed WW technologies —underlined and italicized in Figure 3—are still at an early stage of development: TiO_2-coated solar light disinfection beds; OMWW treatment via microfiltration followed by polyphenol adsorption on selective resins; immobilized enzyme bioreactors for the degradation of pharmaceuticals in MWW and dyes in TWW; UV-oxidation with TiO_2-coated beds followed by immobilized enzyme bioreactors for the degradation of fungicides in FVPWW.

As for the water demand domain, on the basis of the main problems associated with irrigation and agricultural WW reuse in Egypt, Morocco, and Tunisia (see section *Current Situation of Wastewater Treatment, Wastewater Reuse, and Irrigation in Egypt, Morocco, and Tunisia*), the proposed irrigation technologies were selected on the basis of the following criteria: 1) suitability for use with treated WW, determined by a low tendency to biofilm formation, a high

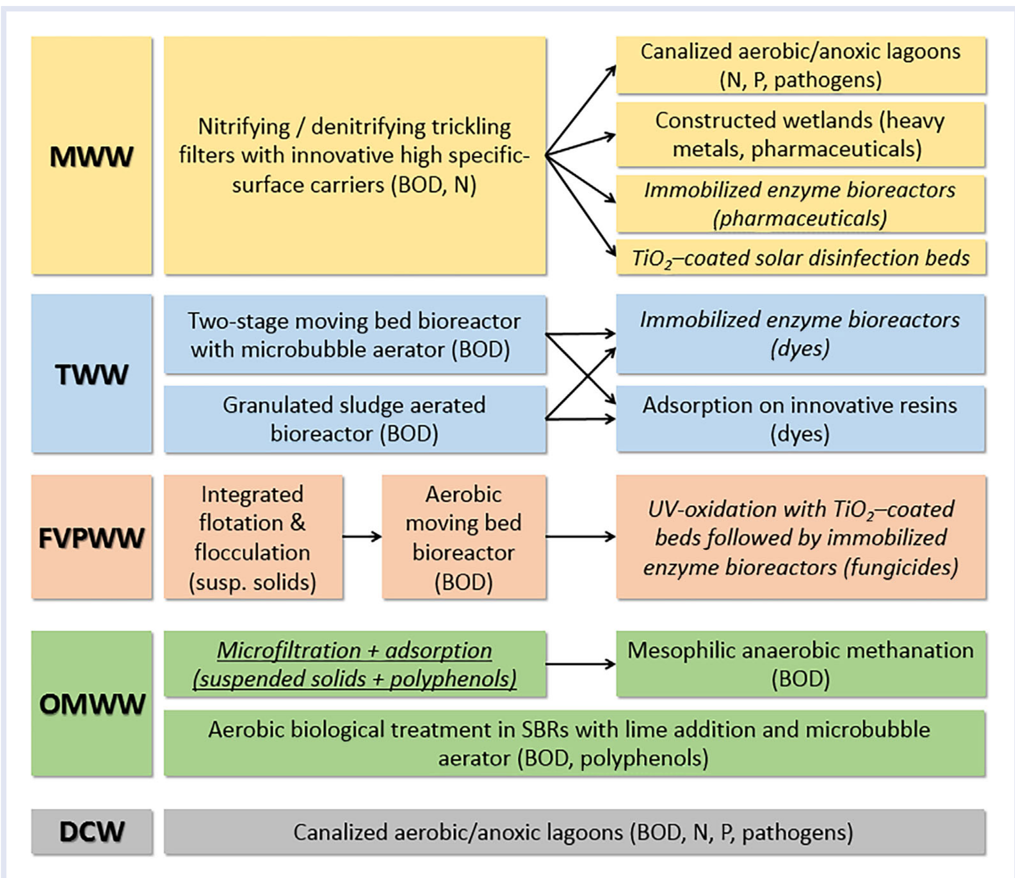

Figure 3. The MADFORWATER WW treatment technologies, articulated by WW type and proposed treatment trains (MWW, municipal WW; DCW, drainage canal water; FVPWW, fruit/vegetable packaging WW; OMWW, olive mill WW; TWW, textile WW). The target pollutants of each technology are reported in parenthesis. The most innovative technologies, still at an early stage of development, are underlined and italicized.

resistance to salinity, and a low formation of aerosols in the case of sprinklers; 2) high efficiency in the delivery of water to crops; and 3) low capital and maintenance cost. Thus, 6 technologies were selected:

1) Low-pressure microsprinkler adapted to dry climates and to treated WW; most of the existing microsprinklers are not suitable for treated WW reuse because of their sensitivity to clogging, wind drift, and aerosolization; conversely, the proposed sprinkler can maintain droplet size in the 0.5- to 2-mm range to avoid wind drift, limit evaporation, and reduce possible soil damage determined by the kinetic energy associated with the generation of large droplets, which may result in surface soil layer degradation and related runoff and erosion (Molle et al. 2016).
2) Low-pressure calibrated nozzle adapted to dry climates and to treated WW, as an alternative to drip irrigation, which is efficient but highly sensitive to clogging in the case of treated WW reuse; sensitivity to fouling and clogging is minimized by a high discharge rate (around 100 L/h), balanced by a pulsed irrigation (every 2–5 min).
3) Re-engineered surface irrigation systems based on calibrated gated pipes, designed to replace traditional and highly inefficient surface irrigation systems.
4) Open-source software to determine the optimal irrigation amount and schedule with different water types (including treated WW) and to optimize the required fertilizer input considering the nutrient input from irrigation with treated WW; thanks to a continuous monitoring of electric conductivity (proportional to salt concentration) in the irrigation water and in the irrigated soil, this software enables the farmer to avoid the excessive salt buildup in the soil that could result from the use of highly saline, treated WW; in particular, in case the soil electric conductivity approaches the crop-specific threshold set by the farmer, the software calculates the optimal mix of treated WW and freshwater to be applied in order to invert the increasing trend in soil salt concentration, so as to ensure soil health.
5) Large spectrum soil moisture sensor (or tensiometer) calibrated for dry soils and saline-treated WW; while existing tensiometers work up to a 2-bar soil moisture tension, the new tensiometer is designed to operate up to 7 bar, which makes it suitable for very dry climates and highly saline irrigation waters; the innovative tensiometer is used to supply the above-mentioned irrigation scheduling tool with consistent data on soil moisture content;
6) Plant growth promoting bacterial inocula constituted by selected soil bacterial strains able to increase crop resistance to water scarcity and salinity, thus reducing the need of irrigation water; genetically modified microorganisms, potential pathogens, and antibiotic multiresistant strains are rigorously excluded from these inocula to avoid any putative environmental and commercial risk.

The development of the WW treatment and irrigation technologies is currently in progress. During the second half of the project, a selection of these technologies will be scaled up and validated by means of 4 demonstration plants (one for each targeted WW type: municipal, agro-industrial, industrial, drainage canal) that will be set up and operated for at least 1 y in selected sites located in the basins listed in Table 3. Each pilot will consist of a WW treatment section, which will handle at least 10 m^3_{WW}/d, and an irrigation section. Each irrigation section will be divided into 2 zones, equipped with the same technologies: the first will receive treated WW from the first section of the plant, and the second will be irrigated with high-quality fresh water. To maximize the impact of the demonstration plants, the technologies to be scaled up will be selected among those initially studied at laboratory scale on the basis of the following criteria:

- Life Cycle Assessment and Cost–Benefit Analysis (CBA);
- evaluation of social and technical suitability in relation to the local context, through the periodic consultation of local stakeholders;
- technical performances, quantified for each quality parameter included in the ISO 16075 standard for treated WW agricultural reuse (BOD, COD, turbidity, total suspended solids, coliforms, intestinal nematodes); for each parameter, the % removal, the volumetric removal rate, and the compliance of the final effluent with the threshold concentrations reported in the ISO 16075 standard are taken into consideration; for some WWs, the evaluation of removal performances is extended to specific pollutants not listed in the latter standard, such as fungicides for FVPWW, polyphenols for OMWW, and dyes for TWW.

The goals of the demonstration plants are 1) to integrate the water supply and water demand technologies, 2) to further optimize and adapt the selected technologies to the local conditions, and 3) to provide an experimental basis for the development of basin-level integrated water management strategies.

Implementation phase

The analysis of the current situation of water management in Egypt, Morocco, and Tunisia highlighted the need for water management strategies capable of 1) guiding stakeholders in the selection of the most effective WW treatment and irrigation technologies and 2) leading to the identification of economic instruments capable of enhancing the adoption of effective water treatment and irrigation technologies and the reuse of treated WW for irrigation. These 2 elements shaped different types of implementation activities that, during the second part of the 4-y project, will aggregate the analysis of the water vulnerabilities (phase 1) and the results of the validation of technologies (phase 2):

- Two decision support tools (DSTs) will be developed and adapted to the selected basins (Akter et al. 2014; Hamouda et al. 2009): the first will support the analysis and selection of WW treatment technologies and facilitate their integration into basin-scale WW management strategies, whereas the second will integrate the project's irrigation technologies into basin-scale strategies for water and land management in agriculture. The second DST will be based on the development of and calibration to the 3 selected basins (Table 3) of an integrated hydro-agro-economic model capable of optimizing cropping patterns and water allocation (D'Agostino et al. 2014; Esteve et al. 2015; Graveline 2016).

- The DSTs will be used to develop strategies for WW management and for agricultural water and land management, tailored for the 3 selected hydrological basins (Table 3). The WW management strategies, aimed at maximizing the amount of irrigation-quality treated WW produced, will include elements such as the addition of a WW technology to treat the effluent of an existing WW treatment plant or the identification of economic instruments that enhance the implementation of innovative WW treatment technologies. The strategies for agricultural water and land management will consider technological, economic, social, environmental, institutional, and governance aspects. They will take into account the increased amount of water obtainable from improved water reuse and the implementation of more efficient irrigation technologies. Each strategy will include the identification of regulatory and economic instruments aimed at enhancing water reuse and the implementation of efficient irrigation technologies. Combinations of the 2 types of strategies will be identified and validated, so as to develop for each tested basin a selection of integrated water and land management strategies (IWLMSs) extended to both the supply and demand side. The proposed IWLMSs will be rated through a series of indicators, such as % of produced WW that gets reused in agriculture, % of agricultural land irrigated with efficient technologies, and food security risk in case of periods of drought. To maximize the project's impact, the proposed IWLMSs will be integrated with guidelines for the adaptation of the MADFORWATER tools, technologies, and approaches to other basins in Morocco, Egypt, and Tunisia and to other North African countries.
- To promote the adoption and the social acceptance of the proposed technologies and management strategies, policy recommendations will be produced, with emphasis on the associated economic instruments (Blanco-Gutiérrez et al. 2013). These recommendations will include suggestions for an update of the standards for WW reuse in agriculture in the target MACs.
- MADFORWATER includes several activities aimed at increasing the level of capacity building in the fields of wastewater treatment, irrigation, and water management in the target MACs, as well as the social acceptance of treated WW agricultural reuse: workshops on the project technologies, water management strategies and policies, train-the-trainer courses aimed at facilitating the adoption of innovative WW treatment and irrigation technologies by stakeholders, on-field trainings at the project pilots, exchange of scientists, technical and dissemination videos, stakeholder consultation workshops, and promotion of farmers associations. These activities, combined with the development of irrigation technologies suitable for the use of treated WW, are also aimed at minimizing the risk that the proposed irrigation devices become clogged or inefficient after a short time due to incorrect use by farmers.

ADAPTATION AND INTEGRATION OF WATER MANAGEMENT TOOLS IN THE MADFORWATER PROJECT

The analysis of the previous and ongoing research projects in the field of water in the 3 target countries suggests that the impact of some projects could be curbed by insufficient effort to adapt the proposed technologies and water management tools to the local conditions or by scarce integration between technological and water management approaches. For this reason, the key concepts of adaptation and integration are transversally applied to each of MADFORWATER's 3 phases. With regard to adaptation, in phase 1 different water vulnerability indicators were selected that were appropriate for the specificities of each basin; in phase 2 real WWs sampled in the selected basins and the local climatic conditions were used for lab-scale technology development, and the most promising technologies will be validated through demonstration plants located in the selected basins; in phase 3 the DSTs for the production of water management strategies will be calibrated by taking into account the specific physical, socioeconomic, and water policy constraints of each target basin. All these adaptation actions are characterized by a participatory approach, thanks to the inclusion in the MADFORWATER advisory board of several MAC stakeholders (managers of wastewater treatment plants, directors of basin authorities, presidents of farmer associations, directors of water or irrigation ministries, experts of nongovernmental organizations active in the 3 target countries). The advisory board gets periodically consulted by means of stakeholder consultation workshops. In particular, an initial stakeholder workshop (articulated in a separate meeting for each target country) took place during the first year of MADFORWATER in order to gather information on the level of water vulnerability in the target MACs. One further workshop is planned at the middle of the project to obtain stakeholder feedback on the suitability for the local context of the target MACs of 1) the water stress and vulnerability maps produced in phase 1, and 2) the WW treatment and irrigation technologies developed in phase 2. One final workshop will take place just before the end of the project, in order to perform a final validation of the proposed technologies, strategies, economic instruments, and policies in the field of water management. Before each workshop, the invited stakeholders receive 1) material on the MADFORWATER technologies, tools, and strategies that will be discussed during the workshop and 2) a questionnaire that each stakeholder is invited to complete in order to provide his or her feedback on the suitability of the project's activities in relation to his/her local context. The first part of each workshop is dedicated to a short presentation of the MADFORWATER technologies, tools, and strategies; a second interactive part allows stakeholders to provide their feedback. At the end of each workshop, each stakeholder returns the completed questionnaire, and a final report on the meeting conclusions is produced.

As for the project's integration approach, in the analytical phase water vulnerability analysis tools relative to WW treatment and water use in agriculture are integrated by means of a framework for the assessment of water vulnerability; in the technological phase, WW treatment and irrigation technologies will be integrated in the 4 demonstration plants; in the implementation phase, the proposed technologies will be integrated by economic and regulatory instruments.

EXPECTED RESULTS AND IMPACT

The expected results of MADFORWATER are listed in Table 2 in relation to each of the previously identified research gaps in the field of WW treatment and water management in the 3 target MACs.

Even though these results are mainly targeted to the 3 selected basins illustrated in Table 3, the project sets the basis for extending the implementation of its outcomes to most areas of Egypt, Morocco, and Tunisia, through a number of impact-driven actions: 1) country-wide identification of the areas characterized by the higher water vulnerability and water reuse potential; 2) policy recommendations to enhance the implementation of the proposed technologies and management strategies for water and land at the country level; 3) guidelines and training packages for adaptation of the MADFORWATER technological and nontechnological outcomes to other basins in the target MACs; 4) capacity-building events characterized by a domino effect, such as train-the-trainer courses and exchanges of scientists; and 5) strong involvement in the project activities, through a frequent consultation of the Advisory Board, of MAC stakeholders, members of international organizations (FAO, UNEP), and members of EU-level organizations such as the European Innovation Partnership on Water, the Joint Programming Initiative on Water, and the Water Supply & Sanitation Technology Platform.

By 2030 in the 3 target MACs, MADFORWATER is expected to increase 1) the production of irrigation-quality treated WW, 2) the reuse of treated WW in agriculture, 3) the fraction of irrigated land equipped with sustainable water-efficient technologies, with a consequent decrease of water consumption in agriculture, 4) the turnover for WW treatment and irrigation companies, 5) agricultural production and food security, and 6) the income of farmers who were able to invest in water-efficient irrigation technologies. The combination of these impacts is expected to lead to an increase in available water, equal to 70%–80% of the current water consumption in households or 6% of current water consumption in agriculture. Such additional water could be used in different ways depending on the political choices: allocation to new agricultural surface, decrease of groundwater overcatchment, or increase of municipal water supply.

CONCLUSION

As Egypt, Morocco, and Tunisia face a relevant water crisis in the next decades, the MADFORWATER project aims to tackle specific water vulnerabilities in these countries. The project's main points of strength are represented by the strong involvement of MAC partners and stakeholders in all project activities, the marked effort to develop technologies and water management tools well adapted to the local context, the high integration between technologies and water management tools as well as between WW treatment and WW agricultural reuse, and the fact that the project is based on a careful analysis of the current needs and research gaps in the target countries in the field of water treatment and management.

The main challenges that MADFORWATER faces include the following: 1) the choice to integrate technologies, water management strategies, and capacity-building activities requires a continuous interaction between a high number of partners with different technical and cultural backgrounds; and 2) the choice to integrate WW treatment technologies with irrigation technologies in the demonstration plants that will be set up in the 3 target countries requires not only strong collaboration between the partners in charge of the different technologies that will be merged in each pilot but also intense work aimed at removing any potential legal, technical, or cultural obstacle toward the successful construction and operation of such plants.

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Disclaimer—The authors declare no conflicts of interest.

Data Accessibility—The data underlying this article are available through the AMS Acta repository at the following DOI: 10.6092/unibo/amsacta/5695. The map of the Water Vulnerability Index relative to Tunisia is available in Supplemental File 1.

SUPPLEMENTAL DATA

Figure S1. Integrated technological and management solutions for wastewater treatment and efficient agricultural reuse in Egypt, Morocco, and Tunisia.

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