

Best Irrigation Practices Designed for Pesticides Use to Reduce Environmental Impact on Groundwater Resource in the Tunisian Context

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Abstract

The irrigated areas in Tunisia were esteemed in 2010 to over 420 thousand hectares and represents 8% of farmland, this little area providing 35% of the total crop production. This situation makes it exert enormous pressure on the irrigated sector that his intensification is very associated to increased inputs including especially pesticides. However, the irrational use and abuse of pesticides associated with an inadequate irrigation system management are a great threat of contamination to groundwater resources and constitute one of the greatest challenges facing Tunisian government today. According to FAO, 2013, the adoption of the concept of best practices can meet this challenge. These best practices are not only a practice that are best, but a practices that have been proven to work well and produce good results, and are therefore recommended as a model. This paper aims to analyze in a framework of global environmental approach, the role of the best irrigation practices (BIPs) to reduce environmental impact on groundwater resource. Finally, it was proposed a set of best irrigation practices completed by the technical recommendations for limiting the environmental impact of pesticide in groundwater resource.

Keywords: Best Irrigation Practices (BIPs), groundwater resource, pesticide, environmental tradeoff

1. Introduction

Land and water resources and the way they are used are central to the challenge of improving food security across the world. The irrigation sector claims about 70% of the freshwater withdrawals worldwide. In summary, irrigation is widely thought to provide 40% of the world's food from around 17 percent of the cultivated area (FAO, 2011). It has been estimated about \$2 billion are spent on irrigation investment each year (Faurés et al., 2007). The agriculture sector and especially the irrigation sector are most depending to pesticides for production of the high-quality crops. In fact, pesticides have now become an integral part to protect agricultural land. It has been estimated about \$38 billion are spent on pesticides each year (Pan-Germany, 2012).

In Tunisia, the water consumption of irrigated land makes 80% of the volumes distributed to all economic sectors of the country. Half of this volume is assured by the groundwater resource (ITES, 2014). However, the quality of groundwater resource is very threatened by the contamination concerning excessive use of fertilizers and especially pesticides from cropland (ITES, 2014). In fact, Tunisia imports every year about 4000 tons of pesticide, (mainly used for weed crop) and the average amount of active substance per application and per hectare is high (about 4 kg), also the used volume remains exaggerated (300 liter/ha) (Bahrouni et al., 2015). This reflects the absence of a global vision which shows no link between irrigation system management and the hug quantity of pesticides used. This situation, should lead necessarily to urgent need for a national action to consider the environmental aspect. On the other hand, the movement of pesticides in the environment depends upon a multitude of factors including soil characteristics, site features, pesticide properties and pesticide use practice. Lal (2008) has proved that the of-farm movements of soil and associated compounds from cropland are due to irrigation or rainfall-induced surface runoff. In the same context, Stephen (2004), has showed that the irrigation traditional methods are characterized by low water application efficiency and a high amount of

irrigation application; which causing a high leaching. In fact, the mastery of the irrigation system management offers tremendous scope to control runoff, and to minimize the contamination of groundwater resource (Jensen et al., 1990). In this sense, Mchugh et al. (2008) have demonstrated that subsurface drip irrigation under deficit irrigation has the potential to store in-crop rainfall more than subsurface drip under full and furrow irrigation in terms of runoff reduction carrying pesticides under rainstorm conditions.

In this context, the groundwater resource protection is a compromise factor for a sustainable use of pesticides and will constitute one of the greatest challenges facing Tunisian government today. Two main strategies could be considered (i) optimize the use of pesticides through Integrated Pest Management (IPM) approach, and (ii) reduce the environmental impact by using the best irrigation practices (BIPs). However, in the last approach, the reduction of the pesticide leaching to groundwater can reach 50% when the best irrigation practices are considered (Spurluk, 2000).

The objective of this study was to investigate the effect of the main factors influencing the Groundwater contamination potential by pesticides and suggests a best irrigation practices (BIPs) for reducing pesticides loss from cropland. Finally, this work was completed by the technical recommendations for limiting the environmental impact of pesticide in groundwater resource.

2. Tunisian Context and Environmental Tradeoff Concept

Many studies in Tunisian aquifer are demonstrated that the phreatic part of groundwater resources is environmentally vulnerable (Raad, 2005; Saidi, 2006; Saidi et al., 2010; Carrubba, 2014). The latter is known by two types. The horizontal vulnerability is due to seawater intrusion caused by overexploitation of groundwater resources whereas a vertical is generated due to drainage of fertilizers and pesticides. The coastal aquifers are subjected to horizontal and vertical vulnerability, while aquifers within the country are subjected only to vertical vulnerability. Regarding the vertical vulnerability study we mention the aquifer case of Hajeb Jelma located in central Tunisia. The evaluation of the potential contamination of this aquifer by the DRASTIC model that is consistent with a national basis allowed to draw its vulnerability map (Saidi et al., 2010). This vulnerability map established to Hajeb-Jelma aquifer shows three classes of contamination: moderate, high and very high. Moreover, the other evaluation result concerns the coastal aquifer in the Ghar El Melh area that is obtained through applying the A.C.V.M methodology (Aquifer Comprehensive Vulnerability Mapping) of the cartography of the horizontal and vertical vulnerability (Carrubba, 2014). This methodology was used to map the aquifer's comprehensive vulnerability the combination of vertical and horizontal vulnerability.

Globally, the contamination of the most Tunisian aquifers which were both already mentioned (Hajeb Jelma, and Ghar El Melh) is mainly due to an increase in the use of agricultural inputs such as chemical fertilizers and pesticides during the last decades. In this context, we noted the absence of a global vision which shows no link between irrigation management and the contamination level by pesticides of soil and groundwater resources.

This reflects an urgent need for a national action to consider the environmental aspect. Indeed, we ask this critical question, how to reduce the environmental impact from pesticides upon groundwater resources? Especially, in the case of agricultural production systems, which are intensified by the enormous amounts of pesticides, and irrigation water volumes, are not well controlled. In Tunisia, we noted, about 4000 tons of pesticide are imported every year, mainly used for weed crop spraying on cereals. Also the sprayed amounts per application and per hectare are high (about 4 kg/ha at a rate of 300 liter/ha) (Bharouni et al., 2015), and the average demand of irrigation water per hectare is estimated by 5500 m³ (ITES, 2014).

In fact, the remainder accumulates in soils, where it may filter especially into groundwater or surface water and prove toxic to micro-organisms, aquatic animals, and humans.

Further to these circumstances, we are witnessing the emergence of great challenge of the environmental tradeoff between two main pillars which are the irrigation demand and pesticides use. Indeed, this represents the only loophole alternative to boost agricultural production system, in order to meet the galloping food demand of the population. Thus, it constitutes an environmental tradeoff concept, which can be motivated in part by the political demands for sustainable agricultural production technologies. The structure of this concept can be formed by several components (Figure 1).

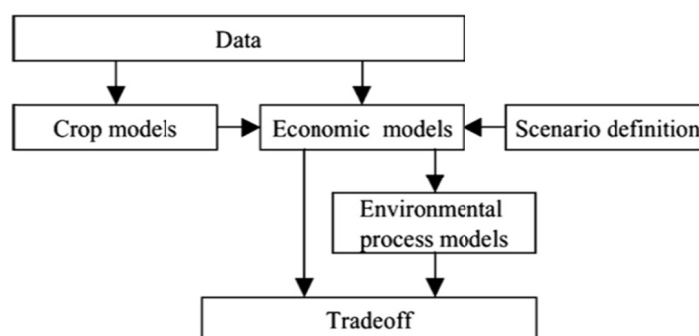


Figure 1. General setup, of the environmental tradeoff concept

However, the tradeoff concept mainly functions as an integrator of different tools and models. For example, crop growth simulation is carried out by models from the DSSAT suite of models (Jones et al., 1998), economic simulation models, and fate simulation of pesticide by environmental process model (LEACHP model, Wagenet & Hutson, 1989). The Tradeoff approach moves the necessary input and output among the different models and provides a format for the coordination of different scenario runs. This integrated approach will allow us to propose a compromise solution according to the adopted scenario between the efficient use of water resources and pesticides.

3. How to Reduce the Environmental Impact from Pesticides upon Groundwater Resources?

To answer to this question is not easily affordable. In fact, the environmental problem can not only be approached from a planning and strategic viewpoint (modeling tools with a data set) but should be integrate a technical and tactic approach (IPM concept) and innovative concept (BIPs). Indeed, Environmental Global approach in this work is to consider the planning strategic concept (environmental tradeoff) consolidated by the technical tactic concept (IPM) and the innovative concept (BIPs). This work will be focused on the role of these best practices that will feed their towers and consolidate the concept of environmental tradeoff that takes into account to the aspect of sustainability of agricultural production system. Before presenting the Environmental Global approach that we have adopted in this work, we recall the main factors that influence the potential contamination of groundwater.

3.1 Main Factors Influencing the Groundwater Contamination Potential

The groundwater contamination is the source of several processes causing the movement of pesticides in water through the soil. The main factors influencing whether pesticides will be leached into groundwater include characteristics of the soil and pesticide, and their interaction with water from a rain-event such as irrigation or rainfall. Table 1 summarizes the factors influencing the groundwater contamination potential by pesticides.

Table 1. Factors influencing the Groundwater contamination potential (McBride, 1989)

Summary of Groundwater Contamination Potential as Influenced by Water, Pesticide and Soil Characteristics		
	Risk of Groundwater Contamination	
	Low risk	High risk
<i>Pesticide Characteristics</i>		
Water Solubility	Low	High
Soil Adsorption	High	Low
Persistence	Low	High
<i>Soil Characteristics</i>		
Texture	Fine Clay	Coarse Sand
Organic matter	High	Low
Macropores	Few, Small	Many, Large
Depth to groundwater	Deep (30 m or more)	Shallow (7 m or less)
<i>Water Volume</i>		
Rain/Irrigation	Small Volumes at Infrequent	Large Volumes at Frequent Intervals

The major part of Tunisian phreatic groundwater is characterized by a vertical vulnerability to chemicals contamination, especially from pesticides that constitute a basic product for agricultural intensification. To prevent or reduce this environmental impact from pesticides to groundwater, users must consider many different site-specific best management practices, including the following: integration of crop and Integrated pest management (IPM), product selection, application rates, timing, placement in relation to the root system, weed cover, soil properties, best soil management practices (BMPs), and best irrigation management practices (BIPs). However, in the last approach, the reduction of the pesticide leaching to the groundwater can reach 50% when adequate best irrigation practices (BIPs) is considered (Spurlok, 2000).

3.2 Environmental Global Approach

The Integrated Pest Management approach (IPM), requires consideration of pesticide selection, when the choice exists, prior to application. Pesticide selection should not be based only on cost effectiveness, but also on toxicity to non-target species, product solubility, persistence, leaching potential, irrigation schedule, soil type, and other site characteristics.

In fact, the new evidence concerning the groundwater environmental protection in this work is to consider simultaneously the irrigation management by the BIPs concept as an essential component to strengthen the pesticides management by the IPM concept. These concepts constitute a great consolidation for the environmental Tradeoff concept and so for the decision-making (Figure 2).

Figure 2 summarizes the environmental global approach to be considered to limit the contamination of the groundwater. In the technical tactic part of our approach, two concepts have been identified, where the intensification of agriculture must take into account. These two concepts are: IPM concept related to pesticides management, and BIPs concept related to the mastery of pesticide leaching by irrigation management. In the planning strategic part of approach, the environmental tradeoff concept integrating the planning tools for future scenarios in order to achieve the robust decision-making for a sustainable development of the agricultural production system. In this article, we focus in the technical tactic approach which is based on the innovative concept (BIPs) and IPM concept.

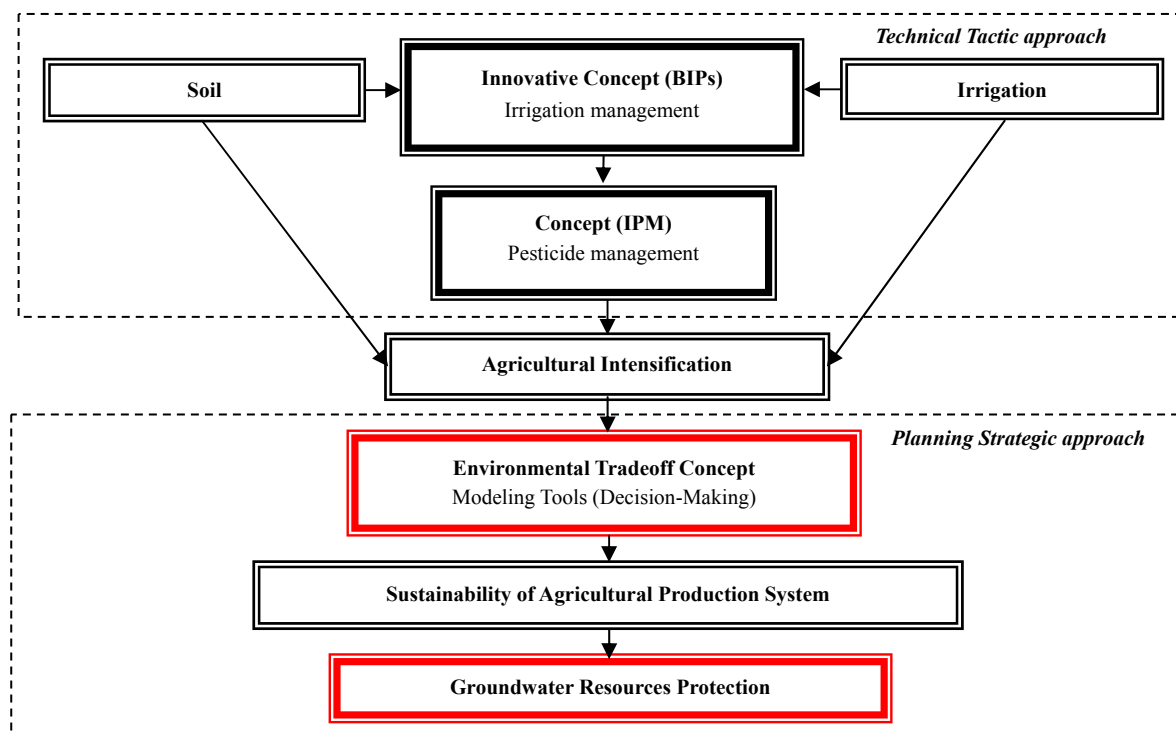


Figure 2. Environmental global approach to reduce impact from pesticides on the groundwater

3.2.1 Integrated Pest Management Concept (IPM)

According to Diane (2011), the IPM is a concept, based in three keys components (Figure 3): Management, Decision-making, and Knowledge. Globally, the mains objectives of IPM concept are:

- Optimize profits (over the long term);
- Rational use of pesticides and minimize pesticide resistance problems, and
- Reduce environmental contamination and costs-soil, groundwater, surface water, pollinators, wildlife, endangered species and sustain resource (agricultural or natural; over the long term).

To achieve these goals, the IPM concept must be supported by a key concept: BIPs which can be combined and optimized for a sustainable IPM concept. The concept of BIPs is defined as an experiment or a successful innovation, tested and validated; accepted and adopted that deserves to be circulated for greater ownership by a larger number of beneficiaries. Indeed, for the IPM concept to acquire the sustainability aspects, it should not be limited to the pesticides management, but it must consider the irrigation water resources management through the BIPs.

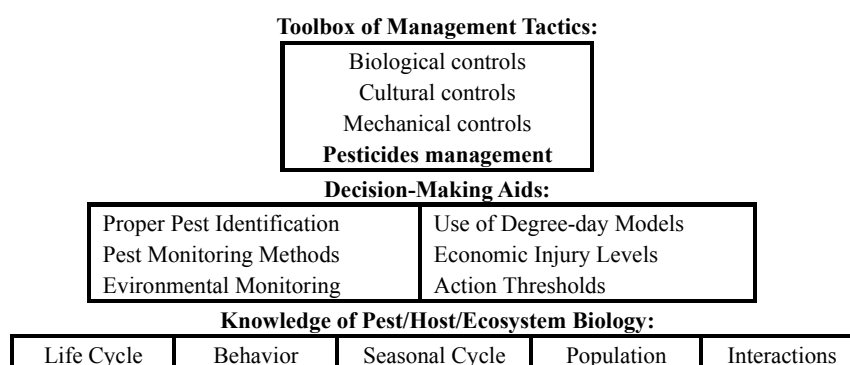


Figure 3. Schematic of IPM concept (Diane, 2011)

3.2.2 Irrigation Management by the BIPs Innovative Concept

Agricultural pesticides are moved through the soil by both rain and irrigation. In addition certain agricultural practices, such as tillage, the use of subsurface drains and irrigation, may appreciably contribute to pesticide leaching and subsequently to groundwater contamination (Gilliom et al., 2007). In this part of study, attention was focused on irrigation management. An adequate water supply is critical for plant growth, and various methods which can be used to supply water to plants. These different irrigation techniques influence water flow patterns in the soil (Bandaranayake et al., 1998) and solute movement in the Tunisian context, where the groundwater resources are menaced by scarcity and environmental problems. In fact, it is important to consider the best irrigation management practices BIPs that reduce pesticide leaching below the root zone, and can also enhance the water use efficiency, and hence allow gaining an economic advantage for farmers while also reducing the environmental burdens. Methods of water use efficiency and better irrigation scheduling could also integrate water and the nutrient management, thus minimizing agrochemical runoff and leaching problems. The main best irrigation practices (BIPs) approved by the major researches works are those based on the choice of irrigation system and irrigation management program. In this framework, we discuss three main BIPs that can be adopted by farmers in the tunisian context.

(1) The first BIPs is to choose an efficient irrigation system:

Many research works approved the important role of efficient irrigation system to minimize the off-site movement and the leaching problems of pesticides in the water surface and groundwater (Terry, 1993; Asare, 2000; Stephen, 2004; Gabriella, 2010). Figure 4 showed that the irrigation traditional methods are characterized by low application efficiency and a high amount of irrigation application; which gives a bad water resource valorization and an important environmental risk for the surface water and groundwater, which is mainly due to high leaching.

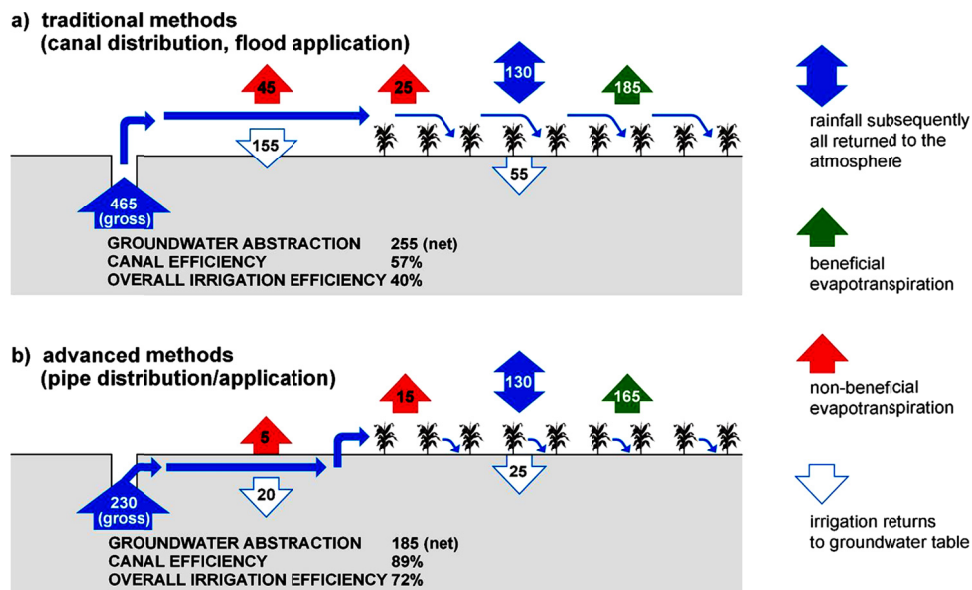


Figure 4. Interactions between Groundwater and soil-water-balance under different irrigation system and humid climatic condition (Stephen, 2004)

On the other hand, the choice of irrigation system and management of irrigation events plays a very crucial role in the off-farm pesticides movements especially through runoff phenomenon. In semi-arid tropical environment condition, Mchugh et al. (2008), have showed that the use of subsurface drip irrigation managed by deficit irrigation (90% Etc) could help achieve economic and environmental goals by producing comparable yield to furrow irrigation coupled with increased water use efficiency, and by minimizing off-site movement of pesticides at the farm scale. In fact, Mchugh et al. (2008) showed precisely that the subsurface drip irrigation managed by deficit irrigation (90% Etc) could reduce more the total quantities of nutrients and pesticides in the runoff and this in comparison with furrow irrigation (Figure 5).

However, with an advanced irrigation methods, we are identifying a better water irrigation saving and a lower environmental risk for the surface water and groundwater which is limited by a very low leaching. Therefore, careful choice of irrigation systems can be very effective in reducing the risk of groundwater contamination. Especially that the irrigation of 105 thousand hectares in Tunisia is ensured by the surface irrigation technique. (Hamdane & Bachta, 2014).

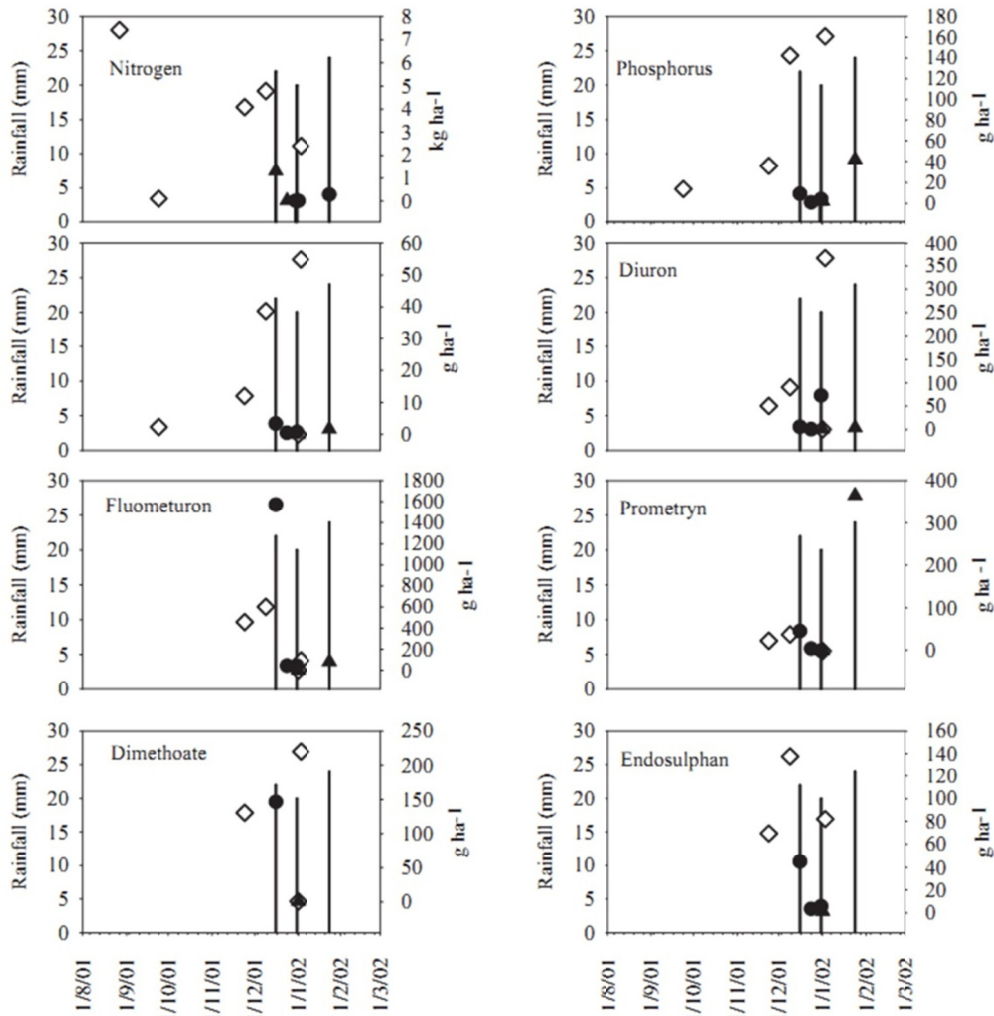


Figure 5. Total quantities of nutrients and pesticides in the runoff samples collected from each rainfall and irrigation event for furrow and subsurface irrigated sites in the first year (2001/2002)

Note. Dates are expressed in dd/mm/yy. Legend: \diamond = Furrow Irrigation, \bullet = Subsurface Drip Irrigation at 120% ETC, \blacktriangle = Subsurface Drip Irrigation at 90% ETC (Mchugh et al., 2008).

(2) The second BIPs consider the coordination between the rate and timing of irrigation and the timing of spraying to minimize pesticides loss:

This BIPs was approved by many research works. Terry (1993) has demonstrated, that the delay in water delivery allows some pesticides to degrade before water is eventually delivered onto the farmers fields. Also, Asare (2000) has approved, that the Leaching under the tensiometer-based irrigation management practices could be minimized by increasing the values of the tensiometer threshold readings at which irrigations are triggered or by delaying 3-7 days before irrigation when the recommended tensiometer threshold readings are observed. Particularly, we do note in the majority of Tunisian farmers fields, a bad synchronization between the trigger of irrigation, the spraying pesticides time and the level contamination of groundwater resource (Bahrouni et al., 2015).

(3) The third BIPs is based on the choice of irrigation scheduling practices according to soil textural:

The choice of irrigation scheduling practices according to soil textural can be very effective to reduce the risk of groundwater contamination. Several research works have shown that the choice of scheduling practices according to soil textural can be very effective in reducing the contamination of pesticides in the groundwater contamination. The research work was carried out by Asare (2000) using the model (IRRSCHM) to evaluate the relative maximum pesticides concentrations resulting from the different irrigation scheduling practices grouped

by soil textural classes during 30-year cropping sequence. The result of this research has demonstrated that the lowest concentrations were predicted in the case of the farmer's practices which have adopted the deficit irrigation practice (Table 2). In fact, the deficit irrigation practice has constituted a potential best irrigation practice to limit the contamination of pesticides in the groundwater.

Furthermore, the same work has proved that the predicted pesticide concentrations increased as soil sand fractions increased, regardless of the irrigation scheduling practice.

Table 2. Relative maximum pesticides (Bladex) concentrations^a resulting from the different irrigation scheduling practices grouped by soil textural classes (Asare, 2000)

Soil textural class	Irrigation Scheduling Practices			
	Farmers practices	Irrigation at 50% PAWD	Scheduled by Tensiometer	
			0.5 depth	0.75 depth
Clay	1.2 E-18	3.2 E-12	1.5 E-06	4.5 E-09
Clay loam	8.4 E-14	2.3 E-07	2.2 E-04	6.7 E-06
Sandy clay loam	1.0 E-11	2.0 E-06	N/A b	N/A b
Loam	6.8 E-10	8.9 E-07	4.7 E-05	5.5 E-07
Sandy loam	1.6 E-07	9.5 E-06	3.0 E-05	9.2 E-07
Loam sand	6.4 E-07	4.2 E-05	N/A b	N/A b
Sand	2.4 E-06	4.3 E-04	3.2 E-04	1.2 E-05

Note. ^a: predicted Bladex concentrations were divided by 1.3×10^{-2} mg L⁻¹, Bladex Health Adevisory level; ^b: No Simulation runs were made for the soil class.

In the Tunisian context, many surveys were carried out in the farms of Medjerda basin by Slatni et al. (2007), and have shown that about 50% of farmers have difficulties to master the irrigation management in terms of conversion between plant water requirement and the irrigation dose to bring along a given irrigation system.

To better control the pesticides leaching from soil to groundwater, we suggest that the best irrigation practices can be associated to soil best management practices, such as: the adding of the organic amendments to the soil (Daniel & Rai, 2006); the use of the cover crops issued from the bed planting technique (Cassigneul et al., 2015) and the incorporate by the techniques of tillage the pesticides to soil before irrigation (B. Gabriela & P. Graciela, 2007).

To better understand the complex processes governing leaching in the groundwater (soil properties, irrigation system management, rainfall, and groundwater depth), a research work was conducted by Gabriella et al. (2010) and aims at investigating the impact of different irrigation systems on pesticide leaching to shallow groundwater by direct monitoring at the field scale over a 3-year period. Sprinkler, border and basin irrigation systems were considered. The simulations results by MACRO 5.1 model (Table 3) have shown that the highest concentrations of pesticides were found in farms using basin irrigation, indicating that this irrigation system can influence the leaching of pesticides. Furthermore, the basin irrigation requires the greatest amount of water which is a valuable resource and should be used in a manner that maximizes crop productivity per liter. The use of this type of irrigation should be avoided in order to protect groundwater from pesticides contamination and to avoid water wastage. Border and sprinkler systems have demonstrated in a similar manner a low contamination of pesticides in the groundwater. Gabriella (2010) has deduced that the coupling of experimental results and mathematical models (IRRSCHEM, MACRO) should always be considered for improving our understanding of the complex processes governing the pesticides leaching.

Table 3. Evaluation by a MACRO 5.1 model the maximum pesticide concentration in groundwater depending on the soil properties, irrigation system management and rainfall (Gabriella et al., 2010)

Treatments	Topsoil Texture (USAD)	Ground-Water Depth (m)	Irrigation System	Number and total amount of irrigation (mm) 2005-2006-2007	Annual Rainfall (mm) 2005-2006-2007	Concentration of Pesticides in the Ground Water ($\mu\text{g/l}$)
Irrigation Practice 1	Clay-loam	0.9-2.8	Sprinkler	3-7-7 120-280-280	752-625-437	0.06
Irrigation Practice 2	Sandy-loam	0.9-1.8	Sprinkler	6-5-7 120-110-126	662-595-785	0.08
Irrigation Practice 3	Loam	1.1-2.8	Sprinkler	1-1-3 30-50-150	1060-783-745	0.38
Irrigation Practice 4	Sandy-loam	0.3-2.7	Sprinkler	1-1-2 30-60-60	1089-573-391	0.03
Irrigation Practice 5	Loam	0.5-1.8	Sprinkler	3-5-no 90-125-no	832-711-965	<0.005
Irrigation Practice 6	Sandy-loam	5.3-6.7	Border	2-3-3 120-180-180	561-663-349	0.01
Irrigation Practice 7	Sandy-loam	4.4-5.4	Border	1-2-2 60-120-120	561-663-349	0.01
Irrigation Practice 9	Sandy-clay	3.8-5.8	Bassin	4-6-6 280-420-420	716-779-689	1.17
Irrigation Practice 10	Sandy-loam	3.6-6.9	Basin	3-5-5 310-350-350	654-525-531	0.34
No Irrigation	Loam	0.7-3.9	Not-irrigation	-	544-637-438	0.08

4. Conclusions and Recommendations

Agricultural pesticides pollution of water surface and groundwater by nutrients and pesticides has been identified as a major problem in Tunisia. Yet, in spite of major research efforts to quantify the problems and develop solutions, the significant programs and national and international funds to reduce these contaminants have not been forth coming. Actually, significant reductions in water surface and groundwater contamination by nitrate, phosphate and pesticides have been achieved that by the use of fertility and Integrated Pest Management (IPM).

However, a large extension of irrigated sector in Tunisia opts to provide at the horizon 2030, about 50% of the total crop production. Following of these circumstances, it emerged a great challenge of the environmental tradeoff between two main pillars: Demand of irrigation and pesticides. Faced with this challenge, the judicious solutions lies in the fact that we need to develop a global research approach that consider combination of IPM concept with the innovative concept of BIPs, and the strategic planning environmental tradeoff.

In effect, this work was focused on the role of these best practices that will feed their towers and consolidate the strategic planning concept of environmental tradeoff that takes into account to the aspect of sustainability of agricultural production system.

From this study, it was demonstrated that the environmental protection of groundwater, must consider simultaneously the pesticides management through the IPM concept and the irrigation management by the BIPs concept as two essential components to strengthen the environmental Tradeoff concept and so for the decision-making. Several relevant results of BIPs have been highlighted as part of this study. These results were from several consolidated research work by the scientific tests. The BIPs can be adopted at the farms level and have to be considered at the level of technical assistance.

In the perspective part of this work, and in order to better control the pesticides leaching from soil to groundwater, we suggest that the BIPs can be associated to BMPs, such as: the adding the organic amendments to the soil, the using the cover crops issued from the bed planting technique and the incorporating by the techniques of tillage the pesticides to soil before irrigation.

In this study we also considered the coupling between the experimental results and mathematical models (IRRSCHM, MACRO) that should always be considered for improving our understanding of the complex processes governing the leaching of pesticides in the groundwater.

Further, advanced approaches such as biotechnology and nanotechnology could also be considered to facilitate the development of resistant genotype or pesticides with fewer adverse effects.

Finally, we closed our work by a proposition of technical support of recommendations to close and simplify the application of best irrigation practices are identified in our work, such as:

- Avoid overspray and chemical drift, especially when surface water is in close proximity to treatment area.
- Avoid applications if wind speed favors drift beyond the intended application area.
- Consider the time pesticide application in relation to soil moisture, anticipated weather conditions, and irrigation schedules to achieve the greatest efficiency and reduce the potential for pesticides off-site transport (drift).
- Avoid pesticide application when soil moisture status or scheduled irrigation increases the possibility of runoff or deep percolation.
- After pesticide application, manages irrigation to reduce the possibility of erosion, runoff and/or leaching may transport pesticide from the target site.
- Ensure that backflow prevention devices are installed and operating properly on irrigation systems used for applying pesticides.
- Use GPS/GIS technology, where appropriate, to aid in pest mapping, pesticide application precision and record keeping.

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