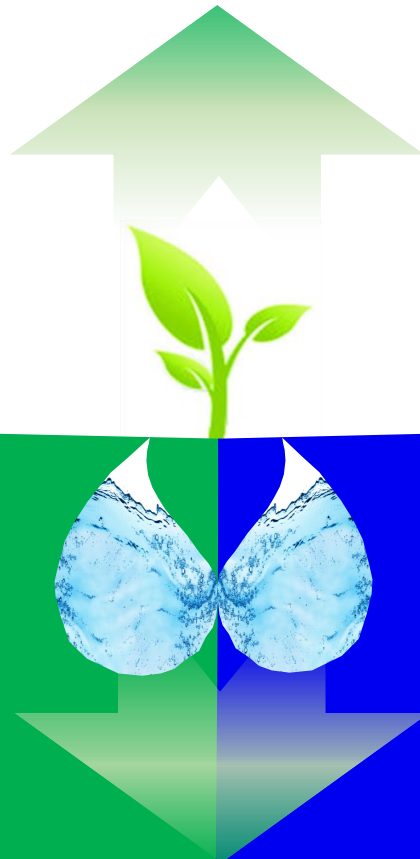


# Green, blue, and grey water footprint reduction in irrigated crop production

Abebe Demissie Chukalla



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# GREEN, BLUE AND GREY WATER FOOTPRINT REDUCTION IN IRRIGATED CROP PRODUCTION

DISSERTATION

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On the authority of the rector magnificus

Prof. dr. T.T.M. Palstra

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Abebe  
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*“What doesn’t kill you makes you stronger” — Friedrich Nietzsche*

# Summary

In the face of increasing freshwater scarcity, reducing the consumptive and degradative water use associated with crop production, the world's largest water user, is indispensable. The thesis explores the potential for reducing the green, blue and grey water footprint (WF) in irrigated crop production by a systematic model-based simulation for a large number of field management practices and different cases. The research has been set up in four subsequent studies, whereby the first two focus on green and blue WF reduction, the third on grey WF reduction and the fourth on the trade-off between blue and grey WF in crop production.

**Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching.** This study aims to explore the potential for reducing the green and blue WF per tonne of crop production by considering four different irrigation techniques, four irrigation strategies, and three mulching practices for various cases, including three crops, four different environments, three hydrologic years (dry to wet), and three soil types. The AquaCrop model is applied to simulate the effect of different combinations of field management practices on evapotranspiration, crop yield, and thus WFs per tonne. WF reduction is calculated by comparing the WF associated with a certain field management package with a reference (furrow technique with no mulching and full irrigation). The result shows that the average reduction in the consumptive WF is 8–10% if we change from the reference to drip or subsurface drip, 13% when changing to organic mulching, 17–18% when moving to (subsurface) drip in combination with organic mulching, and 28% for (subsurface) drip in combination with synthetic mulching. Reduction in overall consumptive WF always goes together with an increasing ratio of green to blue WF. The WF of growing a crop for a particular environment is smallest under deficit irrigation, followed by full irrigation, supplementary irrigation and zero irrigation (rain-fed). Growing crops with sprinkler irrigation has the largest consumptive WF, followed by furrow, drip and subsurface drip.

**Marginal cost curves for green and blue water footprint reduction in irrigated agriculture: guiding a cost-effective reduction of crop water consumption to a permit or benchmark level.** This study aims to develop marginal cost curves (MCCs) for WF reduction in crop cultivation. MCCs present information on the cost-effectiveness of various field management practices, and can be used to estimate the cost associated with a certain WF reduction target (WF permit or benchmark). AquaCrop is used to estimate the effect of different management packages on evapotranspiration and crop yield and thus on WF of crop production, for three crops. The annual average cost for each management package is estimated as the sum of the annualized capital cost, and the annual operation and maintenance costs. The WFs and annual costs associated with the management packages are used to develop alternative WF reduction pathways, after which the most cost-effective pathway is selected to develop the MCC for WF reduction. It is shown that the most cost-effective way to reduce the WF of crop production is to change the irrigation strategy,

followed by the mulching practice and finally the irrigation technique. The application of MCC for WF reduction to a certain WF permit level is shown using a hypothetical example.

**Grey water footprint reduction in irrigated crop production: effect of nitrogen application rate, nitrogen form, tillage practice and irrigation strategy.** The study aims to explore the potential for reducing the grey WF per tonne of crop production by assessing the effect of different combinations of nitrogen (N)-application rate, from 25 to 300 kg N ha<sup>-1</sup> y<sup>-1</sup>, inorganic-N or manure-N, conventional or no-tillage and full or deficit irrigation, for irrigated maize on loam soil in a semi-arid environment. The APEX model is applied to estimate the N loads and crop yield for different field management practices, and thus to calculate the grey WF per tonne. Compared to the reference case of an N-application rate of 300 kg N ha<sup>-1</sup> y<sup>-1</sup>, with inorganic-N as fertilizer, conventional tillage and full irrigation, the grey WF can be reduced by 91% by reducing the N-application rate to 50 kg N ha<sup>-1</sup> y<sup>-1</sup>. It can be further reduced by applying manure-N and deficit irrigation. Water pollution can be reduced dramatically, but this comes together with a great yield reduction, and a much lower water productivity as well. The overall (green, blue plus grey) WF per tonne is found to be minimal at an N application rate of 150 kg N ha<sup>-1</sup>, with manure, no-tillage and deficit irrigation (with crop yield of 9.3 t ha<sup>-1</sup>).

**Trade-off between blue and grey water footprint of crop production at different nitrogen application rates under various field management practices.** The study explores the trade-off between blue and grey WF by changing N-application rates from 25 to 300 kg N ha<sup>-1</sup> y<sup>-1</sup> under a reference management package (inorganic-N, conventional tillage, full irrigation), or by changing the field management practices for irrigated maize on loam soil and in semi-arid environment. The APEX model is applied to simulate the effect of field management practices (seven N-application rates, two N forms, two tillage practices and two irrigation strategies) on evapotranspiration, N load to freshwater and crop yield, and thus blue and grey WFs per unit of crop are calculated. The result shows that increasing N application from 25 to 50 kg N ha<sup>-1</sup> y<sup>-1</sup>, is a no-regret move, because crop yield is increased by a factor 2, and blue and grey WFs per tonne are reduced by 40% and 8%, respectively. Decreasing the N application from 300 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup> is a no-regret move as well, with a grey WF per tonne reduced by 72%, while the blue WF and yield remain the same. Increasing the N application from 50 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup> involves a trade-off between blue and grey WF, because crop yield is increased by a factor 3, and the blue WF per tonne declines by 60% but the grey WF increases by 210%. The minimum blue WF per tonne is found at an N application of 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, while the minimum grey WF per tonne is at 50 kg N ha<sup>-1</sup> y<sup>-1</sup>.

**Conclusion:** The thesis contributes to the advancement of the field of water footprint assessment in numerous ways. First, a shadow water-balance method was developed and applied to explicitly distinguish between the green and blue WF of crop production. Second, the APEX model was applied to estimate the grey WF of crop production for the first time in the thesis. Third, the thesis offers the first comprehensive and systematic study of the potential for reducing the green, blue and grey WF per unit of crop production by changing field management practices under various cases. Fourth, the study shows the trade-off

between the blue and grey WF, and between WFs and crop yield at different N-application rates and under various field management practices (N-forms, tillage practices and irrigation strategies). Finally, the thesis shows how one can develop and apply a model-driven MCC for irrigated crop production.





# Samenvatting

Door de verwachte stijgende waterschaarste is het noodzakelijk duurzaam watergebruik voor gewasproductie, als 's werelds grootste watergebruiker, te bevorderen. Deze thesis onderzoekt de mogelijkheden om de groen, blauw en grijze watervoetafdruk van geïrrigeerde gewasproductie te verkleinen door verschillende typen veldbeheer en cases te simuleren door middel van een systematische modelgebaseerde aanpak. Dit onderzoek bestaat uit vier studies, de eerste twee studies richten zich op de groen en blauwe watervoetafdruk, de derde focust zich op de grijze watervoetafdruk en de vierde onderzoekt de mogelijke afwegingen tussen de blauwe en de grijze watervoetafdruk van gewasproductie.

**Het reduceren van de groen en blauwe watervoetafdruk van geïrrigeerde landbouw: de effecten van irrigatie technieken, irrigatie strategieën en mulchen.** Deze studie poogt de potentiële reductiemogelijkheden van de groen en blauwe watervoetafdruk (WV) per ton gewasproductie in kaart te brengen door vier verschillende irrigatie technieken, vier verschillende irrigatie strategieën, en drie typen van mulchen (bodembedekkingen) te analyseren. De analyses bevatten drie gewassoorten, vier verschillende gebieden, drie hydrologische jaren van droog naar nat en drie verschillende grondsoorten. Om de effecten van het type veldbeheer op evapotranspiratie, gewasopbrengsten, en dus op de WV per ton, te kunnen simuleren is het AquaCrop model gebruikt. De WV reductie is berekend door de WV van een type veldbeheer te vergelijken met een basis type veldbeheer als referentie (ploegvoren zonder bodembedekking en volledige irrigatie). De analyses tonen aan dat er verschillende mogelijkheden bestaan om de consumptieve WV te reduceren door van het type veldbeheer als referentie te veranderen. Zo kan een gemiddelde reductie worden behaald van 8-10% als men overgaat naar een druppel- of oppervlakte druppelirrigatiesysteem. Een reductie van 13% kan worden behaald als men overgaat naar organische bodembedekking, 17-18% wanneer (oppervlakte) druppelirrigatie in combinatie met organische bodembedekking wordt toegepast, en 28% als (oppervlakte) druppel irrigatie wordt toegepast in combinatie met synthetische bodembedekking. Daarnaast blijkt dat elke reductie van de consumptieve WV altijd gepaard zal gaan met een toenemende verhouding tussen de groene en de blauwe WV. De consumptieve WF van gewasproductie in een bepaald gebied is het kleinste wanneer deficit irrigatie wordt toegepast, gevolgd door volledige irrigatie, aanvullende irrigatie en geen irrigatie (berekening). De grootste consumptieve WV van gewasproductie wordt gerealiseerd door het toepassen van sprinkler irrigatiesystemen, gevolgd door veebesproeiers, druppelirrigatie en oppervlakte druppelirrigatie.

**De marginale kostencurves van het reduceren van de groen en blauwe watervoetafdruk in geïrrigeerde landbouw: richtlijnen voor een kosteneffectieve vermindering van het consumptieve water gebruik voor gewasverbouwing volgens gestelde WV benchmarks en licenties.**

Deze studie poogt marginale kostencurves te ontwikkelen voor de reductie van watervoetafdrukken van gewasverbouwing in de landbouw. De marginale kostencurves geven de kosteneffectiviteit van verschillende typen veldbeheer weer en kunnen worden gebruikt om de bijkomende kosten van het reduceren de WV tot bepaalde targets in te schatten (WV benchmarks en licenties). Het AquaCrop model is gebruikt om de effecten van verschillende combinaties van typen veldbeheer op evapotranspiratie en gewasopbrengst, oftewel op de WF van gewasproductie, in te schatten voor drie gewassoorten. De jaarlijkse gemiddelde kosten voor elke combinatie veldbeheer is berekend door de jaarlijkse kapitaalkosten en de jaarlijkse operationele- en onderhoudskosten te sommeren. De watervoetafdrukken en de jaarlijkse kosten, gerelateerd aan de combinaties van veldbeheer, zijn gebruikt om alternatieve WV reductiemogelijkheden te bepalen waarna de meest kosteneffectieve opties zijn geselecteerd om de marginale kostencurve voor een gereduceerde WV te ontwikkelen. Uit het onderzoek is gebleken dat de meest kosteneffectieve wijze om de WV van gewasproductie te reduceren gerealiseerd kan worden door de irrigatiestrategie te wijzigen, gevolgd door het toepassen van bodembedekking, en tot slot door het veranderen van de irrigatie techniek. De marginale kostencurves van de reductie van de WV tot een bepaalde target is in het onderzoek weergegeven met een hypothetisch voorbeeld.

### **Verminderen van de grijze watervoetafdruk in geïrrigeerde gewasproductie: het effect van applicatiesnelheden van stikstof, stikstof vormen, bodembewerking en irrigatie strategieën.**

Deze studie onderzoekt de mogelijkheden om de grijze WV per ton gewasproductie te reduceren door het effect van verschillende stikstof aanbrengsnelheden van stikstof, van 25 tot 300 kg N ha<sup>-1</sup> y<sup>-1</sup>, anorganisch stikstof of organische stikstof, conventioneel of geen veldbeheer, en volledige of deficit irrigatie, voor geïrrigeerde mais op leem in semi-aride gebieden te analyseren. Het APEX model is gebruikt om de stikstofbelasting en gewasopbrengst van verschillende typen veldbeheer, oftewel het berekenen van de grijze watervoetafdruk per ton, te beoordelen. Vergeleken met een basisscenario waar een aanbrengsnelheid van 300 kg N ha<sup>-1</sup>y<sup>-1</sup> geldt, met gebruik van anorganisch stikstof als kunstmest en conventionele bodembewerking en volledige irrigatie, dat de grijze watervoetafdruk met 91% kan worden verminderd door de hoeveelheid stikstof tot 50 kg N ha<sup>-1</sup>y<sup>-1</sup> te verlagen. Een verdere vermindering kan worden gerealiseerd door organisch stikstof te gebruiken en deficit irrigatie toe te passen. Daarnaast kan watervervuiling drastisch verminderd worden hoewel dit gaat gepaard met een sterke vermindering van de gewasproductie en een lagere waterproductiviteit. De totale WV per ton is minimaal bij een applicatiesnelheid van 150 kg N ha<sup>-1</sup> met gebruik van organisch stikstof, zonder grondbewerking, en met deficit irrigatie (gewasproductie van 9.3 t ha<sup>-1</sup>).

### **Afwegingen tussen de blauwe en grijze watervoetafdruk van gewasproductie met verschillende stikstof applicatiesnelheden onder verschillende typen veldbeheer.**

Deze studie onderzoekt de afwegingen tussen de grootte van de blauwe en de grijze water voetafdruk door het effect van verschillende stikstof applicatiesnelheden te analyseren van 25 tot 300 kg N ha<sup>-1</sup>y<sup>-1</sup> voor een bepaald type veldbeheer dienend als referentie

(anorganisch stikstof, conventionele grondbewerking, volledige irrigatie), of door het veranderen van het type veldbeheer voor geïrrigeerde mais productie op leem in semi-aride gebieden. Het APEX-model is gebruikt om het effect van typen veldbeheer te simuleren (zeven stikstof applicatiesnelheden, twee stikstof vormen, twee grondbewerkingsmethoden en twee irrigatie strategieën) op evapotranspiratie, stikstofbelasting in de binnenwateren en gewasopbrengsten, oftewel om de blauw en grijze watervoetafdrukken per eenheid gewas te berekenen. De resultaten tonen aan dat een verhoging van de stikstof applicatie van 25 naar 50 kg N ha<sup>-1</sup>y<sup>-1</sup> aanzienlijke effecten tot gevolg hebben. Zo wordt de gewasopbrengst daardoor met factor 2 verhoogd, en de blauw en grijze water voetafdrukken per ton verminderd met 40% en 8%, respectievelijk. Het verminderen van de stikstof applicatie van 300 naar 200 kg N ha<sup>-1</sup>y<sup>-1</sup> blijkt ook voor aanzienlijke effecten te zorgen. Namelijk, waar de grijze watervoetafdruk per ton wordt verminderd met 72% blijven de blauwe WV en de gewasopbrengst onveranderd. Met het verhogen van de stikstof applicatie van 50 naar 200 kg N ha<sup>-1</sup>y<sup>-1</sup> gaat een afweging gemoeid tussen de blauwe en de grijze watervoetafdruk omdat de gewasopbrengst met factor 3 wordt verhoogd, de blauwe watervoetafdruk per ton wordt verminderd met 60% en de grijze watervoetafdruk wordt verhoogd met 210%. Een minimale blauwe WV per ton wordt behaald bij een stikstof applicatie van 200 kg N ha<sup>-1</sup>y<sup>-1</sup>, terwijl een minimale grijze WV per ton wordt gerealiseerd bij een stikstof applicatie van 50 kg N ha<sup>-1</sup>y<sup>-1</sup>.

## **Conclusie**

Deze thesis draagt op verschillende manieren bij aan het huidige onderzoek op het gebied van de watervoetafdruk. Ten eerste, is er een waterbalans schaduwmethode ontwikkeld en toegepast om een expliciet onderscheid te kunnen maken tussen de groen en blauwe watervoetafdruk van gewasproductie. Ten tweede, het APEX-model was voor het eerst in deze thesis toegepast om de grijze watervoetafdruk van gewasproductie te berekenen. Ten derde, deze thesis komt als eerste met een alomvattende en systematische benadering om de mogelijkheden te onderzoeken om de groen, blauw en grijze watervoetafdrukken te reduceren per eenheid gewasproductie door middel van het veranderen van het type veldbeheer onder verschillende omstandigheden. Ten vierde laat deze thesis de verschillende afwegingen zien die gemaakt kunnen worden tussen de blauw en grijze watervoetafdruk, en tussen de watervoetafdruk per eenheid en de gewasopbrengst met verschillende stikstof applicatiesnelheden en onder verschillende type veldbeheer (stikstofvormen, methoden voor bodembeheer en irrigatie strategieën). Ten slotte toont dit onderzoek aan hoe een model gedreven marginale kostencurve voor geïrrigeerde gewasproductie ontwikkeld en toegepast kan worden.



# 1 Introduction

## 1.1 Background

The world's freshwater resources have limited renewal rates (Rockström et al., 2009; Steffen et al., 2015) and face pressure from increasing demand, driven by population growth, economic development, and changes in dietary habits, while there is a growing recognition of environmental water needs as well (Ercin and Hoekstra, 2014). Anthropogenic climate change, which affects precipitation and evaporation patterns (Trenberth, 2011), further aggravates the burden on freshwater availability (Milly et al., 2005). As a result, the maximum sustainable water use is reached or breached in many river basins across the world, with two-thirds of the global citizens currently facing water scarcity at least one month per year (Mekonnen and Hoekstra, 2016). To manage freshwater scarcity and ensure sustainability at a river basin scale, Hoekstra (2014) proposes a cap (limit) to the consumptive and degradative water use per river basin, in order to stay within maximum sustainable levels, and to issue no more water use permits to sectors or individual users than fit within the cap. Additionally, in order to increase water use efficiency, Hoekstra (2014) proposes water footprint benchmarks for specific processes and products as a reference for what is a reasonable level of water use per unit of production. In irrigated crop production, this would urge reduction of consumptive and degradative water use in catchments where actual water consumption and pollution in irrigation currently exceeds levels that are maximally sustainable in the long term. Satisfying the future demand for food, feed, fibre and biofuel within a maximum volume of water allocated for irrigation, it is required to manage irrigation water more effectively (de Fraiture and Wichelns, 2010). Improving water efficiency in food production can be approached from two sides: i) produce more crop with less consumption and pollution of water, by reducing non-beneficial evaporation and leaching and runoff of nutrients (Molden, 2007), and ii) produce more nutritional value with less water, by changing towards less water-intensive consumption patterns (Hoekstra, 2013). This thesis focusses on the first point: more crop per drop of water consumed or polluted, with a further focus on irrigated crop production.

Water efficiency in irrigated crop cultivation at field level can be measured with different indicators, of which the most widely employed are: irrigation efficiency (IE), water productivity (WP) and water footprint (WF) (Zhuo and Hoekstra, 2017). IE at field level measures the fraction of the volume of irrigation water applied to the field that is beneficially used by the crop, which means it is taken up and transpired by the plants (Israelsen, 1950; Bos and Nugteren, 1982; Jensen, 2007). IE focuses on irrigation water (blue water), neglecting rainwater (green water), which however plays an important role in global food production as well (Falkenmark and Rockström, 2006). Besides, IE takes an engineering perspective, focussing on efficient use of irrigation water and infrastructure; from an environmental (river basin) perspective, the IE concept can be a bit problematic, because increasing IE does not necessarily mean that water is saved for the environment. When IE

is increased by reducing non-beneficial evaporation, this means that the water remains in the basin and is thus saved, but when IE is increased by reducing drainage, the return flow to the basin is reduced, which cannot be regarded as a saving for the environment (Hoekstra, 2013; Seckler, 1996). WP measures the ratio of the crop yield (Y) or the value derived from the crop yield to the consumptive water use (i.e., the evapotranspiration ET) over the growing period (Molden et al., 2010; van Halsema and Vincent, 2012). WP refers to the productivity of the sum of rainwater and irrigation water consumption and is thus one number; no distinction can be made as to the source of water consumed (rainwater or irrigation water), because the yield is essentially the result of the sum of green and blue water inputs. Dividing the full yield over the green water consumption or blue water consumption only doesn't provide a meaning full metric. The inverse of WP,  $ET/Y$ , is called the consumptive WF (Hoekstra et al., 2011). Now, water consumption is in the counter instead of the numerator, which means that one can distinguish between the green and blue WF. The green WF measures the volume of rainwater consumed to produce a certain crop yield; the blue WF measures the volume of irrigation water consumed to produce a certain crop yield. The sum of the green and blue WF is the total consumptive WF. WF has a third component as well, called the grey WF, which measures water pollution and is calculated by dividing the pollutant load entering freshwater by the difference between the maximum acceptable concentration for that pollutant and the natural background concentration for that pollutant, and dividing the resultant 'polluted water volume' by the crop yield. In all of these cases, WF is expressed as a water volume per tonne of crop; we can also express WF as a water volume per ha, which is the volume of consumptive or degradative water use over the crop growing period per unit area. This thesis focuses on the green, blue and grey WF in irrigated crop production.

The green, blue and grey WF in irrigated crop cultivation can be reduced through improving field management practices, whereby sometimes all three WF components can be reduced simultaneously, while other times there will be a trade-off, whereby one WF component reduces while another one increases. Field management practices in crop production affect the water and nutrient fluxes, the soil moisture and nutrient available for crop growth. Management practices may differ in terms of irrigation technology, irrigation strategy, mulching practice, the form in which nutrients are applied, nutrient application rate and tillage practice. The effect of these field management practices on the classical water efficiency indicators such as irrigation efficiency, water productivity, and nutrient use efficiency are reported in various meta-studies (Qin et al., 2015; Corbeels et al., 2014; Chivenge et al., 2011; Tonitto et al., 2006; Katerji et al., 2008; Burzaco et al., 2014; Quemada et al., 2013). The earlier studies provide insight in the effects of individual field management practices or a few of their combinations, on blue water, on N leaching and sometimes on both. None of the earlier studies consider the effect of management practices on the efficiency of green water use, which is generally the most important water resource stored in the root zone. Besides, while looking at N leaching per hectare, none of the studies consider the effect of different management practices on the N load per unit of crop yield or the effect on the grey WF per tonne. Furthermore, none of the previous studies undertake a systematic effort to study the effects of the large variety of combinations that

can be made when considering management packages. Therefore, under increasing demand and fierce competition for limited freshwater, it is worth to answer these questions: what are the smallest achievable green, blue and grey water footprints per tonne of crop production, and what are the most cost-effective field management practices to reduce WFs?

## 1.2 Research objective and thesis outline

The objective of the research is to explore the potential for reducing the green, blue and grey water footprints (WF) in irrigated crop production by a systematic model-based assessment of different (combinations of) field management practices at field level.

In order to achieve the objective, the thesis has been designed in four parts (Figure 1.1), which will be reported in Chapters 2-5:

- Green and blue WF reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching (Chapter 2);
- Marginal cost curves for green and blue WF reduction in irrigated agriculture: guiding a cost-effective reduction of crop water consumption to a permit or benchmark level (Chapter 3);
- Grey WF reduction in irrigated crop production: effect of nitrogen application rate, nitrogen form, tillage practice and irrigation strategy (Chapter 4);
- Trade-off between blue and grey WF of crop production at different nitrogen application rates under various field management practices (Chapter 5).

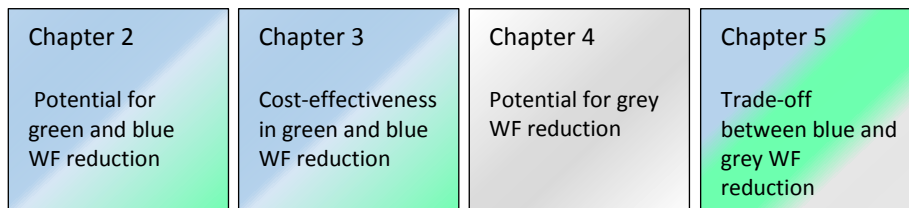


Figure 1.1 Overview of the main chapters of the thesis

Chapter 2 explores the potential for reducing the green and blue WF (consumptive WF) in irrigated crop production by applying the AquaCrop model of the Food and Agriculture Organization at field scale to simulate the effect of four irrigation techniques, four irrigation strategies and three mulching practices, for three crops in four environments, three hydrologic years, and three soil types. The chapter presents the effectiveness of different field management practices in reducing the blue WF per tonne of crop, as well as in reducing the sum of green and blue WF per tonne, compared to a reference management package.

Chapter 3 analyses the cost-effectiveness of twenty-four management packages to reduce the consumptive WF per tonne, as well as per hectare, by estimating the annualized cost and the WF reduction associated with each management package. Subsequently, marginal

cost curves (MCCs) are developed that rank management packages according to their cost-effectiveness to reduce the WF. Each management package consists of a specific combination of an irrigation technique, irrigation strategy, and mulching practice. The annualized cost of a management package includes capital, operation, and maintenance costs. We considered three crops grown in four environments, under three different hydrologic years, on three soil types. We applied the tool of the MCC in a hypothetical example that shows how one can most cost-effectively reduce the WF of a crop at field level to a certain WF permit or benchmark level.

Chapter 4 evaluates the potential grey WF reduction in irrigated crop production by applying the APEX model at field scale to simulate the effect of seven nitrogen-application rates, two forms of nitrogen (N), two tillage practices and two irrigation strategies for a period of twenty years in a semi-arid environment for irrigated maize on loam soil. The chapter presents the potential grey WF reduction by reducing the N-application rate and by changing management practices (de Fraiture and Wichelns), as well as the optimum N-application rates to minimize either grey WF per tonne or consumptive WF per tonne or to maximize crop yield.

Chapter 5 investigates the trade-off between the blue and grey WF in irrigated crop production for seven N-application rates, under eight field management packages in a semi-arid environment for irrigated maize on loam soil. The chapter identifies when changing the N-application rate or field management practice can be done at 'no regret' (reducing both blue and grey WF per tonne) and when it implies a trade-off between blue and grey WF per tonne. Additionally, it presents the N-application rates to minimize either grey or blue WF and estimates the economically optimal N-application rate when putting a price to pollution.

Chapter 6 concludes the thesis by explaining how this thesis contributes to the advancement of the field of Water Footprint Assessment, and identifying new avenues for research.



# 2 Green and blue water footprint reduction in irrigated agriculture: Effect of irrigation techniques, irrigation strategies and mulching<sup>1</sup>

## *Abstract*

Consumptive water footprint (WF) reduction in irrigated crop production is essential given the increasing competition for fresh water. This study explores the effect of three management practices on the soil water balance and plant growth, specifically on evapotranspiration (ET) and yield (Y) and thus the consumptive WF of crops (ET/Y). The management practices are: four irrigation techniques (furrow, sprinkler, drip and subsurface drip (SSD)); four irrigation strategies (full (FI), deficit (DI), supplementary (SI) and no irrigation); and three mulching practices (no mulching, organic (OML) and synthetic (SML) mulching). Various cases were considered: arid, semi-arid, sub-humid and humid environments in Israel, Spain, Italy and UK, respectively; wet, normal and dry years; three soil types (sand, sandy loam and silty clay loam); and three crops (maize, potato and tomato). The AquaCrop model and the global WF accounting standard were used to relate the management practices to effects on ET, Y and WF. For each management practice, the associated green, blue and total consumptive WF were compared to the reference case (furrow irrigation, full irrigation, no mulching). The average reduction in the consumptive WF is: 8-10% if we change from the reference to drip or SSD; 13% when changing to OML; 17-18% when moving to drip or SSD in combination with OML; and 28% for drip or SSD in combination with SML. All before-mentioned reductions increase by one or a few per cent when moving from full to deficit irrigation. Reduction in overall consumptive WF always goes together with an increasing ratio of green to blue WF. The WF of growing a crop for a particular environment is smallest under DI, followed by FI, SI and rain-fed. Growing crops with sprinkler irrigation has the largest consumptive WF, followed by furrow, drip and SSD. Furrow irrigation has a smaller consumptive WF compared with sprinkler, even though the classical measure of 'irrigation efficiency' for furrow is lower.

Key words: Water footprint, soil water balance, crop growth, AquaCrop, irrigation techniques, irrigation strategies, mulching

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<sup>1</sup> Chapter is based on: Chukalla et al. (2015).

## 2.1 Introduction

One of the important prospects to relieve increasing water scarcity is to reduce the consumptive water use in the agricultural sector, which takes the largest share in global freshwater consumption (Hoekstra and Mekonnen, 2012). In crop production substantial gains can be achieved by increasing yield and reducing water losses, with the latter referring to the non-beneficial consumptive water use at field level and the non-recoverable losses at system level (Steduto et al., 2007; Hoekstra, 2013; Perry et al., 2009; Falkenmark and Rockström, 2006). At field level, the focus is to decrease the field evapotranspiration (ET) over the growing period per unit of yield (Y), a ratio that is called the consumptive water footprint (WF) (Hoekstra et al., 2011). Decreasing this ratio  $ET/Y$  is the same as increasing the inverse ( $Y/ET$ ), which is called the water productivity (WP) (Amarasinghe and Smakhtin, 2014; Molden et al., 2010).

The soil moisture status in the root zone regulates plant growth and influences ET. Management practices that influence soil moisture include irrigation techniques, irrigation strategies and mulching practices. The particular irrigation technique influences the way irrigation water is applied, which influences for instance the percentage of surface-wetting, which again influences ET (Raes et al., 2013). The particular irrigation strategy applied determines how much and when irrigation is applied. The mulching practice determines soil cover and in this way influences non-productive evaporation.

Various previous studies considered the effects of management practices on the amount of irrigation water to be applied, drainage, ET and yield (Gleick, 2003; Perry et al., 2009; Perry, 2007). Most studies varied only irrigation technique, only irrigation strategy or only mulching practice, or considered only a few combinations. Besides, most studies are confined to just one crop and one specific production environment (soil, climate). For example, Rashidi and Keshavarzpour (2011) show the effects of three management practices for one specific crop in Iran, showing yields to increase from surface irrigation to drip irrigation and finally to drip irrigation with mulching. Al-Said et al. (2012) show the effect of drip versus sprinkler irrigation on vegetables yield in Oman, showing that the yield per unit of irrigation water applied is higher for drip irrigation. The effect of irrigation strategies such as deficit or supplementary irrigation on ET and Y were studied by different scholars (Igbadun et al., 2012; Qiu and Meng, 2013; Jiru and Van Ranst, 2010; Bakhsh et al., 2012; Jinxia et al., 2012). In a literature review, Geerts and Raes (2009) point out that deficit irrigation strategy decreases the consumptive water use per unit of yield compared to full irrigation. Supplementary irrigation is a strategy to apply some irrigation water when most needed, to overcome drought periods; this increases yield compare to rain-fed conditions without much increase in ET (Oweis and Hachum, 2006; Oweis et al., 1999; Tadayon et al., 2012). Mulching is a method of covering the soil surface that otherwise loses moisture through evaporation. Various studies show the importance of mulching to decrease ET per unit yield in crop production (Ogban et al., 2008; Zhao et al., 2003; Zhou et al., 2011; Mao et al., 2012; Jalota and Prihar, 1998).

Previous studies can be distinguished into two categories: they either focus on the relation between  $Y$  and blue water applied (irrigation water applied) or on the relation between  $Y$  and total transpiration ( $T$ ) or total ET. The former category of studies has two caveats: they ignore green water use and, by focusing on irrigation water application, they ignore the fact that, through return flow (drainage and surface runoff) some of the blue water applied will return to the water system from which it was withdrawn. The caveat of the latter category of studies is that, by considering total  $T$  or ET, they do not explicitly distinguish between  $T$  or ET from rainwater (green  $T$  or ET) and  $T$  or ET from irrigation water (blue  $T$  or ET). Understanding water resource use in crop production by source (rainwater, irrigation water from surface and groundwater, water from capillary rise) is vital for water resources management. In this regard, the concepts of green versus blue water by Falkenmark and Rockström (2006) and green versus blue water footprint by Hoekstra et al. (2011) is a useful advance.

The objective of this study is to explore the potential of reducing the green and blue water footprint of growing crops by using a systematic model-based assessment of management practices in different environments. We systematically consider the effect of a large number of management practices, considering four irrigation techniques, four irrigation strategies and three mulching practices. We do so in a large number of different cases: arid, semi-arid, sub-humid and humid environments; wet, normal and dry years; three soil types; and three crops. This is the first systematic model study analysing the effect of field management practices on green and blue ET,  $Y$  and green and blue WF under a variety of conditions. The advantage of a model study is that field experiments on the effects of a comprehensive list of management practices in range of cases would be laborious and expensive (Geerts and Raes, 2009). Our cases, however, are based on four real environments, in Israel, Spain, Italy and the UK.

## **2.2 Method and data**

### **2.2.1 Soil water balance and crop growth modelling**

To balance simplicity, accuracy and robustness of simulating soil water balance, crop growth and yield process, we use the AquaCrop model (version 4.1) (Steduto et al., 2009a). AquaCrop is available as standalone Windows-based software and as plug-in to GIS software; both run with daily time steps using either calendar or thermal time (Raes et al., 2011). In this study, the Plug-in version was applied with daily thermal time.

AquaCrop keeps track of the soil water balance over time by simulating the incoming and outgoing water fluxes with well-described subroutines. The AquaCrop model enables to simulate various degrees of water supply to the plant, varying from rain-fed and supplementary irrigation to deficit and full irrigation. AquaCrop considers capillary rise to the root zone from shallow groundwater. It estimates capillary rise based on the depth of the water table and two parameters that are specific to hydraulic and textural characteristics of the soil (Raes et al., 2012). The two parameters are estimated for different textural classes of the soil that have similar water retention curve. The capillary rise from

AquaCrop is comparable with the estimate from the UPFLOW model, using the Darcy equation and relating matric potential to hydraulic conductivity (Feres et al., 2012). Water limitations to plant growth are modelled through three sorts of water-stress response: canopy expansion rate, stomatal closure and senescence acceleration (Steduto et al., 2009b).

The crop growth engine of AquaCrop first estimates the biomass (B) from a water productivity parameter (WP) and transpiration (T):  $B = WP \times \Sigma T$ . The harvestable portion of the biomass (yield Y) is then determined by multiplying biomass with a crop-specific harvest index (HI):  $Y = B \times HI$ . WP is the water productivity parameter in kg (biomass) per m<sup>2</sup> (land area) per mm (water transpired), normalized for atmospheric evaporative demand and atmospheric CO<sub>2</sub> concentration (Steduto et al., 2009a). The modelling of biomass water productivity (WP), which remains constant for a given crop species after normalization, forms the core of the AquaCrop growth engine (Steduto et al., 2007; Raes et al., 2009).

AquaCrop separates the actual evapotranspiration (ET) into non-productive and productive water fluxes, viz. soil evaporation (E) and crop transpiration (T). Hence, AquaCrop can simulate the effect of the management practices on these two types of consumptive water use distinctively.

AquaCrop calculates soil evaporation (E) by multiplying evaporative power of the atmosphere (ET<sub>o</sub>) with factors that consider the effect of water stress, and the fraction of the soil surface not covered by canopy. Crop canopy expands from the initial canopy cover, which is the product of plant density and the size of the canopy cover per seedling. The canopy is considered in the evaporation calculation after adjustment for micro-advective effects. The soil moisture conditions determine evaporation from the soil surface not covered by canopy in two stages. In the first stage, when the soil surface is wetted by rainfall or irrigation, the evaporation rate is fully determined by the energy available for soil evaporation until the Readily Evaporable Water. In the second stage, the falling rate stage, the evaporation is not only determined by the available energy but depends also on the hydraulic properties of the soil. The two-stages approach for calculating evaporation is described in detail and validated in Ritchie (1972), who confirmed the ability of the method to predict evaporation for a wide variety of soil types and climatic conditions.

The soil evaporation is adjusted for withered canopy, mulches and partial wetting by irrigation. The AquaCrop model simulates the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. Soil evaporation under mulching practice is simulated by correcting E with a factor that is described by two variables (Raes et al., 2013): soil surface covered by mulch (from 0 to 100%); and mulch material (f<sub>m</sub>). Quoting the paper by Allen et al. (1998), the values of the parameters for mulch material (f<sub>m</sub>) are suggested to vary between 0.5 for mulches of plant material and close to 1.0 for plastic mulches (Raes et al., 2013). The correction factor for mulching is calculated as:

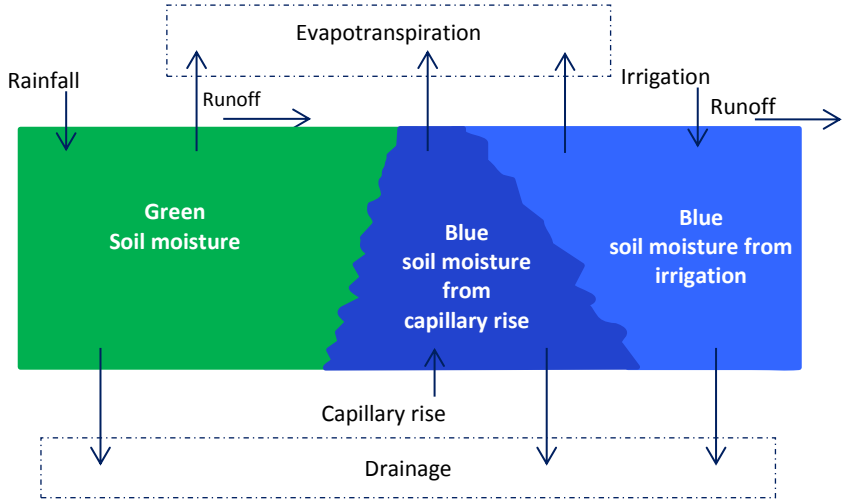
$$\text{Correction factor for mulching} = \left(1 - f_m \frac{\text{percent covered by mulch}}{100}\right) \quad (2.1)$$

Soil evaporation is also corrected with a factor that is equivalent to the fraction of the surface wetted by irrigation. The adjustment for partial wetting is not applied when the soil surface is wetted by rain. If the soil surface is covered by mulches and at the same time partially wetted by irrigation, only one of the correction factors, the minimum value of the two, is applied.

Experimental field studies confirm the ability of the AquaCrop model to reasonably simulate evaporation and transpiration for various conditions. Research on potato for three levels of irrigation (100%, 75% and 50% of plant water requirement) at experimental fields in eastern Iran shows that AquaCrop has good ability in simulating evaporation and transpiration of crops and yield (Afshar and Neshat, 2013). Another study found that AquaCrop is able to simulate ET and yield of maize under different irrigation regimes (full and deficit) and mulching practices (plastic and organic mulching) in the North Delta of Egypt (Saad et al., 2014).

### 2.2.2 The green and blue water footprint of growing crops

The green WF ( $\text{m}^3 \text{t}^{-1}$ ) and blue WF ( $\text{m}^3 \text{t}^{-1}$ ) of crops were obtained following the definitions and methodological framework of the global WF accounting standard (Hoekstra et al., 2011). They are calculated by dividing the green ET ( $\text{m}^3 \text{ha}^{-1}$ ) and blue ET ( $\text{m}^3 \text{ha}^{-1}$ ) over the growing season by the marketable crop yield (t). AquaCrop simulates yield in  $\text{kg ha}^{-1}$  of dry matter. Unlike maize, the marketable yield for tomato and potato are in their fresh form. We calculated the marketable yield of tomato and potato by assuming the dry matter of tomato and potato to be 7% and 25% respectively (Steduto et al., 2012). The AquaCrop output was post-processed to partition soil water content and the various ingoing and outgoing water fluxes into green and blue components. In addition, the blue soil water content and the blue water fluxes were further separated into blue water originating from irrigation water ( $S_{b-I}$ ) and blue water originating from capillary rise ( $S_{b-CR}$ ). This partitioning enables to track what fractions of ET originate from rainwater, irrigation water and capillary rise, respectively (Figure 2.1).



**Figure 2.1** Incoming and outgoing water fluxes of the green ( $S_g$ ) and blue ( $S_b = S_{b-I} + S_{b-CR}$ ) soil water stocks.

In the daily green-blue soil water balance calculation, the next procedures are followed: rainfall ( $R$ ) adds to the green soil water stock; irrigation ( $I$ ) adds to the blue soil water stock originating from irrigation; capillary rise ( $CR$ ) adds to the blue soil water stock originating from capillary rise; evaporation ( $E$ ), transpiration ( $T$ ) and drainage ( $Dr$ ) in a certain day are partitioned into the three 'colours' (green, blue from irrigation, blue from capillary rise) based on the relative colour composition of soil water content in that day; runoff ( $RO$ ) in a particular day is partitioned into two colours (green and blue from irrigation) in proportion to the amount of rainfall and irrigation, respectively. Changes in the green ( $S_g$ ), blue from irrigation ( $S_{b-I}$ ) and blue from capillary rise ( $S_{b-CR}$ ) soil water stocks are described in the following three equations:

$$\frac{dS_g}{dt} = R - (Dr + ET) \left( \frac{S_g}{S} \right) - RO \left( \frac{R}{I+R} \right) \quad (2.2)$$

$$\frac{dS_{b-CR}}{dt} = CR - (Dr + ET) \left( \frac{S_{b-CR}}{S} \right) \quad (2.3)$$

$$\frac{dS_{b-I}}{dt} = I - (Dr + ET) \left( \frac{S_{b-I}}{S} \right) - RO \left( \frac{I}{I+R} \right) \quad (2.4)$$

where  $dt$  is the time step of the calculation (1 day),  $R$  rainfall [mm],  $I$  irrigation [mm],  $RO$  surface runoff [mm],  $ET$  ( $E+T$ ) evapotranspiration [mm],  $Dr$  drainage (percolation) [mm], and  $CR$  capillary rise [mm].

The simulations with AquaCrop were initialized with typical soil moisture content. This was determined by running the model for each case for a successive period of twenty years (1993 to 2012) and taking the average soil moisture content at the start of the growing period over the full period as the initial condition for another run for the same period of twenty years. We did this iteratively, until the twenty-year average output stabilized. We thus used the twenty-year average soil moisture content at the start of the growing season

as initial condition for our simulations. The partitioning of the soil moisture content into green and blue water components was initialized based on a similar procedure. The green and blue water footprints were finally calculated by dividing the green and blue ET over the growing period by the yield.

In the Appendix 2A we provide an illustration of the simulation of green and blue soil moisture content over time for a specific case.

### 2.2.3 Experimental setup

A comprehensive set of simulations was carried out, applying different management practices in an extensive number of cases (Table 2.1).

**Table 2.1** Research model: management practices considered in a number of cases to simulate the effect on ET, Y, and consumptive WF.

Management practices	Modelling	Effects
Four irrigation techniques: furrow, sprinkler, drip and subsurface drip.	Soil water balance and crop growth model (AquaCrop)	- ET - Yield
Three irrigation strategies: full, deficit and supplementary irrigation; + rain-fed.	Global WF	- Consumptive WF
Three mulching practices: no mulching, organic and synthetic mulching.	accounting standard	

Cases: Four environments (arid, semi-arid, sub-humid and humid), three crops (maize, potato and tomato), three soils (loam, sandy loam and silty clay loam), three types of years (wet, normal and dry).

### Management practices

#### *Irrigation techniques*

Irrigation techniques can be classified based on various themes: energy or pressure required, how or where the irrigation water is applied and wetted area by irrigation (Ali, 2011). Based on the wetted surface area, irrigation techniques can be listed as flood irrigation, trickle or localised irrigation and sprinkler irrigation. The first of these, flood irrigation comprises furrow, border and basin irrigation. The second, trickle irrigation comprises drip and subsurface drip. Given the existing irrigation practices in the four environments that we consider, we analyse four irrigation techniques: furrow (with 80% surface wetting), sprinkler (100% surface wetting), drip (30% wetting) and subsurface drip (0% wetting). Generic assumptions have been made on the specific details of the different irrigation techniques, following default settings in the model. For furrow irrigation, an 80% wetting percentage is assumed to be representative for every furrow (narrow bed) from the indicative range of 60% to 100% in the AquaCrop manual (Raes et al., 2013). Alternative field management choices would connect to other (lower) wetting percentages: alternated furrow (30% to 50%) and every furrow for wide beds (40% to 60%).

### *Irrigation strategies*

Irrigation strategy concerns the timing and volume of artificial soil water replenishment. Four irrigation strategies were considered: full irrigation, deficit irrigation, supplementary irrigation and no irrigation (rain-fed). Irrigation scheduling, when and how much to irrigate, is central to defining these irrigation strategies. Full irrigation is an irrigation strategy in which the full evaporative demand is met; this strategy aims at maximizing yield. It was simulated through automatic generation of irrigation requirement for no water stress condition. AquaCrop simulates water stress response for three thresholds of soil moisture depletion (Steduto et al., 2009b), relating to affected canopy expansion, stomatal closure and senescence acceleration. The depletion level for minimum stress (effect on canopy expansion) in AquaCrop starts far before the soil moisture depletion reaches 100% of the readily available water (RAW). The irrigation scheduling in the no water stress condition is crop dependent. The soil moisture was refilled to the field capacity (FC) when 20%, 36% and 30% of RAW of the soil is depleted for maize, potato and tomato respectively (FAO, 2012). This scheduling results in a high irrigation frequency, which is impractical in the case of furrow and sprinkler irrigation. To circumvent such unrealistic simulation for the case of furrow and sprinkler irrigation, we firstly generated the irrigation requirement automatically for no water stress condition, which obviously results in high irrigation frequency especially for coarse texture soil type. Then the irrigation depths were aggregated and shifted a few days forward, practically allowing more depletion than the no water stress level, in such a way that a time gap of a week is maintained between two irrigation events.

Deficit irrigation (DI) is the application of water below the evapotranspiration requirements (Feres and Soriano, 2007) by limiting water applications particularly during less drought-sensitive growth stages (English, 1990). The deficit strategy is established by reducing the irrigation supply from the full irrigation requirement. We extensively tested various deficit irrigation strategies that fall under two broad categories: (1) regulated deficit irrigation, where a non-uniform water deficit level is applied during the different phenological stages; and (2) sustained deficit irrigation, where water deficit is uniformly distributed over the whole crop cycle. In general, the larger the deficit the smaller the simulated yield, as expected. The non-linear relation between yield and ET (and thus irrigation supply) gives rise to the existence of an optimum, i.e. the deficit irrigation strategy with the lowest consumptive WF in  $\text{m}^3 \text{t}^{-1}$ . In the analysis of simulations, the paper used the specific deficit strategy that is optimal according to the model experiments.

Supplementary irrigation (SI) is defined as the application of a limited amount of water to increase and stabilize crop yields when rainfall fails to provide sufficient water for plant growth (Oweis et al., 1999). Supplementary irrigation was simulated to be a one-time event of refilling the root zone to field capacity when 100% of the RAW was depleted or when the threshold for stomata closure was triggered.



### *Mulching practices*

Mulching has various purposes: reduce soil evaporation, control weed incidence and its associated water transpiration, reduce soil compaction, enhance nutrient management and incorporate additional nutrients (McCraw and Motes, 1991; Shaxson and Barber, 2003). The mulching practice in AquaCrop considers mainly evaporation reduction from the soil surface. Three mulching practices were distinguished: no mulching, organic mulching with  $f_m=0.5$  and synthetic mulching with  $f_m=1$ . A mulch cover of 100% for organic and 80% for synthetic materials was assumed.

### **Cases**

We carry out the model experiments for four different locations: Israel (Bakhsh et al.), Spain (semi-arid), Italy (sub-humid) and the UK (humid). Per location we consider wet, normal and dry years, three soil types (loam, sandy loam, silty clay loam), and three crops (maize, potato and tomato). This yields a number of cases as summarized in Table 2.2.

**Table 2.2** Research cases.

Environment (location)	Soils	Type of year	Crops	Groundwater <sup>a</sup>
Arid (Eilat, Israel)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		
Semi-arid (Badajoz, Spain)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		
Sub-humid (Bologna, Italy)	Loam	Dry	Maize, potato and tomato	Average 1.5 m
	Sandy loam	Normal		
	Silty clay loam	Wet		
Humid (Eden, UK)	Loam	Dry	Maize, potato and tomato	Deep
	Sandy loam	Normal		
	Silty clay loam	Wet		

<sup>a</sup> A deep groundwater table means that capillary rise does not contribute moisture to the root zone.

### **2.2.4 Data**

The input data to run the AquaCrop were collected for four sites: Eilat in Israel (29.33 °N, 34.57 °E; 12m above mean sea level), Badajoz in Spain (38.88 °N, -6.83 °E; 185m amsl), Bologna in Italy (44.57 °N, 11.53 °E; 19m amsl) and Eden in the UK (52.26° N, 0.64°E; 69m amsl).

The daily rainfall, minimum and maximum temperatures, reference evapotranspiration ( $ET_0$ ) and the mean annual atmospheric carbon dioxide concentration are the input climatic data to run AquaCrop. Daily observed rainfall and temperature data (for the period 1993-

2012) were extracted from the European Climate Assessment and Dataset (ECAD) (Klein Tank et al., 2002). The ECAD data undergo homogeneity testing and the missing data is filled with observations from nearby stations (i.e. within 12.5 km and with height differences less than 25m) (Klein Tank, 2007). Daily  $ET_o$  was derived with the FAO  $ET_o$  calculator (Raes, 2012), which uses the FAO Penman-Monteith equation. The evapotranspiration and precipitation of the research sites are summarized in Table 2.3.

**Table 2.3** Evapotranspiration and precipitation in the four environments.

Environments	$ET_o$	Precipitation	Precipitation			Actual E and $ET^a$				
			20-year average (mm year <sup>-1</sup> )	Wet (mm per growing season)	Normal (mm per growing season)	Dry (mm per growing season)	Rain-fed		Irrigated <sup>b</sup>	
							E	ET	E	ET
Arid	2476	16	60	11.3	2.4	16	16	85	322	
Semi-arid	1308	449	129	76	62	49	171	108	393	
Sub-humid <sup>c</sup>	977	585	359	170	147	87	314	85	312	
Humid	688	722	834	665	657	79	282	128	390	

<sup>a</sup> E is evaporation in a normal year; ET is actual evapotranspiration.

<sup>b</sup> Under conditions of full irrigation, furrow irrigation, potato, loam soil and no mulching practice.

<sup>c</sup> The groundwater table in the selected sub-humid environment is shallow, at 1.5m, which implies that capillary rise feeds moisture to the root zone.

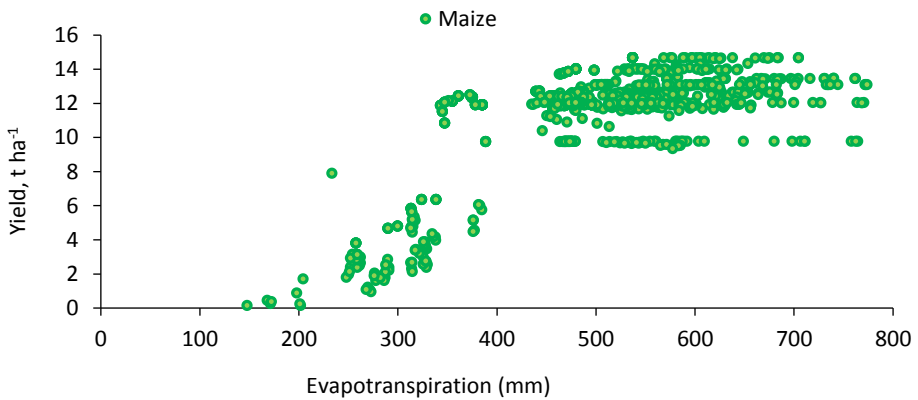
Data on soil texture were extracted from the 1×1km<sup>2</sup> resolution European Soil Database (Hannam et al., 2009). The type of soils were identified using the Soil Texture Triangle Hydraulic Properties Calculator from (Saxton et al., 1986). The physical characteristics of the soils were adopted from AquaCrop, which includes a soil characteristics database of FAO. Observed soil data at one of the sites representing the humid environment (at Bologna, Italy) was shown to be comparable to the soil type and characteristics from the FAO and European Soil Database. Soil fertility stress was assumed to not occur. Regarding crop parameters, we take the default values as represented in AquaCrop, except for the maximum rooting depth for maize in Italy, which was limited to 0.7 m to account for the actual local conditions. Moisture supply from capillary rise to the root zone was considered only for Bologna, because the local groundwater table at the Bologna site is shallow (average 1.5 m). Chemical applications, such as fertilisers and pesticides, were assumed optimal.

## 2.3 Results

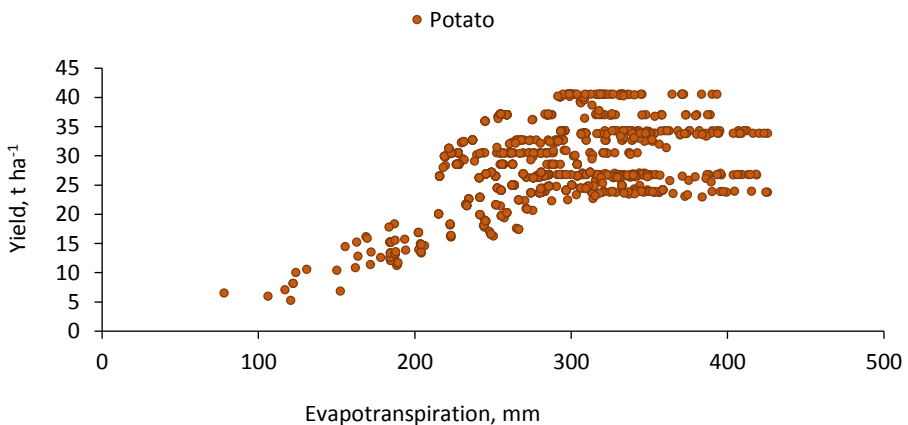
### 2.3.1 Overview of experimental results

The outcomes for ET (mm), Y (t ha<sup>-1</sup>) and consumptive WF (m<sup>3</sup> t<sup>-1</sup>) in the full set of model experiments are plotted in scatter diagrams in Figures 2.2a, 2.2b, 2.2c and 2.3. The ET-Y plot in Figures 2.2a, 2.2b and 2.2c show an increase in yield with increasing ET for all three crops,

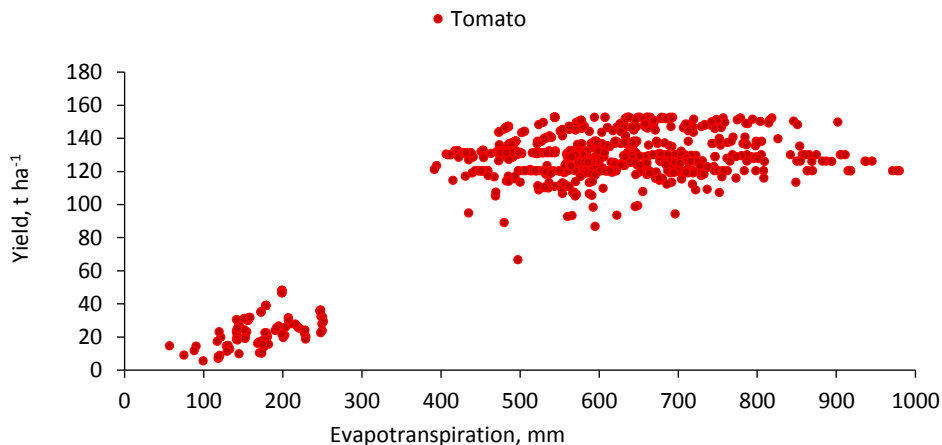
though there is no increase in Y anymore at larger ET values. The yields for ET less than 200 mm in Figures 2a, 2b and 2c are under rain-fed conditions (in semi-arid environment) and high deficit irrigation (with drip/subsurface drip techniques), with synthetic mulching practice. In such conditions, the evaporation is almost zero and transpiration takes the lion share of ET. The corresponding yield is very small, less than one third of the maximum. Fig. 2.3 illustrates the ET-WF relationship: small ET is associated with the large WFs due to the low yields resulting from water stress. Smallest WFs can be found at intermediate ET values, where yield still is not optimal, but additional ET goes along with decreasing productivity.



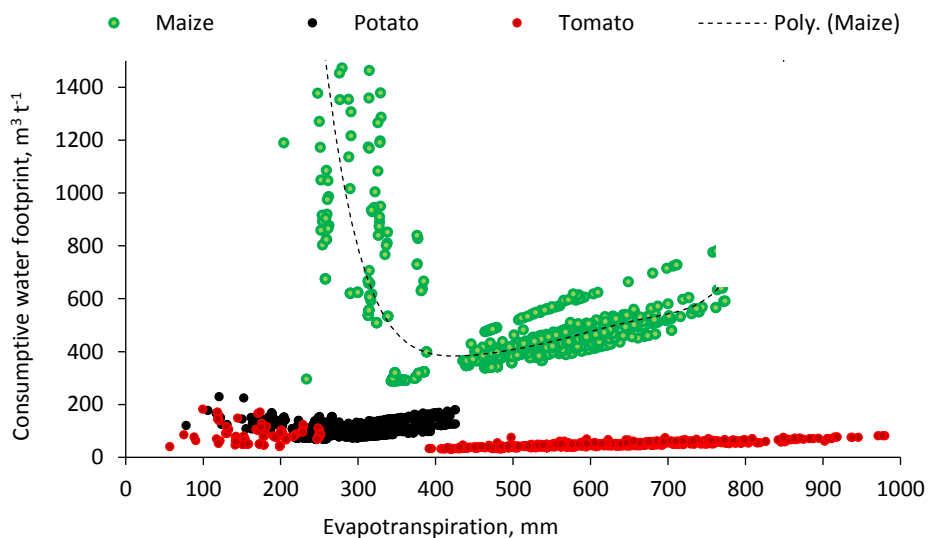
**Figure 2.2a** The resultant ET and Y of maize for all experiments: different management practices for all cases.



**Figure 2.2b** The resultant ET and Y of potato for all experiments: different management practices for all cases.



**Figure 2.2c** The resultant ET and Y of tomato for all experiments: different management practices for all cases.

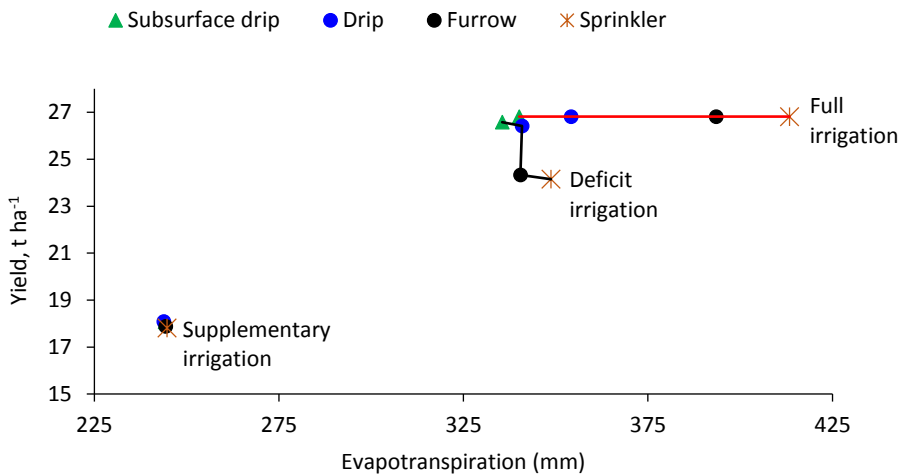


**Figure 2.3** The resultant ET and consumptive WF for all experiments: different management practices for all cases. The dotted line is a polynomial fit to data points for maize.

### 2.3.2 Effect of the management practice on ET, Y and consumptive WF

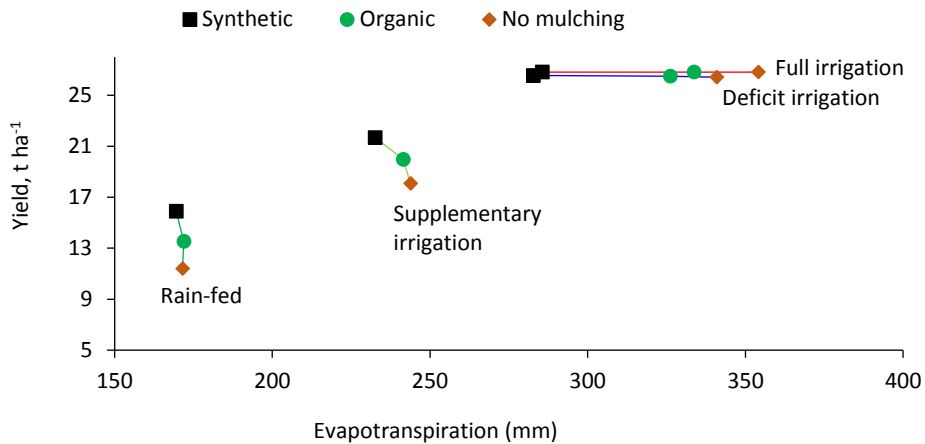
Figure 2.4 illustrates the effect of the four irrigation techniques on ET and Y under full, deficit and supplementary irrigation conditions for the case of potato production on loam soil in a normal year in Spain. We see that under full irrigation, moving from sprinkler to

furrow and then to drip and subsurface drip irrigation will stepwise reduce ET in quite a substantial way, while yield remain at the same high level. The reduction in ET fully refers to a reduction in the unproductive E; the productive T remains constant. Under deficit irrigation, moving from sprinkler through furrow and drip to subsurface drip irrigation, ET will slightly decrease, while Y increases. The Y can increase because it is the non-productive soil evaporation component in ET that decreases, while the productive transpiration component increases. Under supplementary irrigation, the irrigation technique applied affects neither ET nor Y, because irrigation is applied only during a short period of time (the drought period), which hardly affects ET over the growing period as a whole.



**Figure 2.4** ET–Y plot for four irrigation techniques, three strategies and no mulching practice for the case of potato on a loam soil, a normal year in a semi-arid environment (Badajoz, Spain). The lines connect cases with one particular irrigation strategy: red and black for the full and deficit irrigation strategies, respectively.

The effect of mulching on ET and Y is illustrated in Figure 2.5, for the same case of potato production on loam soil in a normal year in Spain. Under full irrigation, moving from no mulching through organic to synthetic mulching will reduce ET (through reduced soil evaporation) with Y remaining constant. Under deficit irrigation, we observe the same trend. Under supplementary irrigation, moving from no mulching through organic to synthetic mulching, ET will slightly decrease, while Y increases. The Y increases because it is the non-productive E that decreases, while the productive T increases. Under rain-fed conditions, organic and synthetic mulching do not affect total ET much, but E decreases while T increases, which leads to an increase in Y.



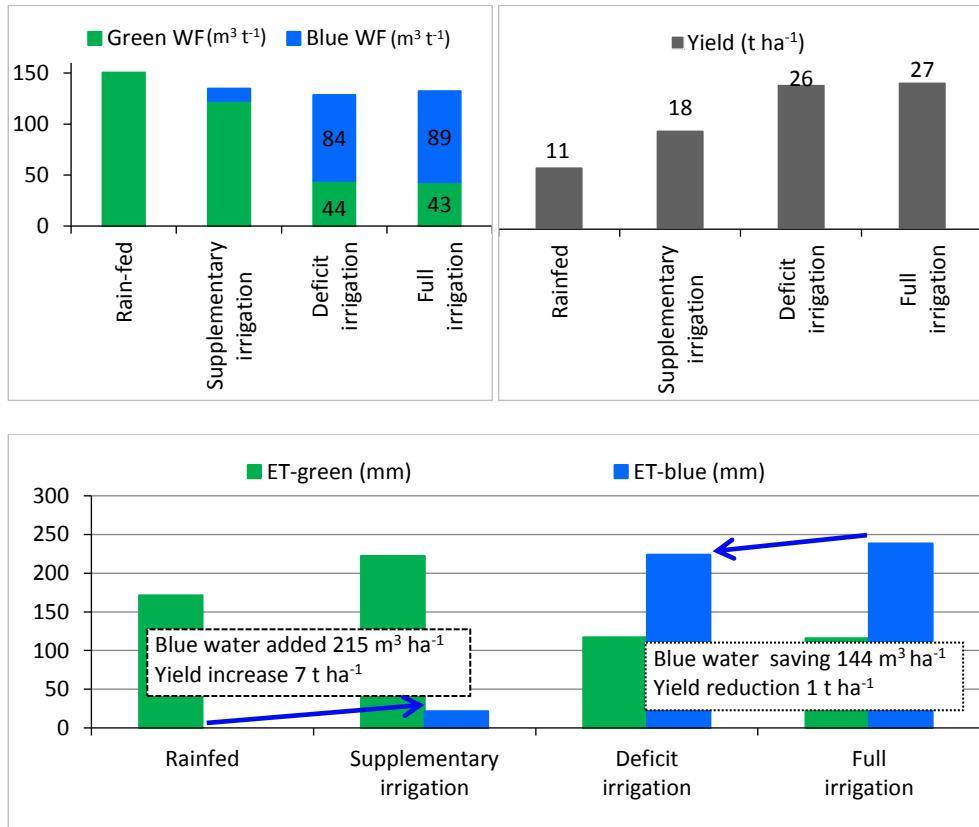
**Figure 2.5** ET-Y plot for mulching practices at rain-fed and drip irrigated fields for the case of potato on a loam soil for a normal year in a semi-arid environment (Badajoz, Spain). The lines connect cases with one particular irrigation strategy: red, blue, light green and green denote full irrigation, deficit irrigation, supplementary irrigation and rain-fed production, respectively.

The effect of different irrigation strategies on ET, Y and consumptive WF is illustrated in Figure 2.6 for the case of potato growth under drip irrigation on a loam soil for a normal year in Spain. Table 2.4 shows the amount of rainfall and irrigation supply during the growing period of potato for the same case. There is an increase in both ET and Y when we shift from rain-fed to supplementary irrigation and further on to deficit and full irrigation. The consumptive WF is smallest with deficit irrigation, followed by full irrigation, supplementary irrigation and finally rain-fed. The change from rain-fed to supplementary irrigation takes a modest amount of irrigation water, 80 mm. The supplementary irrigation allowed an additional ET of 51 mm of green water plus 21 mm of blue water, making a significant impact on crop growth, thus making a small blue WF, but the resultant yield increase leads to a decrease of the overall (green plus blue) WF.

The deficit irrigation supply was 281 mm (80 mm reduction as compared to full irrigation). The change from full irrigation to deficit irrigation slightly reduces yield (by 1.5%), but reduces blue ET (by 14 mm or 6%), with a slight decrease of the consumptive WF as a result (by 2%). The significant reduction in total irrigation depth in the case of the deficit irrigation thus resulted in only minor yield losses. In the case of full irrigation, blue ET and total ET is larger, but green ET is slightly smaller than in the case of deficit irrigation. This results from the fact that irrigation water saturates the soil, causing a larger fraction of rainwater to run off. Deficit irrigation thus makes more effective use of rainwater.

**Table 2.4** The irrigation supply and ET values for supplementary, deficit and full irrigation plus rain-fed of the potato production.

	Rain (mm)	Irrigation supply (mm)	ET-green (mm)	ET-blue (mm)
Rain-fed	63	0	171	0
Supplementary irrigation	63	80	222	21
Deficit irrigation	63	281	117	224
Full irrigation	63	361	115	238



**Figure 2.6** ET, Y and WF under different irrigation strategies for the case of potato production under drip irrigation on loam soil in a normal year in a semi-arid environment (Badajoz, Spain).

### 2.3.3 Relative changes in green and blue WF compared to the reference case

We compared the effects of all different management practices on the green and blue WF against the reference case of furrow and full irrigation and no mulching practice. We present the results in six groups, whereby each group has a specific irrigation strategy and mulching

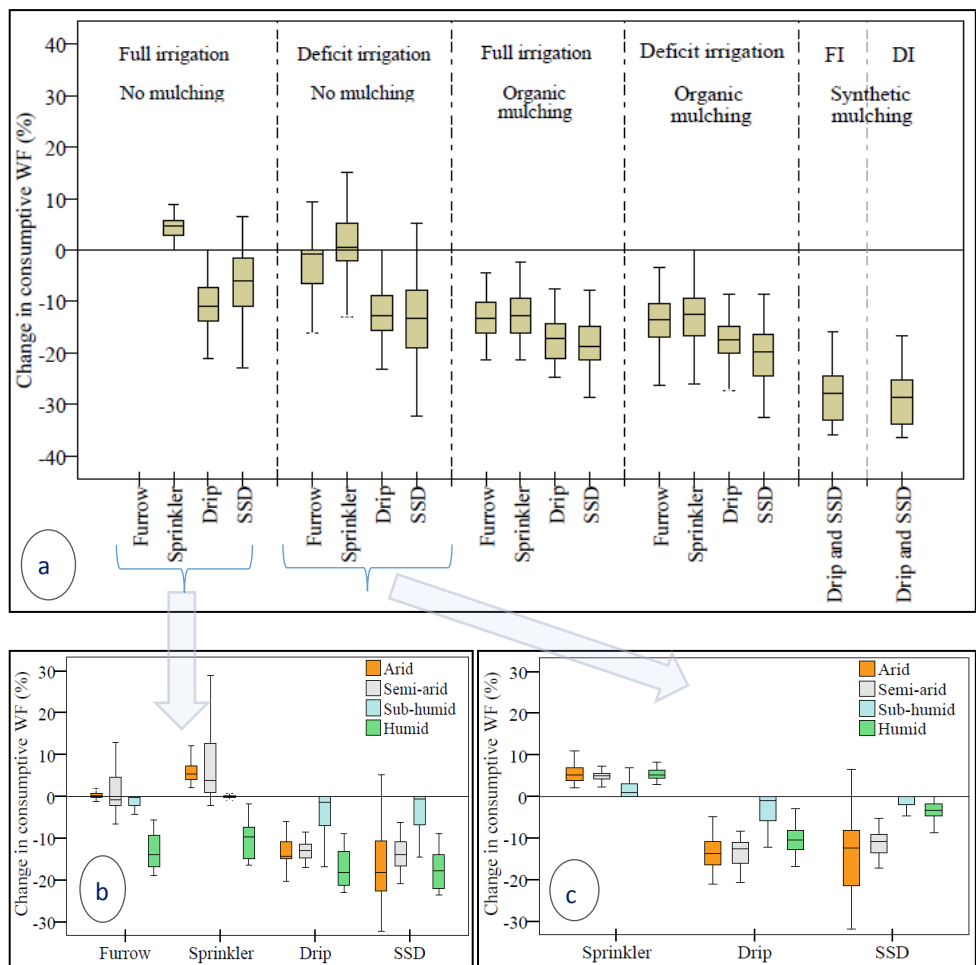
practice, with the irrigation technique as a variable. We consider the following six combinations of irrigation strategy and mulching practice:

- Full irrigation (FI), no mulching practice (NoML);
- Deficit irrigation (DI), no mulching practice (NoML);
- Full irrigation (FI), organic mulching (OML);
- Deficit irrigation (DI), organic mulching (OML);
- Full irrigation (FI), synthetic mulching (SML); and
- Deficit irrigation, (DI), synthetic mulching (SML).

The change in total consumptive WF from the reference for all management practices is shown in Figure 2.7. Given a particular mulching practice, the largest WF is found for sprinkler, followed by furrow, drip and subsurface drip irrigation. Only for the case of full irrigation and no mulching, drip irrigation results in a smaller WF than for subsurface drip irrigation. The effect of drip and subsurface drip irrigation on consumptive WF depends on two variables limiting soil evaporation: energy and soil moisture. Under full irrigation, as can be seen in Figure 2.7b, drip irrigation reduces the consumptive WF more than subsurface drip irrigation, with the largest difference in the humid environment. The reason is that energy is here the limiting factor to evaporation. Under deficit irrigation, as can be seen in Figure 2.7c, subsurface drip irrigation reduces the consumptive WF more than drip irrigation, with the largest difference in the arid environment. This is explained by the fact that now moisture is the limiting factor to evaporation.

Compared to the reference case of no mulching, organic mulching substantially reduces the consumptive WF, and synthetic mulching even further. In the case of full irrigation, organic mulching results, on average, in an additional consumptive WF reduction compared to no mulching of 17% with sprinkler, 13% with furrow, 7% with drip and 11% with subsurface drip irrigation. In the case of deficit irrigation, these additional reductions are slightly lower: 14% with sprinkler, 11% with furrow, 6% with drip and 7% with subsurface drip irrigation. Considering drip and subsurface drip irrigation, synthetic mulching results, on average, in an additional consumptive WF reduction of 10% compared to organic mulching.

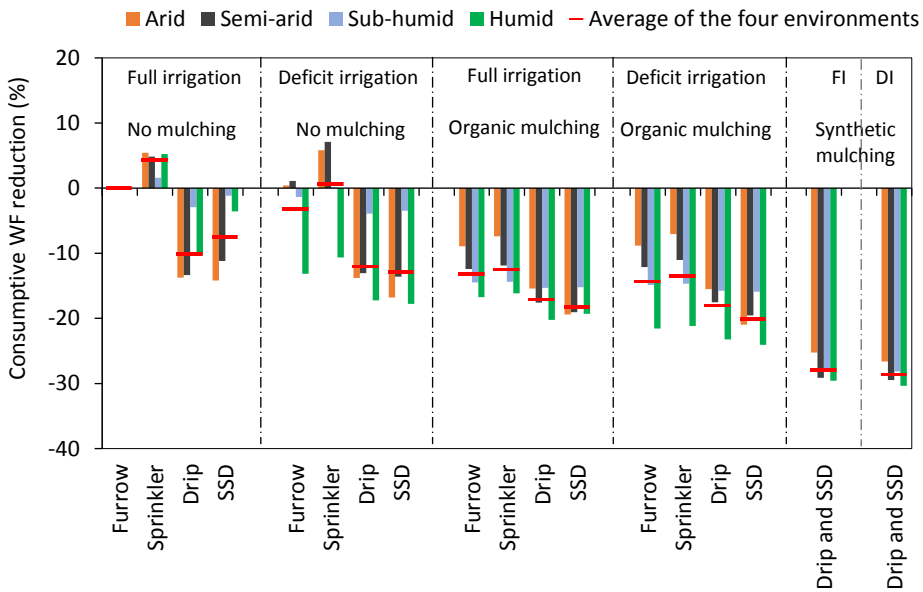




**Figure 2.7** Change in consumptive WF from the reference for all management practices. The range for each management practice represents the variation of changes found for the various cases. The upper and lower ends of the whiskers are the largest and smallest changes found. 50% of the cases fall within the range represented by the upper and lower value of the box. The line within the box represents the change in the median case. Figure (a) gives an overview for all management practices; Figures (b) and (c) zoom in for the practices of full and deficit irrigation, respectively, without mulching, showing specific WF changes per type of environment. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

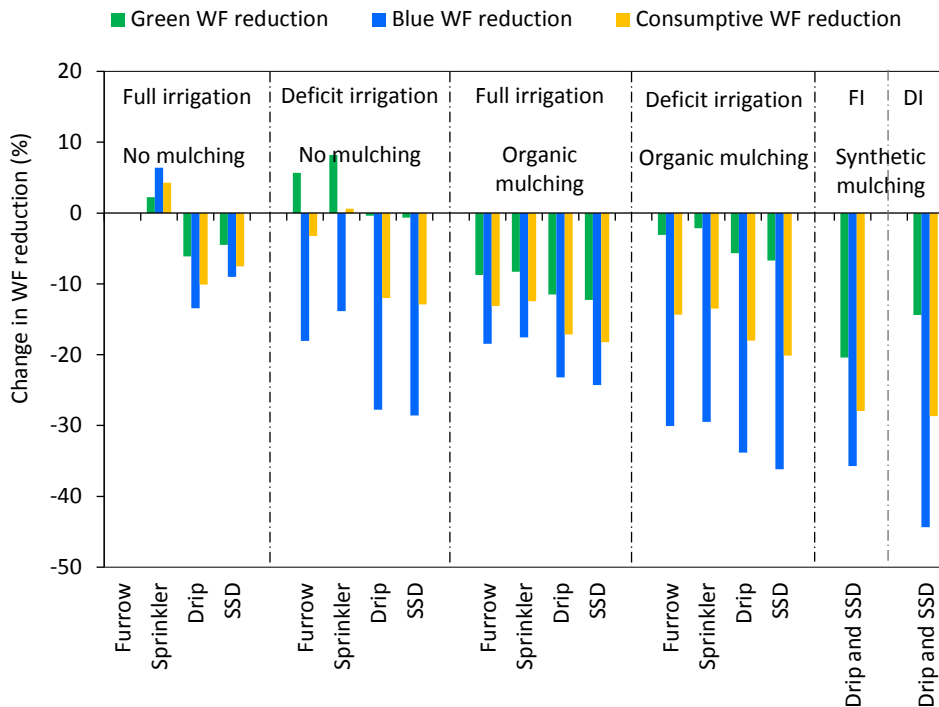
Figure 2.8 shows the average changes in consumptive WF for management practices, specified per type of environment. The average reduction in the consumptive WF is: 8-10% if we change from the reference to drip or subsurface drip irrigation; 13% when changing from the reference to drip or subsurface drip to organic mulching; 17-18% when moving to drip or subsurface drip

irrigation in combination with organic mulching; and 28% when shifting to drip or subsurface drip irrigation with synthetic mulching. All before-mentioned reductions increase by one or a few per cent when moving from full to deficit irrigation. In our case of the sub-humid environment, with the selected location in Italy having shallow groundwater, we find relatively small WF reductions when we have no mulching, because capillary rise keeps feeding the soil moisture content, resulting in continued soil evaporation.



**Figure 2.8** Average change in consumptive WF from the reference for all management practices, specified for the four types of environment. The horizontal red lines represent averages for the four environments. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

The average change in green, blue and total consumptive WF from the reference for all management practices is presented in Figure 2.9. Relative changes in blue WF are always larger than relative changes in the total consumptive WF, while the relative changes in green WF are always smaller. In other words, when management practices reduce the total consumptive WF they do so particularly by reducing the blue WF and to a lesser extent by reducing the green WF. The latter even increases in the practice that combines sprinkler irrigation without mulching. In all cases, overall consumptive WF reduction goes together with an increasing green/blue ratio for the WF of a crop. Given a certain irrigation technique and mulching practice, deficit irrigation will always reduce the blue WF of the crop, when compared to the practice of full irrigation.



**Figure 2.9** Average change in green, blue and total consumptive WF from the reference for all management practices. SSD stands for subsurface drip, FI for full irrigation, DI for deficit irrigation, NoML for mulching practice, OML for organic mulching and SML for synthetic mulching.

## 2.4 Discussion

An interesting result from this study is that sprinkler irrigation does have a larger consumptive WF in  $\text{m}^3 \text{t}^{-1}$  (i.e., smaller water productivity in  $\text{t} \text{m}^{-3}$ ) than furrow irrigation, while sprinkler irrigation is known to have larger so-called irrigation efficiency compared to furrow irrigation (Brouwer et al., 1988). With sprinkler irrigation, a larger soil surface is wetted than in the case of furrow irrigation (Ali, 2011). Thus, for an equal level of production, sprinkler irrigation results in larger ET (because of larger soil evaporation) and consumptive WF than furrow irrigation. Compared to sprinkler, furrow irrigation has higher percolation and runoff fluxes, variables that define irrigation efficiency. These fluxes return to the catchment and are not a loss from the system and therefore not considered to contribute to consumptive WF (Hoekstra et al., 2011).

The findings of this study indicate that subsurface drip irrigation is most useful for consumptive WF reduction in the arid environment. The reason is that with subsurface drip irrigation moisture content in the topsoil will be smaller and thus limit soil evaporation. In

the other environments, the difference between drip and subsurface drip irrigation is minor. With full irrigation in the humid environment, subsurface drip irrigation even results in a larger consumptive WF than in the case of drip irrigation. We believe that these results are plausible, as they are consistent with findings from (Dehghanisanij and Kosari, 2011). Dehghanisanij and Kosari (2011), who explain that the net energy available for soil evaporation for SSD irrigation is larger than for drip. The reason is that drip irrigation gives a cooling effect on the topsoil, reducing the energy available for evaporation, thus limiting soil evaporation. This is due to heat convection or a higher soil heat flux along with droplets of water moving from the soil surface into the soil in the case of drip. Therefore, with full irrigation in the humid environment where the net radiation energy for evaporation is limiting, drip results in smaller consumptive WF than SSD.

The ET versus Y plots made based on our model experiment results (Figures 2a, 2b and 2c) are comparable with the production function in earlier studies (Amarasinghe and Smakhtin, 2014; Wichelns, 2015). Amarasinghe and Smakhtin (2014) derived the production function from observed data under various agro-ecological conditions, water availability constraints and management practices.

Net irrigation supply simulated using AquaCrop for our semi-arid case in Spain is consistent with the values reported by the Guadiana river basin authority. We simulate net irrigation supply in the range of 200-600 mm for full irrigation under different irrigation techniques and soil types for a normal year for the case of tomato in our Spanish site, which is within the observed range of 150-650 mm as reported by the Guadiana river basin authority (CHG – Confederación Hidrográfica del Guadiana, 2013). Our simulated values for net irrigation supply for the same site are also consistent with the reported values for maize and potato. The simulated net irrigation supply for potato is in the range of 180-350 mm and the reported range is 150-380 mm. For maize we find a simulated range of 450-600 mm and a reported range of 450-630 mm.

The AquaCrop model has been validated for herbaceous crops at diverse locations in different environments (Steduto et al., 2011). It is designed to be applicable under various climate and soil conditions, with no need for calibration once it has been parameterized for a specific crop species (Hsiao et al., 2011). This study is made for crops that had already been parameterized in AquaCrop. The sensitivity of AquaCrop-simulated yields to model parameters, under diverse environmental conditions, was studied by Vanuytrecht et al. (2014). That study shows that the parameters describing crop responses to water stress were not often among those showing highest sensitivity. The particular root and soil parameters indeed need attention during calibration. We did not perform a specific sensitivity analysis for these inputs or a specific uncertainty analysis propagating parameter uncertainty through the model, which both would be interesting. The current analysis, however, already shows the robustness of the AquaCrop-simulated effects of irrigation method, irrigation strategy and mulching for a large set of conditions for soil, crop, climate and weather. Together with the sensitivity results of Vanuytrecht et al. (2014), we believe the overall evidence to support the conclusions is strong.

We note that AquaCrop has inherent limitations, including for instance the neglect of lateral water flows in the field, the inability to simulate the effects of nutrient limitation, fertilizer application, effect of organic mulching on the organic content of the soil and decomposition of organic materials, interception losses from sprinkler and the inability to define the depth at which subsurface drip irrigation takes place. These limitations put a disclaimer to the results of our study, but we believe that the results of this study can provide a useful reference to similar future studies with other models. We see the need for further validation of our model results with field experiments, but this is costly and will generally need to focus on varying just a few management practices under a limited number of cases. In our model experimental setup, we varied a large number of variables (irrigation techniques, strategies, mulching practices, environments, soils, crops, and dry, normal and wet years) in all possible combinations, which is impossible in a field experiment.

By focussing on the effect of irrigation and mulching, we excluded from this study the effects of other agricultural practices such as the use of agrochemicals and tillage. Besides, by focussing on management practices at field level, we have excluded measures that could be applied to reduce consumptive WF in the stages before irrigation water is applied to the field, like measures to reduce evaporative losses from storage reservoirs and distribution canals.

## **2.5 Conclusion**

Water footprint reduction in irrigated crop production is the way forward for efficient and sustainable water resource use. This paper provides the first detailed and comprehensive study regarding the potential for reducing the consumptive WF of a crop at field level by changing management practice such as irrigation technique, irrigation strategy and mulching practice. The effect of the various combinations of irrigation technique and strategy and mulching practice were compared to the reference of furrow and full irrigation without mulching. We found the largest WF reduction (average of 35% for different soils and years) for tomato production under drip or subsurface drip irrigation with synthetic mulching under the semi-arid environment. If we consider all the cases of drip or subsurface drip irrigation with synthetic mulching, including all crops and environments, we find an average consumptive WF reduction of 28% for full irrigation and 29% for deficit irrigation. In the latter case, the corresponding blue WF reduction is 44% and the green WF reduction 14%.

Irrigation techniques and strategies and mulching practices can be ordered based on their potential to reduce the blue or total consumptive WF, from low to high potential:

- Irrigation techniques: sprinkler, furrow, drip / subsurface drip irrigation.
- Irrigation strategies: rain-fed, supplementary irrigation, full irrigation, deficit irrigation.
- Mulching practices: no mulching, organic mulching, synthetic mulching.

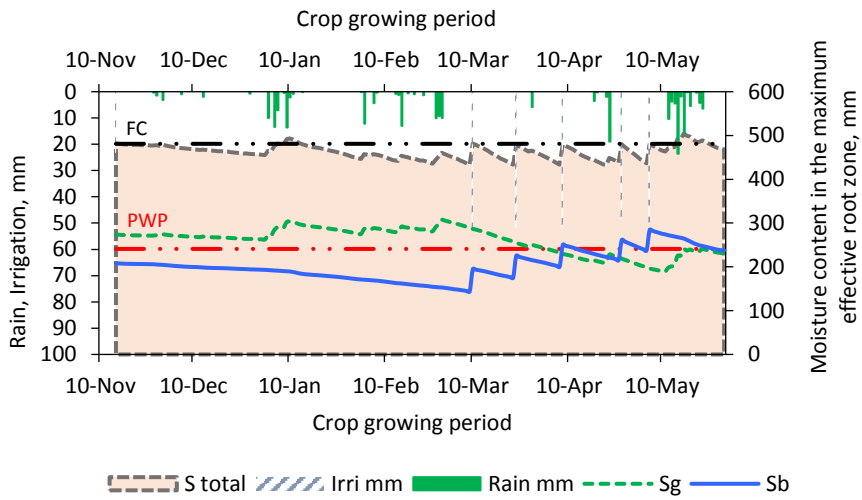
The percentage of blue WF reduction is always larger than the percentage of total consumptive WF reduction. Generally, reduction in the total consumptive WF includes a reduction in the green WF as well. However, when we move from full to deficit irrigation (other things equal), the green WF will increase. Note still that deficit irrigation reduces the blue WF and the overall consumptive WF. The increased blue water and overall water productivity achieved through deficit irrigation thus slightly reduces the green water productivity.

This study can be used as a reference in future studies regarding the potential effect of management practices on the consumptive WF. The results can contribute to making strategic choices to achieve greater crop water productivity and setting WF benchmarks for crop production. The findings of this paper can be used in subsequent studies at a basin scale, with the help of an appropriate model that can simulate the effects of additional management practices like fertilizer application as well, to study the possible water saving (while producing the same crop amount) and water scarcity reduction at basin scale or the possible crop production increase without increasing water use. The ranking of irrigation methods, irrigation strategies and mulching practices as provided in this paper gives a first indication of what can be done to increase water productivity and the potential gains that can be achieved through certain combinations of practices. Formulations are still with caution as relevant considerations such as fertilizer application and associated grey water footprints and possible economic trade-offs are outside the scope of the present paper. However, although our conclusions regarding the effectiveness of different irrigation techniques and strategies and mulching practices are generally valid, we must be careful in translating the general findings to very specific cases, because the precise WF reduction that can be achieved in a particular case will always be context specific.

## **Appendix 2A Illustration of the simulation of green and blue soil moisture content**

Initial soil moisture was quantified for the four environments as follows: 10% green and 90% blue for the arid environment; 35% green and 65% blue for the semi-arid environment; 48% green, 37% blue from capillary rise and 15% blue from irrigation water for the sub-humid environment (with shallow groundwater); and 98% green and 2% blue for the humid environment.

Figure 2A illustrates the development of green and blue soil water content over the growing period as simulated with AquaCrop and our additional module partitioning the soil water content and fluxes into green and blue components.



**Figure 2A** The development of the green ( $S_g$ ) and blue (Vörösmarty et al.) soil water content over the growing period for the case of maize on a loam soil and a normal year at Badajoz in Spain. The symbol S represents total soil moisture, Irri irrigation, FC field capacity, and PWP permanent wilting point.





# 3

## **Marginal cost curves for water footprint reduction in irrigated agriculture: guiding a cost-effective reduction of crop water consumption to a permit or benchmark level<sup>2</sup>**

### *Abstract*

Reducing the water footprint (WF) of the process of growing irrigated crop is an indispensable element in water management, particularly in water-scarce areas. To achieve this, information on marginal cost curves (MCCs) that rank management packages according to their cost-effectiveness to reduce the WF need to support the decision making. MCCs enable the estimation of the cost associated with a certain WF reduction target, e.g. towards a given WF permit (expressed in m<sup>3</sup> per hectare per season) or to a certain WF benchmark (expressed in m<sup>3</sup> per tonne of crop). This paper aims to develop MCCs for WF reduction for a range of selected cases. AquaCrop, a soil-water-balance and crop-growth model, is used to estimate the effect of different management packages on evapotranspiration and crop yield and thus WF of crop production. A management package is defined as specific combination of management practices: irrigation technique (furrow, sprinkler, drip or subsurface drip); irrigation strategy (full or deficit irrigation); and mulching practice (no, organic or synthetic mulching). The annual average cost for each management package is estimated as the annualised capital cost plus the annual costs of maintenance and operations (i.e. costs of water, energy, and labour). Different cases are considered, including: three crops (maize, tomato and potato); four types of environment (humid in UK, sub-humid in Italy, semi-arid in Spain, and arid in Israel); three hydrologic years (wet, normal and dry years) and three soil types (loam, silty clay loam and sandy loam). For each crop, alternative WF reduction pathways were developed, after which the most cost-effective pathway was selected to develop the MCC for WF reduction. When aiming at WF reduction one can best improve the irrigation strategy first, next the mulching practice and finally the irrigation technique. Moving from a full to deficit irrigation strategy is found to be a no-regret measure: it reduces the WF by reducing water consumption at negligible yield reduction, while reducing the cost for irrigation water and the associated costs for energy and labour. Next, moving from no to organic mulching has a high cost-effectiveness, reducing the WF significantly at low cost. Finally, changing from sprinkler or furrow to drip or sub-surface drip irrigation reduces the WF but at significant cost.

Key words: water abatement cost curve, water saving, irrigation practice, soil water balance, crop growth, crop modelling

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<sup>2</sup> Chapter is based on: Chukalla et al. (2017).

### 3.1 Introduction

In many places, water use for irrigation is a major factor contributing to water scarcity (Rosegrant et al., 2002; Mekonnen and Hoekstra, 2016), which will be enhanced by increasing demands for food and biofuels (Erkin and Hoekstra, 2014). In many regions, climate change will aggravate water scarcity by affecting the spatial patterns of precipitation and evaporation (Vörösmarty et al., 2000; Fischer et al., 2007). Reducing the water footprint (WF) of crop production, i.e. the consumption of rainwater (green WF) and irrigation water (blue WF) per unit of crop, is a means of increasing water productivity and reduce water scarcity (Hoekstra, 2017). To ensure that the blue WF in a catchment remains within the maximum sustainable level given the water renewal rate in the catchment, Hoekstra (2014) proposes to establish a blue WF cap per catchment and issue no more blue WF permits to individual users than fit within the cap. This would urge water users to reduce their blue WF to a level that is sustainable within the catchment. Additionally, in order to increase water use efficiency, Hoekstra (2014) proposes water footprint benchmarks for specific processes and products as a reference for what is a reasonable level of water consumption per unit of production. This would provide an incentive for water users to reduce their WF per unit of product down to a certain reasonable reference level. The reduction of the WF in irrigated agriculture to the benchmark level relates to improving the physical water use efficiency or increasing water productivity (Molden et al., 2010), thus relieving water scarcity (Mekonnen and Hoekstra, 2014; Zhuo et al., 2016; Zwart et al., 2010). WF reduction in irrigated crop production can be achieved through a range of measures, including a change in mulching practice or in irrigation technique or strategy. Chukalla et al. (2015) studied the effectiveness of different combinations of irrigation technique, irrigation strategy and mulching practice in terms of WF reduction. No research thus far has been carried out regarding the costs of WF reduction. A relevant question though is how much it costs to reduce the WF of crop production to a certain target such as a WF benchmark for the water consumption per tonne of crop or a WF permit for the water consumption per area.

The current study makes a first effort in response to this question by analysing the cost effectiveness of various measures in irrigated crop production in terms of cost per unit of WF reduction and introducing marginal cost curves (McCraw and Motes) for WF reduction. An MCC for WF reduction is a tool that presents how different measures can be applied subsequently in order to achieve an increasing amount of WF reduction, whereby measures are ordered according to their cost effectiveness (WF reduction achieved per cost unit). Every new measure introduced brings an additional (i.e. marginal) cost and an incremental (marginal) reduction of the WF. There are model-driven and expert-based approaches to develop an MCC. The two approaches have been applied extensively to assess the costs of carbon footprint reduction in various studies, focusing on various sectors and regions. Enkvist et al. (2007) show cost curves for reducing greenhouse gas emissions for different regions in the world. Lewis and Gomer (2008) develop an MCC for reducing greenhouse gas emissions of all sectors in Australia, and MacLeod et al. (2010) develop an MCC for the agricultural sector in the UK. A detailed method to derive MCCs for the most economically

efficient reductions in greenhouse gas emissions in the agricultural sector is presented by Bockel et al. (2012). The weaknesses and strengths intrinsic to different methods of deriving MCCs of greenhouse gas reduction are reviewed in different papers (Kesicki, 2010; Kesicki and Strachan, 2011; Kesicki and Ekins, 2012).

The application of MCCs in the water sector is just starting. Addams et al. (2009) apply MCCs for closing the gap between water supply and demand in irrigated agriculture, particularly focussing on the reduction of irrigation water withdrawal. Khan et al. (2009) discuss two possible pathways to increase water productivity and energy use efficiency in food production. This work, however, does not explicitly specify the measures and their cost effectiveness, which would inform the unit cost of improving water and energy use efficiency. Other studies, like Gonzalez-Alvarez et al. (2006) and Samarawickrema and Kulshreshtha (2009) focus on the marginal cost of water, but don't develop MCCs. The first study mentioned studies how farmers would respond if the marginal cost of irrigation water is changed; the second study assesses the marginal value of irrigation water in the production of alternative crops in order to allocate the water based on the highest marginal value. In the area of WF reduction specifically, MCCs have been developed only once, not in the agricultural sector however, but in a case for some factories in different industrial sectors using the expert-based approach (Tata-Group, 2013). The current paper pioneers by developing and applying a model-driven MCC in the area of WF reduction in irrigated agriculture. It thus fills a gap of existing literature on WF reduction, which generally lacks the practical and economic component: what are the subsequent steps and associated costs to achieve increasing levels of water footprint reduction.

The objective of this study is to develop alternative WF reduction pathways and the MCC for WF reduction in irrigated crop production. We do so for a number of crops and environments. We apply the AquaCrop model, a soil-water-balance and crop-growth model that can be used to estimate the WF of crop production under different management practices, linked with a cost model that calculates annual costs related to different management practices, to systematically assess both WF and costs of twenty management packages. Four case study areas are considered: Rothamsted in the UK, Bologna in Italy, Badajoz in Spain, and Eilat in Israel. Based on the outcomes we construct WF reduction pathways and marginal cost curves. Finally, we illustrate the application of the MCC for WF reduction with a selected case with a certain WF reduction target given a situation where the actual WF needs to be reduced given a cut in the WF permit.

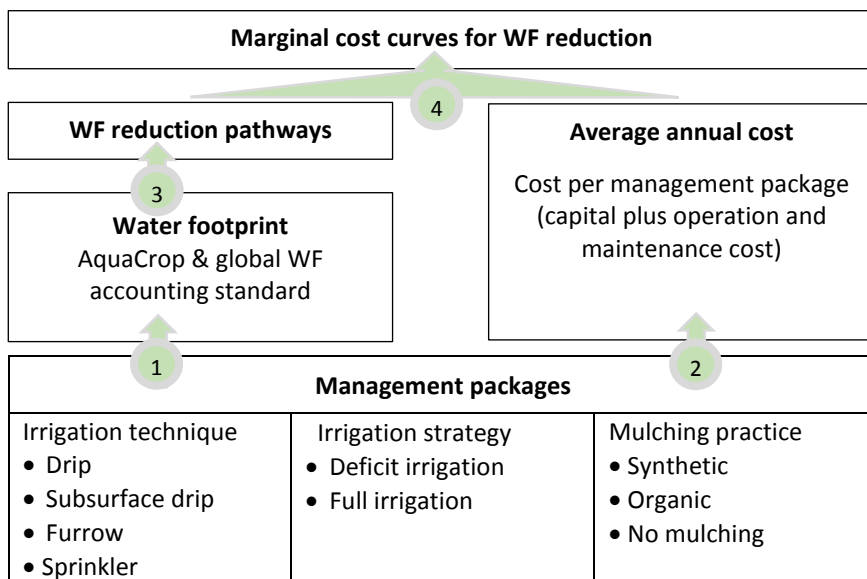
## **3.2 Method and data**

### **3.2.1 Research set-up**

We consider the production of three crops (maize, tomato and potato) under four environments (humid, sub-humid, semi-arid and arid), three hydrologic years (wet, normal and dry year) and three soil types (loam, silty clay loam and sandy loam). We distinguish twenty management packages, whereby each management package is defined as specific combination of management practices: irrigation technique (furrow, sprinkler, drip or

subsurface drip); irrigation strategy (full or deficit irrigation); and mulching practice (no, organic or synthetic mulching).

We develop the marginal cost curves (MCCs) for WF reduction in irrigated crop production in four steps (Figure 3.1). First, we calculate the WF of growing a crop under the different environmental conditions and management packages using the AquaCrop model (Raes et al., 2013). Second, the total annual average cost for the management packages were calculated. Third, we constructed plausible WF reduction pathways starting from different initial situations. A WF reduction pathway shows a sequence of complementary measures, stepwise moving from an initial management package to management packages with lower WFs. Finally, MCCs for WF reduction were deduced based on reduction potential and cost effectiveness of the individual steps. This approach does not aim to represent a cost-benefit analysis from an agro-economic perspective. Reduced costs through water savings are included, but monetary benefits to the farmer through increased yield or product quality are not included. In this way, the approach fully focusses on costs to save water. Yield increases do have a direct impact on final results by reducing the WF per unit of product.



**Figure 3.1** Flow chart for developing marginal cost curves for crop production

### 3.2.2 Management packages

Each management package is a combination of a specific irrigation technique, irrigation strategy and mulching practice. We consider four irrigation techniques, two irrigation strategies and three mulching practices. From the 24 possible combinations, we exclude four unlikely combinations, namely the combinations of furrow and sprinkler techniques

with synthetic mulching (with either full or deficit irrigation), leaving 20 management packages considered in this study.

The four irrigation techniques differ considerably in the wetted area generated by irrigation (Ali, 2011). In the analysis, default values from the AquaCrop model are taken for the wetted area for each irrigation, as recommended by (Raes et al., 2013). For furrow irrigation, an 80% wetting percentage is assumed to be representative for a narrow bed furrow, from the indicative range of 60% to 100%. For sprinkler, drip and subsurface drip irrigation techniques, wetted areas by irrigation of 100%, 30% and 0%, respectively, are used.

Two irrigation strategies are analysed: full and deficit irrigation. Irrigation requires two principal decisions of scheduling: the volume of water to be irrigated and timing of irrigation. Full irrigation is an irrigation strategy in which the full evaporative demand is met; this strategy aims at maximizing yield. Its irrigation schedule is simulated through automatic generation of the required irrigation to avoid any water stress. The irrigation schedule in the no water stress condition is crop-dependent: the soil moisture is refilled to field capacity (FC) when 20%, 36% and 30% of readily available water (RAW) of the soil is depleted for maize, potato and tomato respectively (FAO, 2012). This scheduling results in a high irrigation frequency, which is impractical in the case of furrow and sprinkler irrigation. To circumvent such unrealistic simulation for the case of furrow and sprinkler irrigation, the simulated irrigation depths are aggregated in such a way that a time gap of a week is maintained between two irrigation events.

Deficit irrigation (DI) is the application of water below the evapotranspiration requirements (Feres and Soriano, 2007) by limiting water applications particularly during less drought-sensitive growth stages (English, 1990). The deficit strategy is established by reducing the irrigation supply below the full irrigation requirement. We extensively tested various deficit irrigation strategies that fall under two broad categories: (1) regulated deficit irrigation, where a non-uniform water deficit level is applied during the different phenological stages; and (2) sustained deficit irrigation, where the water deficit is managed to be uniform during the whole crop cycle. In the analysis of simulations, the specific deficit strategy that is optimal according to the model experiments and for yield reduction not exceeding 2% is used. AquaCrop simulates water stress responses triggered by soil moisture depletion using three thresholds for a restraint on canopy expansion, stomatal closure and senescence acceleration (Steduto et al., 2009b).

Mulching is the process of covering the soil surface around a plant to create good-natured conditions for its growth (Lamont et al., 1993; Lamont, 2005). Mulching has various purposes: reduce soil evaporation, control weed incidence and its associated water transpiration, reduce soil compaction, enhance nutrient management and incorporate additional nutrients (McCraw and Motes, 1991; Shaxson and Barber, 2003; Mulumba and Lal, 2008). The AquaCrop model simulates the effect of mulching on evaporation and represents effects of soil organic matter through soil hydraulic properties influencing the soil water balance. Soil evaporation under mulching practices is simulated by scaling the evaporation

with a factor that is described by two variables (Raes et al., 2013): the fraction of soil surface covered by mulch (from 0 to 100%); and a parameter representing mulch material ( $f_m$ ). The correction factor ( $CF$ ) for the effect of mulching on evaporation is calculated as:

$$CF = (1 - f_m \times mc) \quad (3.1)$$

with  $mc$  being the fraction of the soil covered by mulch. We assume a mulching factor  $f_m$  of 1.0 for synthetic mulching, 0.5 for organic mulching and zero for no mulching as suggested by Raes et al. (2013). Further we take a mulch cover of 100% for organic and 80% for synthetic materials, again as suggested in the AquaCrop reference manual (Raes et al., 2013).

### 3.2.3 Calculation of water footprint per management package

The water footprint (WF) of crop production is a volumetric measure of fresh water use for growing a crop, distinguishing between the green WF (consumption of rainwater), blue WF (consumption of irrigation water or consumption of soil moisture from capillary rise) and the grey WF (water pollution) (Hoekstra et al., 2011). The green and blue WF, which are the focus in the current study, are together called the consumptive WF. To allow for a comprehensive and systematic assessment of consumptive WF, this study employs the AquaCrop model to estimate green and blue evapotranspiration (ET) and crop yield (Y) to calculate blue and green WF of crop production.

We use the plug-in version of AquaCrop 4.1 (Steduto et al., 2009a; Raes et al., 2011) and determine the crop growing period based in growing degree days. AquaCrop model simulates the soil water balance in the root zone with a daily time step over the crop growing period (Raes et al., 2012). The fluxes into and from the root zone are runoff, infiltration, evapotranspiration, drainage and capillary rise. The green and blue fractions in total ET are calculated based on the green to blue water ratio in the soil moisture, which in turn is kept track of over time by accounting for how much green and blue water enter the soil moisture, following the accounting procedure as reported in (Chukalla et al., 2015).

AquaCrop simulates actual ET and biomass growth based on the type of crop grown (with specific crop parameters), the soil type, climate data such as precipitation and reference ET ( $ET_o$ ), and given water and field management practices. We estimate  $ET_o$  based on FAO's  $ET_o$  calculator that uses the Penman-Monteith equation (Allen et al., 1998). The model separates daily ET into crop transpiration (productive) and soil evaporation (non-productive).

Evaporation (E) is calculated by multiplying reference ET ( $ET_o$ ) with factors that consider the fraction of the soil surface not covered by canopy, and water stress. When the soil surface is soaked by rainfall or irrigation or when soil moisture is beyond a level called readily evaporable water (RAW), the evaporation rate is fully determined by the energy available for soil evaporation (Ritchie, 1972). When soil moisture drops below RAW, the so-called

falling rate stage, the evaporation is determined by the available energy and hydraulic properties of the soil. field Experimental studies in different environments have shown that the AquaCrop model reasonably simulates evaporation, transpiration and thus ET (Afshar and Neshat, 2013;Saad et al., 2014).

The crop growth engine of AquaCrop estimates the biomass by multiplying water productivity and transpiration and computes yield by multiplying biomass with the harvest index. Water productivity is assumed to respond to atmospheric evaporative demand and atmospheric CO<sub>2</sub> concentration (Steduto et al., 2009a).

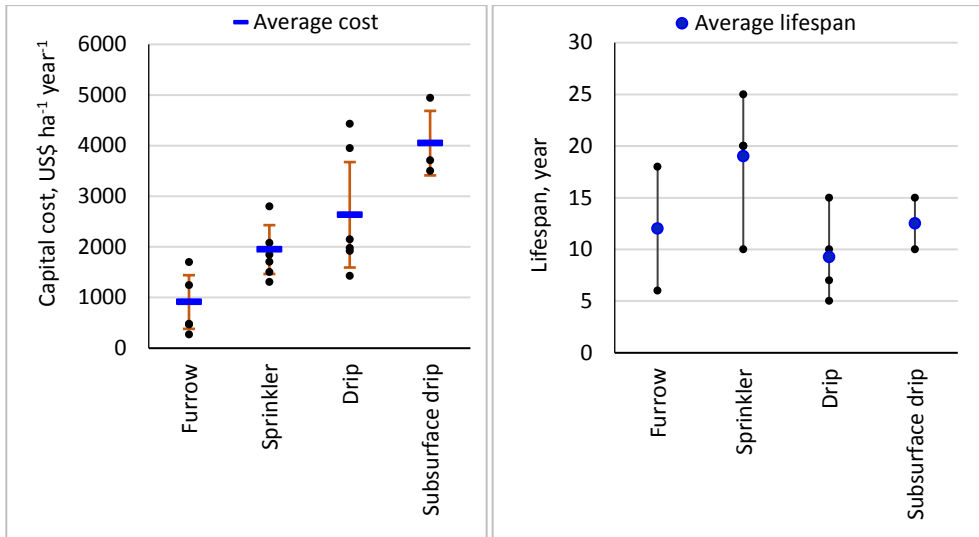
We express the WF of crop production in two ways. The green and blue WF per unit of land (m<sup>3</sup>/ha) are calculated as the green and blue evapotranspiration over the growing period of a crop. The green and blue WF per unit of production (m<sup>3</sup>/tonne) are calculated by dividing green or blue evapotranspiration over the growing period of a crop (m<sup>3</sup>/ha) by the crop yield (tonne/ha). The crop yield in terms of dry matter per hectare as obtained from the AquaCrop calculations is translated into a fresh crop yield (the marketable yield) per hectare. The dry matter fractions of marketable yield for tomato, potato and maize are estimated to be 7%, 25% and 100%, respectively (Steduto et al., 2012). The variability of green and blue WF are presented by calculating the standard deviation of the estimated WFs across different environments, hydrologic years and soil types.

### **3.2.4 Estimation of annual cost per management package**

The overall cost of a management package includes initial capital or investment costs (IC), operation costs (OC), and maintenance costs (MC). Investment costs include costs of installing a new irrigation system and/or buying plastics for synthetic mulching. Operation cost refer to costs for irrigation water, energy and labour. Maintenance costs include labour and material costs. Both OC and MC are expressed as annual cost (US\$/ha per year).

Figure 3.2 shows the average annual investment cost of irrigation techniques and their lifespan. The data are derived from different sources as specified in Appendices 3A and 3B. Investment costs that were reported as one-time instalment costs were converted to equivalent annual costs based on a 5% interest rate and the lifespan of the techniques. The average annual maintenance cost per irrigation technique – including costs for labour and material – is assumed to be equivalent to 2% of the annualised investment costs (Kay and Hatcho, 1992).

The average annual investment costs of US\$ 1112 per ha for synthetic mulching is based on the sources as specified in Appendix 3C. We further assume an average operation and maintenance costs of US\$ 140 per ha per year for synthetic mulching and US\$ 200 per ha per year for organic mulching.



**Figure 3.2** Annual investment cost and lifespan for irrigation techniques

The operational cost related to the use of irrigation water is calculated from the amount of irrigation water applied and an average unit price of water ( $0.09 \pm 0.02$  US\$ per  $m^3$ , Appendix 3E). The amount of irrigation supply is calculated by dividing the irrigation volume applied at field level simulated by AquaCrop by the application efficiency (Phocaidis, 2000). Application efficiency, the ratio of actually applied to supplied irrigation water, is different per irrigation technique (Table 3.1). The operational cost related to energy use for sprinkler, drip and subsurface drip irrigation is calculated as the total energy demand over the growing season multiplied by the cost of energy (Appendix 3F). The total energy demand (kWh) is calculated as follows (Kay and Hatcho, 1992):

$$\text{Seasonal energy demand} = \frac{I \times h}{367 \eta} \quad (3.2)$$

where  $I$  is the volume of irrigation water to be pumped in a crop season (in  $m^3$ ),  $h$  the pressure head (in m) given in Table 3.1 and  $\eta$  the pump efficiency. The pump efficiency can be between 40% and 80% for a pump running at optimum head and speed and is assumed at 60% here (Kay and Hatcho, 1992). Energy required to transport surface water to the field or to pump up groundwater is not included in the estimates.

The operational cost related to labour is calculated as the required labour hours per irrigation event times the number of irrigation events times the cost of labour per hour. The number of irrigation events in the crop growing period is simulated with AquaCrop. The required labour hours per irrigation event is shown in Table 3.1 and the cost of labour per hour is given in Appendix 3D.



**Table 3.1** The application efficiency, labour intensity and pressure head required per irrigation technique.

Irrigation technique	Application efficiency (%)	Labour intensity (hour ha <sup>-1</sup> per irrigation event)	Pressure head (m)
	Sources: Brouwer et al. (1989), Kay and Hatcho (1992), Phocaides (2000)	Source: Kay and Hatcho (1992)	Sources: Reich et al. (2009) and Phocaides (2000)
Furrow	60	2.0-4.0	0
Sprinkler	75	1.5-3.0	25
Drip	90	0.2-0.5	13.6
Subsurface drip	90	0.2-0.6	13.6

Uncertainties in the cost estimations are represented by their standard deviation. The standard deviations in the investment and maintenance costs and operational costs for water, energy and labour were systematically combined in calculating the standard deviation for the total cost estimation.

### 3.2.5 Marginal cost curves for WF reduction

After having calculated the total cost and WF associated with each management package, the MCC for reducing the WF per area or per unit of crop in irrigated agriculture is developed in two steps:

1. Identify alternative WF reduction pathways by arranging plausible progressive sequences of management packages from a baseline management package to a management package with the smallest WF.
2. Select the most cost-effective pathway for a certain baseline and derive from that pathway the MCC for WF reduction.

We consider two baseline management packages: the full irrigation strategy and no mulching practice combined with either furrow or sprinkler irrigation. These two management packages are the most widely deployed types of water and field management (Baldock et al., 2000).

The marginal cost (MC) of a unit WF reduction when shifting from one management package to another is calculated as:

$$\text{MC of a unit WF reduction} = \frac{(TC_2 - TC_1) + (R_1 - R_2)}{WF_1 - WF_2} \quad (3.3)$$

We consider both the additional annual cost of the new management package compared to the previous one and the reduced revenue due to crop yield reduction that may result from the new management package. In the equation,  $TC_x$  refers to the total annual cost of

management package  $x$ ,  $R_x$  to the revenue from crop production when applying management package  $x$ , and  $WF_x$  to the water footprint of management package  $x$ .

The MCC shows how subsequent WF reductions can be achieved in the most cost-effective way by moving from the baseline management package to another package, and further to yet another package and so on. It shows both cost and WF reduction achieved with each step. With each step, the marginal cost of WF reduction will increase.

### **3.2.6 Data**

The WFs were calculated for four locations (UK, Italy, Spain and Israel), three hydrological years (wet, normal and dry years) and three soil types (loam, silty clay loam, and sandy loam). The input data on climate and soil were collected from four sites: Rothamsted in the UK (52.26° N, 0.64°E; 69m above mean sea level), Bologna in Italy (44.57 °N, 11.53 °E; 19m amsl), Badajoz in Spain (38.88 °N, -6.83 °E; 185m amsl), and Eilat in Israel (29.33 °N, 34.57 °E; 12m amsl). These sites characterise humid, sub-humid, semi-arid, and arid environments respectively. Daily observed climatic data (rainfall, minimum and maximum temperature) were extracted from the European Climate Assessment and Dataset (ECAD) (Klein Tank et al., 2002). Wet, normal and dry years were selected from 20 years of daily rainfall data (observed data from the period 1993 to 2012). Daily  $ET_o$  for the wet, normal and dry years were derived using FAO's  $ET_o$  calculator (Raes, 2012). Soil texture data, which is extracted with the resolution of  $1 \times 1 \text{ km}^2$  from European Soil Database (Hannam et al., 2009), is used to identify the soil type based on the Soil Texture Triangle calculator (Saxton et al., 1986). The physical characteristics of the soils are taken from the default parameters in AquaCrop. For crop parameters, by and large we take the default values as represented in AquaCrop. However, the rooting depth for maize at the Bologna site is restricted to the maximum of 0.7m to account for the actual local condition of a shallow groundwater table (average 1.5 m). The main components of the average annual cost per management package have been collected from literature. We use crop prices per crop and per country averaged over five years (2010-2015) from FAOSTAT (2017); the costs for water, labour and energy are averaged over data for Spain, Italy and the UK, i.e. from three of the four countries studied here. An overview of the costs and their sources are presented in Appendices 3A to 3F. In presenting the WF estimates per management package, we show averages over the different cases as well as the range of outcomes for the cases (different environments, hydrologic years and soil types). For developing the MCCs we use the averages.

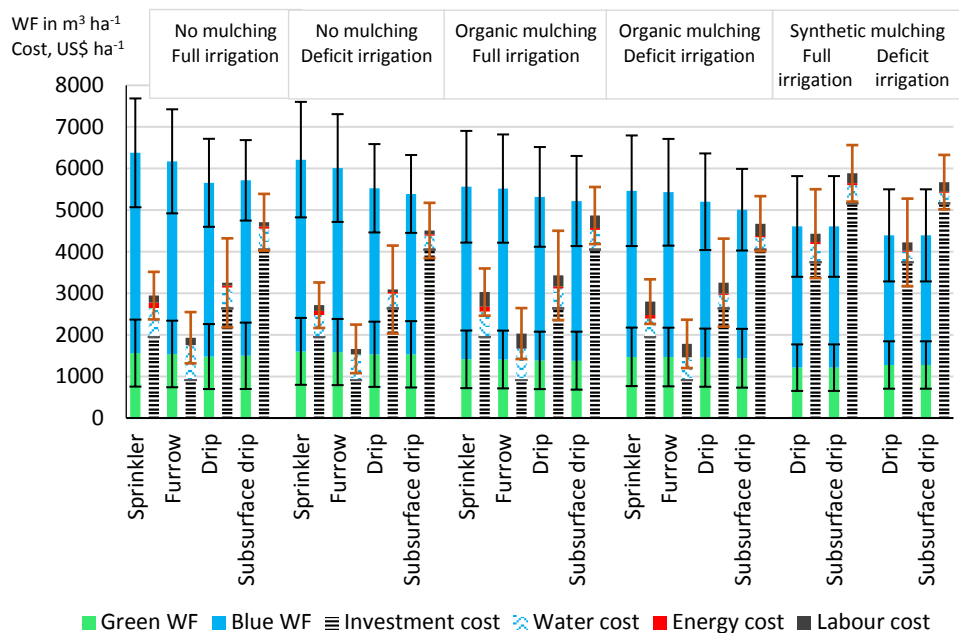
## **3.3 Results**

### **3.3.1 Water footprint and cost per management package**

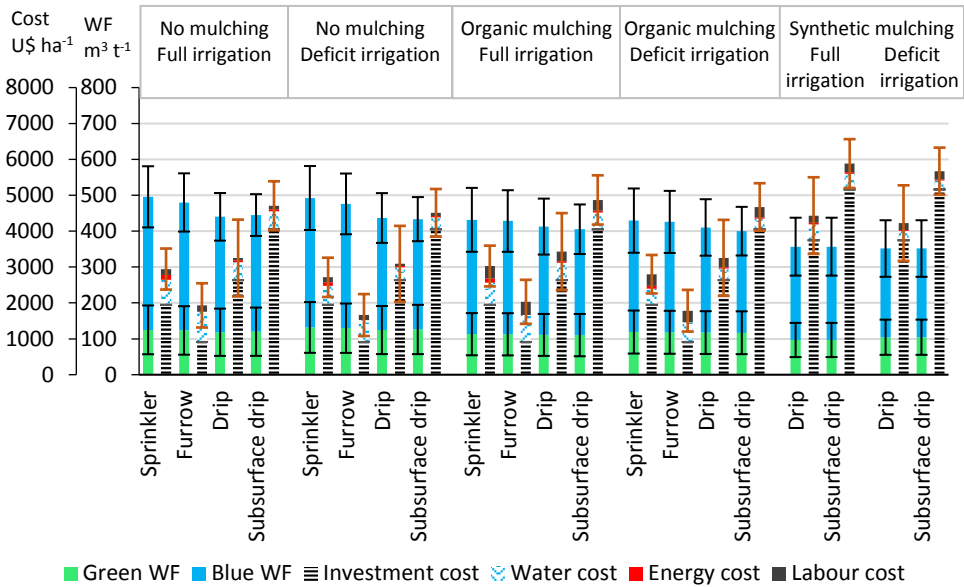
Figure 3.3 and 3.4 show the WF per area and WF per unit of crop, and the annual average costs corresponding to twenty management packages.

For each combination of a certain mulching practice and irrigation strategy, the consumptive WF and the blue WF in particular decrease when we move from sprinkler to furrow to drip and further to subsurface drip irrigation. Under given irrigation strategy and mulching practice, the WF in m<sup>3</sup>/ha in case of subsurface drip irrigation is 6.2-13.3% smaller than in case of sprinkler irrigation. The annual average cost always increases from furrow to sprinkler and further to drip and subsurface drip irrigation. Under given mulching practice and irrigation strategy, the cost in case of furrow irrigation is 58-63% smaller than in case of subsurface drip irrigation. The cost of furrow irrigation is small particularly because of the relatively low investment cost, which is higher for sprinkler and even higher for drip and subsurface drip irrigation. The operational costs, on the contrary, are higher for sprinkler and furrow than for drip or subsurface drip irrigation, because of the higher water consumption and thus cost for sprinkler and furrow. Sprinkler has the highest operational cost because it requires a high pressure head to distribute the water (thus higher energy cost).

Under given irrigation technique and mulching practice, deficit irrigation (DI) always results in a slightly smaller WF in m<sup>3</sup>/ha (in the range of 1.6-5.7%) and lower cost (in the range of 4-14%) as compared to full irrigation (FI). The decrease in cost is due to the decrease in water and pumping energy. The WF of crop production always reduces in a stepwise way when going from no mulching to organic mulching and then to synthetic mulching, while the costs increase along the move. This cost increase relates to the growing material and labour costs when applying mulching (most with synthetic mulching), but the net cost increase is tempered by the fact that less water and pumping energy will be required.

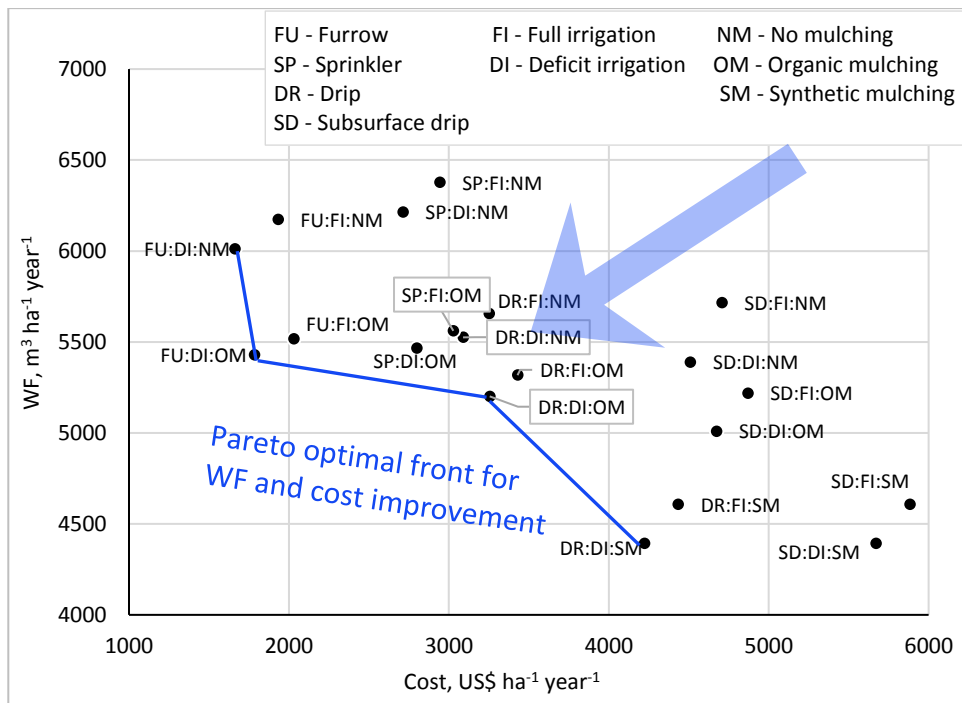


**Figure 3.3** Average WF per area ( $\text{m}^3 \text{ha}^{-1}$ ) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers around cost estimates indicate uncertainties in the costs. WF estimates are split up in blue and green components; costs are split up in investment, water, energy and labour costs.



**Figure 3.4** Average WF per product unit ( $\text{m}^3 \text{t}^{-1}$ ) for maize production and average annual costs associated with 20 management packages. The whiskers around the WF estimates indicate the range of outcomes for the different cases (different environments, hydrologic years and soil types). The whiskers around cost estimates indicate uncertainties in the costs.

Figure 3.5 shows the scatter plot of the twenty management packages, the abscissa and ordinate of each point representing the average annual cost and average WF, respectively, of a particular management package. In this graph, the blue arrow indicates the direction of decreasing WF and costs. The points or management packages connected by the blue line are jointly called the Pareto optimal front or non-dominated Pareto optimal solutions. Moving from one to another management package on the line means that WF will reduce while cost increases, or vice versa, which implies that along this line there will always be a trade-off between the two variables. “Best solutions” may be identified using the MCC when policy goals are specified, for instance a certain WF reduction target in  $\text{m}^3/\text{tonne}$  or  $\text{m}^3/\text{ha}$  is to be achieved, or the largest WF reduction is to be achieved with a given limited budget. Each management package that is not on the line can be improved in terms of reducing cost or reducing WF at no cost for the other variable, or even WF reduction and cost decrease can be achieved simultaneously.

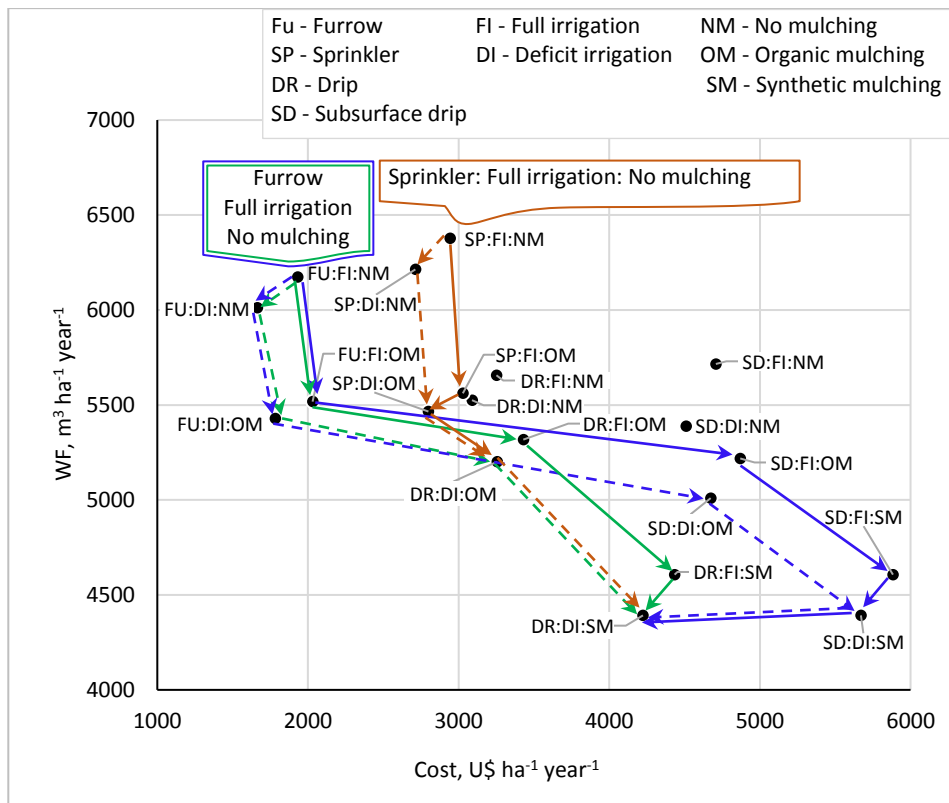


**Figure 3.5** Pareto optimal front for WF and cost reduction in irrigated crop production. The dots represent the annual cost of maize production and the WF per area for twenty management packages. The line connects the Pareto optimal management packages.

### 3.3.2 Water footprint reduction pathways

In developing a new irrigation scheme or renovating an existing one in a water-scarce area, it would be rational to implement one of the management packages from the Pareto optimal set if the goal is to arrive at a cost-effective minimization of the WF of crop production. In an existing farm, where the management package is not in the Pareto optimal set, there can be alternative pathways towards reducing the WF. This involves a stepwise adoption of complementary measures that eventually leads to a management package in the Pareto optimal set.

Figure 3.6 shows alternative WF reduction pathways from the two most common baseline management packages: full irrigation and no mulching with either furrow or sprinkler irrigation. The figure shows four WF reduction pathways from the baseline with furrow irrigation and two pathways from the baseline with sprinkler irrigation. In all pathways, the WF of crop production is continually reduced by changing one thing at a time, i.e. either the irrigation technique, the irrigation strategy or the mulching practice. In some cases, a step may be accompanied by a cost reduction, but in the end most steps imply a cost increase. Logically, all pathways end at a point at the Pareto optimal front.



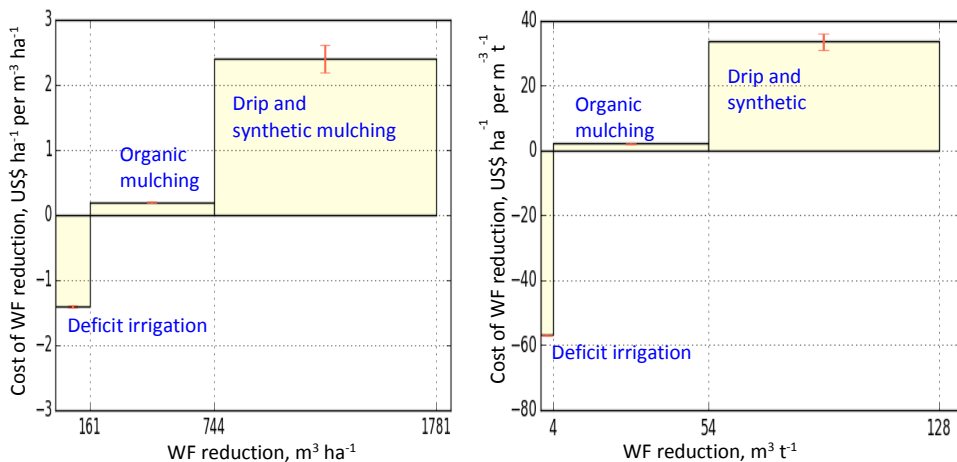
**Figure 3.6** WF reduction pathways for maize from two baseline management packages: full irrigation and no mulching with either furrow or sprinkler irrigation.

### 3.3.3 Marginal cost curves for WF reduction

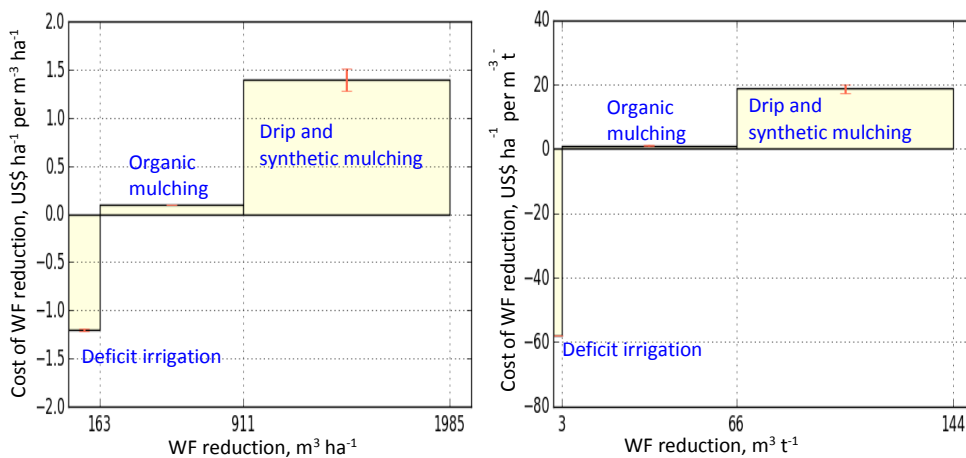
Not all alternative WF reduction pathways from a specific baseline are equally cost effective. In both cases it makes much sense to move from full to deficit irrigation first, because that reduces the WF and cost at the same time. Next, it is best to move from no to organic mulching because the cost-effectiveness of this measure is very high, which can be measured in the graph (Figure 3.6) as the steep slope (high WF reduction per dollar). Finally, the most cost-effective measure, in both cases, is to move towards drip irrigation in combination with synthetic mulching. One could also move to drip irrigation and stay with organic mulching, which is also Pareto optimal; the cost of this will be less, but the WF reduction will be less as well. However, moving to drip irrigation in combination with synthetic mulching is more cost-effective (higher WF reduction per dollar) than moving to drip irrigation while staying with organic mulching.

For both baseline management packages, we have drawn the MCCs in Figure 3.7 and 3.8 for the case of maize. The curves are shown both for reducing the WF per area (Figure 3.7a and 3.8a) and the WF per unit of product (Figure 3.7b and 3.8b). From these curves, we can

read the most cost-effective measures that can subsequently be implemented. For each step we can read in the graph what is the associated marginal cost and what is the associated WF reduction. In both cases, the first step goes at a negative cost, i.e. a benefit, while next steps go at increasing marginal cost. Each step is shown in the form of a bar, with the height and width representing the cost per unit WF reduction and the WF reduction, respectively. The area under a bar represents the total cost of implementing the measure.



**Figure 3.7** Marginal cost curves for WF reduction for maize for the baseline of furrow irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.



**Figure 3.8** Marginal cost curve for WF reduction of maize for the baseline of sprinkler irrigation combined with full irrigation and no mulching. Left: WF reduction per area. Right: WF reduction per unit of product.



For tomato and potato we find similar results as for maize, as shown by the data presented in Appendix 3G.

### 3.3.4 Application of the marginal cost curve

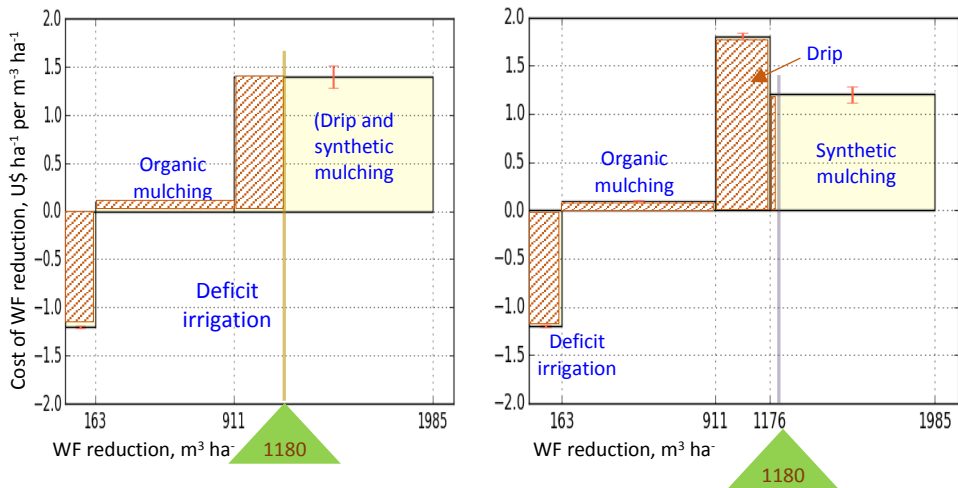
In this section, we elaborate a practical application of an MCC for WF reduction, using a selected case with a certain WF reduction target given a situation where the actual WF needs to be reduced given a cut in the WF permit. The future introduction of WF permits to water users or WF benchmarks for products in water-scarce areas is likely if the sustainable development goals (SDGs) are to be met, particularly SDG 6.4, which reads: “by 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity, and substantially reduce the number of people suffering from water scarcity”. Here we will illustrate how an MCC for WF reduction can help in achieving a certain WF reduction goal.

An MCC for WF reduction – ranking measures according to their cost-effectiveness in reducing WF – can be used to estimate what measures can best be taken and what is the associated total cost to achieve a certain WF reduction target. For farmers, it will not be attractive to go beyond the implementation of those WF reduction measures that reduce cost as well, but from a catchment perspective further WF reduction may be required. An MCC will show the societal cost associated with a certain WF reduction goal. Governments, food companies and investors can make use of this information to develop incentive schemes for farmers and/or investment plans to implement the most-cost effective measures in order to achieve a certain WF reduction in a catchment or at a given farm.

In a hypothetical example, the WF in the river basin exceeds the maximum sustainable level. Agriculture in the basin consists of irrigated maize production with a current consumptive WF on the farms of  $6380 \text{ m}^3 \text{ ha}^{-1}$ . The farms apply sprinkler and full irrigation and no mulching. In order to reduce water consumption in the basin to a sustainable level, the river basin authority proposes various measures including a regulation that prohibits land expansion for crop production and the introduction of a WF permit to the maize farmers that allows them to use no more than  $5200 \text{ m}^3 \text{ ha}^{-1}$ . This means they have to reduce the WF of maize production by  $1180 \text{ m}^3 \text{ ha}^{-1}$ . Figure 3.9 shows how the MCC for WF reduction can help in this hypothetical example to identify what measures can best be taken to reduce the WF by the required amount and what costs will be involved.

As shown in the figure, we best implement deficit irrigation first (providing a total benefit of  $189 \text{ USD ha}^{-1}$ , which is the net result of a  $231 \text{ USD}$  gain from saved water and a  $42 \text{ USD}$  loss from crop yield decline), followed by organic mulching (with a total cost of  $72 \text{ USD ha}^{-1}$ ). The third and last step to finally achieve the required WF reduction can be to implement drip irrigation combined with synthetic mulching on 25% of the maize fields (at a total cost of  $366 \text{ USD ha}^{-1}$ ). The other 75% is then still with sprinkler and organic mulching, but the combined result is meeting the target. Alternatively, because in this particular case the cost-

effectiveness of moving to drip irrigation with organic mulching is close to the cost-effectiveness of moving to drip irrigation with synthetic mulching, one could move in the third step on 100% of the fields to drip irrigation with organic mulching, which would result in a WF reduction of 1176 m<sup>3</sup> ha<sup>-1</sup>. In order to meet the full target, a small percentage of the total fields would need to implement synthetic mulching in addition.



**Figure 3.9** Application of the MCC in an example where the WF of maize production needs to be reduced. The baseline is sprinkler, full irrigation and no mulching with a WF of 6380 m<sup>3</sup> ha<sup>-1</sup>. This needs to be reduced by 1180 m<sup>3</sup> ha<sup>-1</sup> in order to meet a given local WF permit. Left: in the third step, drip irrigation combined with synthetic mulching is implemented on 25% of the area. Right: in the third step, drip irrigation (maintaining organic mulching) is implemented on 100% of the area, while in a fourth step synthetic mulching is implemented on 0.5% of the area.

### 3.4 Discussion

The current paper introduces the method for developing MCCs for WF reduction in irrigated agriculture, and shows how the MCCs can be applied to achieve a certain WF reduction target, like reducing the WF to a certain WF permit level (in m<sup>3</sup> ha<sup>-1</sup>) or WF benchmark level (in m<sup>3</sup> t<sup>-1</sup>). Water availability per catchment is limited to runoff minus environmental flow requirement (Hoekstra, 2014). When dividing the maximum amount of water available in a catchment over the croplands that need irrigation, one finds a maximum volume of water available per ha of cropland. This could be translated in water allocation policy into a maximum WF permit per hectare; this is just one way of promoting WF reduction in areas where that is needed. Another way is to create incentives to reduce the WF per unit of production to a certain benchmark level. Thus, the MCCs we develop can be used for analysing a cost-effective WF reduction pathway given either a target level for WF per hectare or a target level for WF per unit of crop.

By comparing the cost effectiveness of measures in reducing the WF of growing crops, we found that one can best improve first the irrigation strategy (moving from full to deficit irrigation), next the mulching practice (moving from no to organic mulching) and finally the irrigation technique (from furrow or sprinkler irrigation to drip or sub-surface drip irrigation). In our cost-effectiveness analysis, we did not include the cost of bringing irrigation water from source to field. The cost will be high when the source is a deep water well and/or far away, and low if irrigation water flows to a field by gravitational force or by natural pressure, for example from an artesian aquifer or an elevated reservoir. Given a certain source and distance, the total cost to bring irrigation water from source to field will depend on the volume of water to be transported, which varies across the management packages. We excluded this cost, because it does not affect the finding from the study as we will explain. The cost of supplying water will be highest for furrow irrigation (because this technique involves the largest irrigation water supply at field level), followed by sprinkler and drip or subsurface drip irrigation. Furthermore, the water supply cost is higher for full than for deficit irrigation. Finally, the water supply cost is highest in case of the no-mulching practice (which requires the highest irrigation water supply, because ET is highest), followed by organic and synthetic mulching. The water supply cost for transporting the water to the field thus decreases in the direction of decreasing WF, which implies that the order of changing management practices in order to reduce WFs in the most cost-effective way doesn't change by including water supply costs in the equation. It implies, though, that we underestimated the cost savings associated with water supply to the field when reducing WFs.

The derivation of plausible WF reduction pathways requires insight in the agronomic plausibility of successive implementation measures in the field. Our findings suggest to first move from full to deficit irrigation, then from no to organic mulching, and finally from furrow or sprinkler irrigation to drip or sub-surface drip irrigation, which is a plausible pathway of changing management practices. Strictly spoken, it would also be cost-effective to first move from sprinkler to furrow and later on to drip irrigation, but in practice that is obviously not plausible given the fact that investment costs need to be spread over the lifespan of a technique. More plausible is to change irrigation technique only once.

One should be cautious in applying the reported specific values for costs and WF values in other areas than the ones studied here. The results may even change for the areas studied when prices change. In addition, we did not use field data for validating the simulated results. This puts a disclaimer to the simulated results, but we believe that the methods for developing MCCs for WF reduction pathways in irrigated agriculture, and the hypothetical example of this study provide a useful reference for similar future studies. The MCCs can be of interest to farmers who are seeking to or are incentivized to reduce the WF of their production. They can also be of interest to companies in the food and beverage sector, since there increasing interest in this sector to formulate water use efficiency targets for their supply chain and to stimulate farmers to reduce their WF. For investors, the MCCs help to explore the investment costs associated with certain WF reduction targets. Finally, the MCCs can be of interest to water managers responsible for water allocation to farmers,

providing them with information on the costs to farmers if they reduce WF permits to farmers.

### 3.5 Conclusion

In this study, we have developed a method to obtain marginal cost curves for WF reduction in crop production. The method is innovative by employing a model that combines soil water balance accounting and a crop growth model and assessing costs and WF reduction for all combinations of irrigation techniques, irrigation strategies and mulching practices. This is a model-based approach to constructing MCCs, which has the advantage over an expert-based approach by considering the combined effects of different measures and thus accounting for non-linearity in the system (i.e. the effect of two measures combined doesn't necessarily equal the sum of the effects of the separate measures). While this approach has been used in the field of constructing MCCs for carbon footprint reduction (Kesicki, 2010), this has never been done before for the case of water footprint reduction.

Developing the MCC for WF reduction for three specific irrigated crops, we found that when aiming at WF reduction one can best improve the irrigation strategy first, next the mulching practice and finally the irrigation technique. Moving from a full to deficit irrigation strategy is found to be a no-regret measure: it reduces the WF by reducing water consumption at negligible yield reduction, while reducing the cost for irrigation water and the associated costs for energy and labour. Next, moving from no to organic mulching has a high cost-effectiveness, reducing the WF significantly at low cost. Finally, changing from sprinkler or furrow to drip or sub-surface drip irrigation reduces the WF but at significant cost.

## Appendices 3

### Appendix 3A Estimates of the investment cost of irrigation techniques (US\$ ha<sup>-1</sup> y<sup>-1</sup>)

No	Irrigation techniques	Furrow	Sprinkler	Drip	Subsurface drip
	Cost	467 - 1312	1844 - 2399	1429 - 2594	
	Remark	The techniques are named as surface pumped, sprinkler and localized pumped. The database focuses on the developing regions of the world for the year 2000.			
	Source	FAO (2016b)			
	Cost	1700	2800	3950	
	Remark	Average prices in Europe in 1997. The irrigation technologies are named as improved surface, sprinkler and micro irrigation			
	Source	Phocaides (2000)			
	Cost	1242	2080	4429	
	Remark	The type of sprinkler is hand moved			

	Source	Custodio and Gurguı (1989)			
	Cost	291	1500	1918	3500
	Remark	The one-time investment cost is annualized based on the average life span of the techniques and an interest rate of 5%			
	Source	Williams and Izaurralde (2006)			
	Cost				3707 - 4942
	Source	Reich et al. (2009)			
	Cost		1305	1976	
	Source	Zou et al. (2013)			
	Cost	271	1706	2147	
	Remark	For a case in China for the year 2000. The irrigation techniques are named as improved surface, sprinkler and micro irrigation			
	Source	Mateo-Sagasta et al. (2013)			

### Appendix 3B Estimates of the lifespan of irrigation techniques from various sources

Irrigation techniques	Lifespan (years)						
	Source	Oosthuizen et al. (2005)	Reich et al. (2009)	Williams and Izaurralde (2006)	Zou et al. (2013)	Average lifespan	
Furrow		6		18			12
Sprinkler			20	25	20	10	20
Drip		7		10	5	15	9.25
Subsurface drip			10	15			12.5

### Appendix 3C Estimates for the cost of mulching (US\$ ha<sup>-1</sup> year<sup>-1</sup>)

Mulching	Average annual investment cost	Operation and maintenance cost	Sources
	1227		Lamont et al. (1993)
	875 to 1750		Shrefler and Brandenberger (2014)
	585	140	Jensen and Malter (1995)
Average cost for plastic mulching cost $\pm$ SD	1112 $\pm$ 434	140	
Average cost for organic mulching		200 $\pm$ 100	Klonsky (2012)

### Appendix 3D Labour cost per hour, in European agriculture for selected countries

Country	Labour cost	Source
Italy (Euro h <sup>-1</sup> )	6.87	
Spain (Euro h <sup>-1</sup> )	4	
UK (Euro h <sup>-1</sup> )	8.6	
Average (Euro h <sup>-1</sup> )	6.5	
Average ± SD (US\$ h <sup>-1</sup> )	7.2 ± 2.3	

### Appendix 3E Cost of water

Country	Water price	Source
UK (Euro m <sup>-3</sup> )	0.06	Lallana and Marcuello (2016)
Spain (Euro m <sup>-3</sup> )	0.07	Gómez-Limón and Riesgo (2004)
Italy (Euro m <sup>-3</sup> )	0.1	Garrido and Calatrava (2010)
Average (Euro m <sup>-3</sup> )	0.08	
Average ± SD (US\$ m <sup>-3</sup> )	0.09 ± 0.02	

### Appendix 3F Cost of energy, Eurostat (2016b)

Country	Year			Average
	2012	2013	2014	
Italy	0.178	0.172	0.174	0.17
Spain	0.12	0.12	0.117	0.12
UK	0.119	0.12	0.134	0.12
Average (Euro / kWh)				0.14
Average ± SD (US\$ / kWh)				0.15 ± 0.03

### Appendix 3G Summary of marginal cost and WF reduction per subsequent measure in the marginal cost curves for WF reduction in maize, tomato and potato production

**Table 3G-I** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in maize production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-1.7	-66.7	161	4	-269

Organic mulching	0.2	2.4	583	50	120
Drip and synthetic mulching	2.4	32.9	1037	74	2441

**Table 3G-II** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in maize production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-1.4	-70.9	163	3	-231
Organic mulching	0.1	1.4	748	63	87
Drip and synthetic mulching	1.3	18.3	1073	78	1424

**Table 3G-III** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in tomato production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-0.4	-256.1	752	1	-331
Organic mulching	0.2	16.0	750	8	122
Drip and synthetic mulching	2.3	270.2	1094	9	2487

**Table 3G-IV** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in tomato production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-0.4	-275.5	840	1	-323
Organic mulching	0.1	7.4	1045	10	73
Drip irrigation		143.2		4	502
Synthetic mulching		153.7		6	983

**Table 3G-V** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in potato production for the baseline of furrow irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-0.8	-40.8	191	4	-157
Organic mulching	0.5	11.9	323	12	146
Drip and synthetic mulching	6.2	174.8	429	15	2660

**Table 3G-VI** Marginal cost and WF reduction per subsequent measure in the MCC for WF reduction in potato production for the baseline of sprinkler irrigation combined with full irrigation and no mulching.

Measures	Marginal cost		WF reduction		Total cost US\$ ha <sup>-1</sup>
	US\$ ha <sup>-1</sup> per m <sup>3</sup> ha <sup>-1</sup>	US\$ ha <sup>-1</sup> per m <sup>3</sup> t <sup>-1</sup>	m <sup>3</sup> ha <sup>-1</sup>	m <sup>3</sup> t <sup>-1</sup>	
Deficit irrigation	-0.7	-33.1	228	5	-157
Organic mulching	0.4	9.6	403	15	147
Drip and synthetic mulching	3.5	101.6	458	16	1623



# 4 Grey water footprint reduction in irrigated crop production: effect of nitrogen application rate, nitrogen form, tillage practice and irrigation strategy<sup>3</sup>

## *Abstract*

Grey water footprint (WF) reduction is essential given the increasing water pollution associated with food production and the limited assimilation capacity of fresh water. Fertilizer application can contribute significantly to the grey WF as a result of nutrient leaching to groundwater and runoff to streams. The objective of this study is to explore the effect of the nitrogen application rate (from 25 to 300 kg N ha<sup>-1</sup>), nitrogen form (inorganic-N or manure-N), tillage practice (conventional or no-tillage) and irrigation strategy (full or deficit irrigation) on the nitrogen load to groundwater and surface water, crop yield and the grey water footprint of crop production by a systematic model-based assessment. As a case study, we consider irrigated maize grown in Spain on loam soil in a semi-arid environment, whereby we simulate the twenty-years period 1993-2012. The water and nitrogen balances of the soil and plant growth at field scale were simulated with the APEX model. As a reference management package, we assume the use of inorganic-N (nitrate), conventional tillage and full irrigation. For this reference, the grey WF at a usual N application rate of 300 kg N ha<sup>-1</sup> (with crop yield of 11.1 t ha<sup>-1</sup>) is 1100 m<sup>3</sup> t<sup>-1</sup>, which can be reduced by 91% towards 95 m<sup>3</sup> t<sup>-1</sup> when the N application rate is reduced to 50 kg N ha<sup>-1</sup> (with a yield of 3.7 t ha<sup>-1</sup>). The grey WF can be further reduced to 75 m<sup>3</sup> t<sup>-1</sup> by shifting the management package to manure-N and deficit irrigation (with crop yield of 3.5 t ha<sup>-1</sup>). Although water pollution can thus be reduced dramatically, this comes together with a great yield reduction, and a much lower water productivity (larger green plus blue WF) as well. The overall (green, blue plus grey) WF per tonne is found to be minimal at an N application rate of 150 kg N ha<sup>-1</sup>, with manure, no-tillage and deficit irrigation (with crop yield of 9.3 t ha<sup>-1</sup>). The paper shows that there is a trade-off between grey WF and crop yield, as well as a trade-off between reducing water pollution (grey WF) and water consumption (green and blue WF). Applying manure instead of inorganic-N and deficit instead of full irrigation are measures that reduce both water pollution and water consumption with a 16% loss in yield.

**Key words:** grey water footprint, nitrogen balance, water balance, deficit irrigation, tillage, crop growth, APEX

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<sup>3</sup> The Chapter has been submitted to *Hydrology and Earth System Sciences* and is under review.

## 4.1 Introduction

Crop yields depend on anthropogenic addition of nitrogen (N), but N fertilizer inevitably result in some N leaching and runoff as well, resulting in the pollution of groundwater and surface water. Freshwater dilutes pollutant loads entering a water body, which can be interpreted as an appropriation of fresh water (Postel et al., 1996; Falkenmark and Lindh, 1974; Chapagain et al., 2006; Hoekstra, 2008). The amount of freshwater appropriated to assimilate the load of pollutants in order to meet ambient water quality standards is called the grey water footprint (WF) (Hoekstra et al., 2011). For crop production, the grey WF can be expressed as the volume of water per hectare or per tonne [ $\text{m}^3 \text{ha}^{-1}$  or  $\text{m}^3 \text{ton}^{-1}$ ]. Global crop production contributes three quarters to the N-related grey WF in the world (Mekonnen and Hoekstra, 2015). Anthropogenic N application in agriculture and the resulting freshwater pollution is expected to increase with the growing production of food, feed, fibre, and biofuel in the world, driven by population growth and improving living standards. The assimilation capacity of freshwater, however, is limited, which calls for appropriate management practices that limit the grey WF per tonne of crop production.

Agricultural management practices that influence the grey WF include the N application rate, the form of N applied (particularly inorganic-N versus manure or organic-N), and the tillage and irrigation practice. A low N application rate will hamper plant growth and thus result in a low crop yield (Raun et al., 2002); water pollution per hectare will be small, but large relative to the volume of crops produced. A high N application rate will result in a high crop yield, but with high water pollution per hectare and per tonne of crop as well. The reason for the high water pollution per tonne of crop is that there is a threshold for the N application rate beyond which yield does not respond (Zhou et al., 2011), while the surplus N contributes to pollution (Carpenter et al., 1998; Vitousek et al., 2009). The form of N applied is another important factor affecting N losses. Inorganic N is readily available for uptake by crops (Haynes, 2012), whereas the organic-N contained in manure becomes available only gradually, as it should first be converted (mineralized) to inorganic form (Ketterings et al., 2005). The mobile nature of nitrate makes it susceptible for higher risk of leaching (Yanan et al., 1997), while the slow disappearance of manure makes it susceptible to N losses through runoff before being taken up by the crop (Withers and Lord, 2002). Field operation practices such as tillage affect the water holding capacity of the soil, the movement of moisture and nutrients in the soil, surface runoff, and eventually crop yield and nutrient load to freshwater. There are various good reasons why conventional tillage is being practiced: it mixes fertilizer, organic matter and oxygen in the soil, breaks up surface soil crusts and reduces weeds (Horowitz, 2011). However, conventional tillage disrupts aggregates within the soil and life cycles of beneficial organisms, increases soil erodability, and results in soil compaction and tillage pan formation (Triplett and Dick, 2008). Alternatively, no-tillage develops mulch cover, improves the soil water holding capacity (Dangolani and Narob, 2013) and increases hydraulic conductivity (Azooz and Arshad, 1996; Triplett and Dick, 2008). The irrigation practice primarily influences the water balance of the soil, but as a side effect it influences nutrient movement in the soil. The advantage of deficit irrigation compared to full irrigation is that there may be less leaching and runoff of

nutrients (Withers and Lord, 2002), but the disadvantage is that it may result in reduced N demand as crop growth diminished and reduced N supply as N transporting agent is reduced and thus reduction in water pollution per unit of crop produced (Gonzalez-Dugo et al., 2010).

Various studies show how increasing N application rates result in both increased crop yield and N leaching (Berenguer et al., 2009; Rong and Xuefeng, 2011; Valero et al., 2005; Zhou et al., 2011; Cooper et al., 2012; Good and Beatty, 2011). Other studies analyse the effect of tillage practices on crop yield (Pittelkow et al., 2015) or the effect of tillage practices and N fertilizer forms on crop yield (Yu et al., 2016) or the effect of manure versus inorganic N fertilizer application on nitrate leaching (Huang et al., 2017; Yanan et al., 1997) or the effect of different tillage practices and N application rates on yield and N leaching (Huang et al., 2015). There are quite some studies also on the relation between rates of irrigation and N application and crop yield (Yin et al., 2014; Al-Kaisi and Yin, 2003; Rimski-Korsakov et al., 2009). These earlier studies provide insight in the effects of individual management practices on yield, water productivity, or leaching, however most of the studies vary only one or two management practices, not considering the combined effect of N application rate, N form, tillage practice and irrigation strategy. Besides, none of these studies consider the effect on the pollutant load per unit of crop obtained or the effect on the grey WF per tonne.

It is challenging to conduct field experimental studies and even more laborious and expensive to study the effects of a comprehensive list of different combinations of management practices. Besides, leaching and runoff of N from fields is difficult to determine through field experiments; N that can be measured in groundwater and streams originates from different sources and cannot easily be attributed to an experimental field. An alternative approach avoiding these downsides is to use modelling (Chukalla et al., 2015; Ragab, 2015).

The objective of this study is to explore the effect of nitrogen application rate, nitrogen form, tillage practice and irrigation strategy on the nitrogen load to groundwater and surface water, crop yield and the grey water footprint of crop production by a systematic model-based assessment. We apply the Agricultural Policy Environmental eXtender (APEX) model, which simulates nutrient and water balances of the soil and plant growth, is able to simulate the effect of a wide variety of agricultural management practices, and has been applied for a wide variety of cases (Wang et al., 2012; Gassman et al., 2010; Liu et al., 2016; Clarke et al., 2017; Chen et al., 2017). As a case study, we consider irrigated maize grown in Badajoz in Spain on loam soil in a semi-arid environment, whereby we simulate the twenty-years period 1993-2012.

The method to estimate grey WFs in the current study is more advanced than in previous studies. (Franke et al., 2013) distinguish three tiers to estimate grey WFs from diffuse pollution. The tier-1 approach is based on expert-based assumptions on which fractions of applied or surplus N in the soil will leach or run off given contextual factors. It provides a

first rough estimate of the N load without describing the interaction and transformation of different chemical substances in the soil or along its flow pathways (see for instance Mekonnen and Hoekstra (2011), and Brueck and Lammel (2016)). The more advanced tier-2 approach for estimating grey WFs from diffuse pollution is based on an N balance approach, applying a simplified model approach (see for example Mekonnen and Hoekstra (2015), and Liu et al. (2012)). The current study is the first one to apply the tier-3 approach, which explicitly considers physical and biochemical processes using an advanced water and nutrient balance model (the APEX model). As an additional component of the current study, we will compare the N leaching-runoff fractions that result from the APEX simulations with the leaching-runoff fractions estimated with the simpler tier-1 approach, in order to find out the added value of employing the advanced model approach.

## **4.2 Method and data**

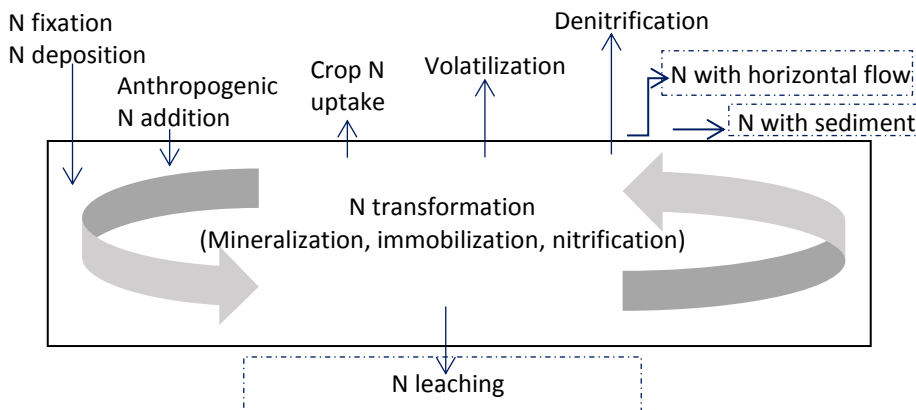
### **4.2.1 Modelling the soil water & nitrogen balances and crop growth**

The effect of various combinations of management practices on water flows (like soil evaporation, crop transpiration, percolation and runoff), N flows (like N uptake by plants, leaching and runoff) and crop growth are simulated using the APEX model, a dynamic, deterministic and process-based model with a daily time step (Williams and Izaurralde, 2006). Below we briefly summarise the processes simulated in the model. More detailed descriptions of the processes and the equations to simulate these processes can be found in the documentation of APEX (Williams et al., 2008).

The water balance component of APEX encompasses key processes that impact the soil water compartment in the hydrologic cycle. Initially, incoming inputs such as precipitation, snowmelt, or irrigation is partitioned between surface runoff and infiltration. Surface runoff volume is simulated using a modified Soil Conservation Service curve number technique described by Williams (1995). Infiltrated water can be stored in the soil profile, be lost via evapotranspiration (ET), percolate vertically to groundwater, or flow laterally as subsurface flow, with a quick and slow component. Reference ET is calculated using the Penman-Monteith method. The actual ET, an important variable in estimating green and blue WF of crop production, is computed by simulating evaporation from the soil and transpiration from plants separately, considering the soil moisture status and how agricultural management practices affect the root zone. Percolation and lateral flow are computed using storage routing and pipe flow equations described by Gassman et al. (2010). A deep groundwater table is assumed and thus capillary rise, which APEX would simulate using storage routing (Gassman et al., 2010), is not considered in the water balance.

The N balance of the soil in APEX is computed based on inputs and outputs and conversion processes (Figure 4.1). N is added to the soil-plant system through natural and anthropogenic pathways. Natural N inputs include wet and dry deposition (Anderson and Downing, 2006) and N fixation, through lightning and through biological fixation by legume plants (Carpenter et al., 1998). Anthropogenic input occurs when inorganic or organic N fertilizers are applied (Vitousek et al., 2009). N outputs include N uptake by crops (partly

harvested and removed later on), denitrification, volatilization, nitrate-N losses through leaching, horizontal losses of organic N with eroded sediments, and horizontal losses of inorganic N through surface runoff, or lateral subsurface flow. N transformation includes mineralization, immobilization and nitrification.



**Figure 4.1** Nitrogen fluxes into and from the root zone, and N transformation.

APEX simulates the growth of annual and perennial crops based on the EPIC model (Williams et al., 1989), an energy-driven crop growth model using a radiation-efficiency approach to simulate the generation of biomass. Potential biomass production is derived as function of leaf area index and climatic variables (solar radiation,  $\text{CO}_2$ , air humidity and temperature). Phenological development of the crop is based on heat unit accumulation. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop (Steduto, 1997). Daily potential growth is lowered to actual growth using the most limiting stress factor, considering stresses caused by water, nutrients (N and P), temperature and aeration, which are evaluated by assigning stress factors (from 0, high stress, to 1, no stress). Root growth is constrained based on the most limiting stress caused by soil strength and temperature. Total biomass is partitioned to root and above ground biomass, and from the above-ground biomass is the economic yield is partitioned using harvest index.

#### 4.2.2 The grey water footprint of growing crops

The grey water footprint (WF), an indicator of appropriated pollution assimilation capacity, is calculated following the Global Water Footprint Standard (Hoekstra et al., 2011), which means that the total pollutant load entering freshwater (groundwater or surface water) is divided by the difference between the maximum acceptable concentration for that pollutant and the natural background concentration for that pollutant. The grey WF can be expressed in two different ways, either as a water volume per ha, or as a water volume per tonne of crop:

$$\text{Grey WF per hectare} = \frac{L}{C_{\max} - C_{\text{nat}}} [m^3 \text{ ha}^{-1} \text{ y}^{-1}] \quad (4.1a)$$

$$\text{Grey WF per tonne} = \frac{\text{Grey WF per hectare}}{Y} [m^3 \text{ t}^{-1}] \quad (4.1b)$$

where  $L$  ( $\text{kg ha}^{-1} \text{ y}^{-1}$ ) is the pollutant load to surface water and groundwater,  $C_{\max}$  and  $C_{\text{nat}}$  are the maximum acceptable and natural concentrations ( $\text{kg m}^{-3}$ ), and  $Y$  the crop yield ( $\text{t ha}^{-1} \text{ y}^{-1}$ ).

The total N load to freshwater ( $L$ , in  $\text{kg N ha}^{-1} \text{ y}^{-1}$ ) is calculated as the sum of the N load in surface runoff, the N in quick subsurface flow, the N in slow subsurface flow, the N adsorbed to eroded sediments and the N in percolation. Each of these N loads are simulated separately in APEX.

A maximum acceptable N concentration of  $50 \text{ mg nitrate-N L}^{-1}$  (or  $11.3 \text{ mg N L}^{-1}$ ) is adopted, based on the EU Nitrates Directive (Monteny, 2001). The natural concentration was considered to be  $0.5 \text{ mg N L}^{-1}$ , following for example (de Miguel et al., 2015).

Next to the grey WF, the green and blue WF of crop production are calculated as well, again using the Global WF standard (Hoekstra et al., 2011). The green WF refers to the rainwater consumed (water evaporated or incorporated into the crop), while the blue WF refers to the irrigation water consumed (which comes from surface water or groundwater). Together, the green and blue WF are called the consumptive WF. The consumptive WF per tonne of crop is calculated by dividing the ET over the growing period by the crop yield.

### 4.2.3 Leaching-runoff fraction

As an additional component of the current study, we will compare the N leaching-runoff fraction simulated through APEX (tier-3 level estimation) with the leaching-runoff fraction estimated with the simpler estimation approach (tier-1) as applied in previous studies, in order to find out when the simple tier-1 approach suffices and when it doesn't.

The leaching-runoff fraction can be defined in two ways (Franke et al., 2013). In the first definition, the leaching-runoff fraction, called  $\alpha$ , is defined as the percentage of the amount of chemical applied to the field as fertilizer that is lost to groundwater through leaching or to surface water through runoff. In the second definition, the leaching-runoff fraction, now called  $\beta$ , is defined as the percentage of the amount of 'surplus chemical' in the soil that is lost to groundwater through leaching or to surface water through runoff. The 'surplus chemical' in the soil is defined as the amount of chemical applied minus the uptake of the chemical by the crop.

$$\alpha = \frac{L}{\text{Appl}} \quad (4.2)$$

$$\beta = \frac{L}{\text{Surplus}} \quad (4.3)$$

where  $\alpha$  and  $\beta$  are the leaching-runoff fractions, and where  $L$  ( $\text{kg N ha}^{-1} \text{y}^{-1}$ ) is the N load to freshwater bodies,  $\text{Appl}$  ( $\text{kg N ha}^{-1} \text{y}^{-1}$ ) the N fertilizer applied, and  $\text{Surplus}$  ( $\text{kg N ha}^{-1} \text{y}^{-1}$ ) the N applied but not taken up by the plant.

At the tier-3 level, the fractions  $\alpha$  and  $\beta$  are not used in the calculations, but they can easily be calculated afterwards, based on the outputs of the model. At the tier-1 level,  $\alpha$  and  $\beta$  can be estimated following the guidelines of Franke et al. (2013). According to these guidelines, the leaching-runoff fractions lie between a minimum and a maximum value (0.01 to 0.25 for  $\alpha$  and 0.08 to 0.8 for  $\beta$ ). The precise value is estimated based context-specific environmental and management factors, using the following equations:

$$\alpha = \alpha_{min} + \left[ \frac{\sum_i s_i * w_i}{\sum_i w_i} \right] * (\alpha_{max} - \alpha_{min}) \quad (4.4)$$

$$\beta = \beta_{min} + \left[ \frac{\sum_i s_i * w_i}{\sum_i w_i} \right] * (\beta_{max} - \beta_{min}) \quad (4.5)$$

where  $s_i$  is score for the leaching runoff potential for environmental or management factor  $i$  and  $w_i$  is the weight of that factor.

#### 4.2.4 Simulation set-up

We carry out model simulations with APEX for 56 management packages, whereby each management package consists of a certain combination of management practices. We consider all possible combinations of seven N application rates, two N forms, two tillage practices, and two irrigation strategies (Table 4.1). As a reference management package, we assume the use of inorganic N fertilizer (nitrate) in combination with conventional tillage and full irrigation. Conventional tillage is the most wide-spread tillage practice in the EU (EUROSTAT, 2013) and full irrigation is the most common irrigation practice, aimed at achieving maximum yield.

**Table 4.1** Research set-up: the APEX model is used to simulate the effect of 56 management packages (combinations of different management practices) on ET, crop yield, nitrogen load to freshwater, and green, blue and grey WF.

Management practices	Modelling	Effects
<ul style="list-style-type: none"> <li>Nitrogen application rates: 25, 50, 100, 150, 200, 250 or 300 <math>\text{kg N ha}^{-1}</math></li> <li>Nitrogen forms: inorganic-N (nitrate) or organic-N (manure)</li> <li>Tillage practices: no-tillage or conventional tillage</li> <li>Irrigation strategies: full or deficit irrigation</li> </ul>	Soil water & nutrient balances and crop growth model (APEX)	<ul style="list-style-type: none"> <li>- ET</li> <li>- Yield</li> <li>- N load</li> <li>- Green, blue, grey WF</li> </ul>

The EU Nitrate Directive legally restricts annual farm application of manure in EU member states to  $170 \text{ kg N ha}^{-1} \text{y}^{-1}$ , or in case of derogation up to  $250 \text{ kg N ha}^{-1}$  (Amery and

Schoumans, 2014; Van Grinsven et al., 2012). Surveys in Spain, however, show that application rates of 300-350 kg N ha<sup>-1</sup> y<sup>-1</sup> are common to cultivate maize in the Ebro Valley (Berenguer et al., 2009) and up to 300 kg N ha<sup>-1</sup> in La Mancha (Valero et al., 2005). As the upper value for the N application rate in our simulations we apply 300 kg N ha<sup>-1</sup>.

The fertilization is assumed to be performed in two splits (30% in a first round, at planting for mineral fertilizer and 15 days before planting for manure; 70% in a second round, one month after planting). In the first round of application, inorganic fertilizer is assumed to be nitrate-N and applied through broadcasting while manure is assumed to be injected. Manure injection is getting recognition in the EU and in the world due to its many advantages, including reduction of N losses to freshwater and to the atmosphere and bad odour (Van Dijk et al., 2015; van den Pol-van Dasselaar et al., 2015). In the second round, both the manure and nitrate-N fertilizers are added as side-dressing.

As for the inorganic N applied, we assume that the N is 100% in the form of nitrate. Manure is generally contained of mostly organic N, and a smaller amount of inorganic N (Ketterings et al., 2005; Pratt and Castellanos, 1981). In this study, we assume the manure composition as in the APEX database: 91.67% organic N, 8.33% inorganic N (0.23% nitrate and 8.10% ammonium N). In addition, the current study assumes that other nutrients (P, K and micro nutrients) do not to constrain crop production.

We simulate conventional tillage in APEX as two times ploughing to a depth of 20 cm at thirty and fifteen days before sowing date and one time harrowing following the emergence of the seed. The two times ploughing is the average of what is most common, namely one to three times tilling (Nagy and Rátonyi, 2013; FAO, 2016a). With the tillage depth of 20 cm we follow the average estimate reported by Townsend et al. (2015) and FAO (2016a). No-tillage, a form of conservation tillage that is strongly encouraged by the EU agricultural policy (De Vita et al., 2007), is simulated as no soil disturbance; the stubble of the previous crop is kept on the field.

We simulate full irrigation in APEX by irrigating up to field capacity as soon as the soil water content would otherwise drop below a level at which water stress occurs. Deficit irrigation is simulated to allow for 20% plant water stress, a deficit level that can achieve 61-100% of full ET (Fereres and Soriano, 2007). With this irrigation strategy, average water productivity is higher than in case of full irrigation (Chukalla et al., 2015). We assume the use of furrow irrigation, the irrigation technique that covered the largest irrigated area in the EU in 2010, particularly in the Eastern and Mediterranean regions of Europe (EUROSTAT, 2016a).

#### **4.2.5 Data**

The following climatic and soil data have been collected for Badajoz in Spain (38.88° N, - 6.83° E; 185 m above mean sea level). Daily observed rainfall and temperature data (for the period 1993-2012) are extracted from the European Climate Assessment and Dataset (Klein Tank et al., 2002). These data have been subject to homogeneity testing and missing data



have been filled with observations from nearby stations (Klein Tank, 2007). Mean monthly wind speed data are taken from the FAO CLIMAWAT database (Smith, 1993). Daily reference evapotranspiration is calculated using the Penman-Montheith equation, as implemented in APEX (Williams et al., 2008). The physical and chemical characteristics of the soil, and nutrient content in the soil (nitrogen, phosphorus, carbon) that are used in APEX are extracted from the 1×1 km<sup>2</sup> resolution European Soil Database (Hannam et al., 2009). Using the Soil Texture Triangle Hydraulic Properties Calculator from (Saxton et al., 1986), we identified the soil at our location as loam soil. We use a soil albedo of 0.13 for a loam soil at its field capacity (Sumner, 1999).

Regarding crop parameters, we use the default values from the APEX model. We simulate zero pest stresses (from insects and diseases) to crop growth.

Soil moisture content is initialised using the standard procedure in APEX, which is based on average annual rainfall within the period considered (1993-2012). We adjust initial organic-N content for each simulation so that the N build-up in the soil over the 20-year period is zero. We apply the graphical time-series inspection method (Robinson, 2002) to determine the warm-up period, i.e. the period in which simulation results are still affected by the model initialization. We find that we best exclude the first five years of the simulation, thus we show results for the period 1998-2012.

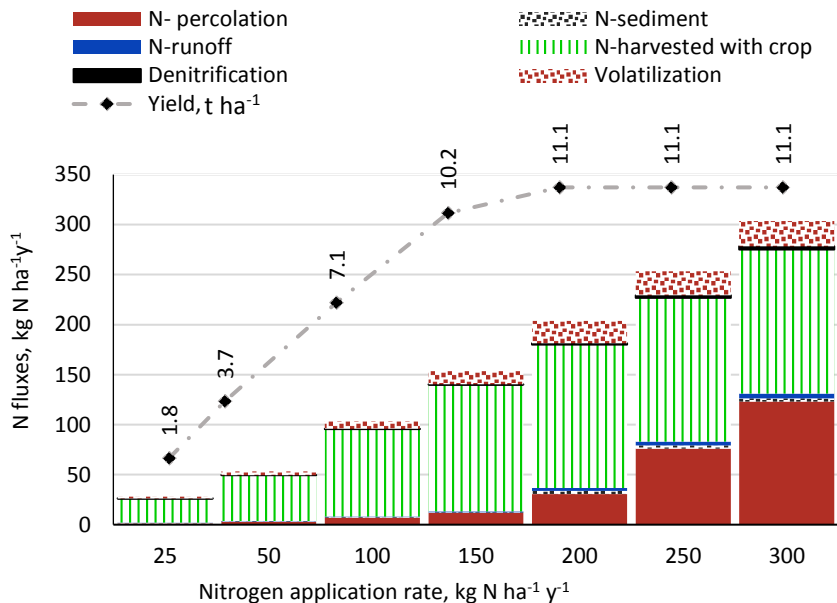
## **4.3 Results**

### **4.3.1 Pollutant loads and grey WF for the reference management package**

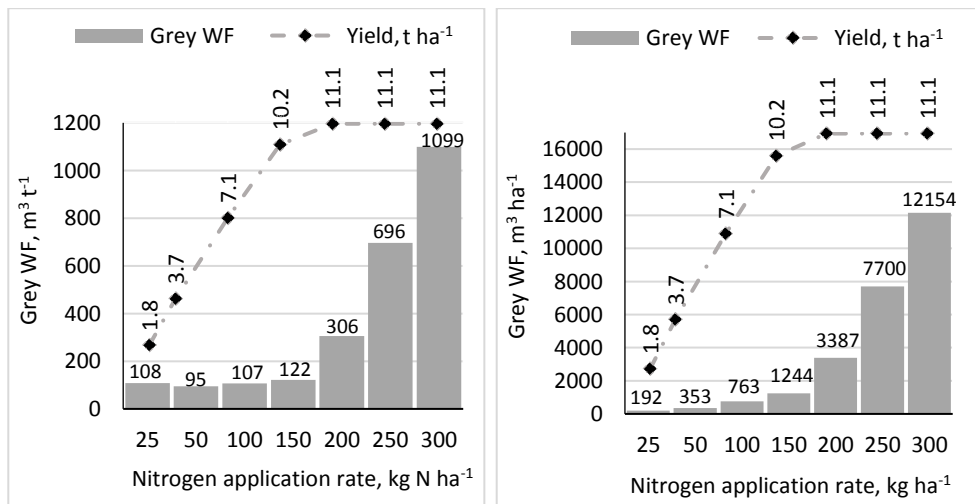
N out-fluxes from the soil for maize production under the reference management package (inorganic-N, conventional tillage, full irrigation) for different N application rates are shown in Figure 4.2. The N out-fluxes are denitrification and volatilization to the atmosphere, N harvested with the crop, and N loads to freshwater adhered to sediment and dissolved in percolation and runoff. All of these N out-fluxes increase with the N application rate and with the N surplus in the root zone (N application minus crop uptake). For all N application rates the N harvested with the crop is the main share of the N out-flux. For larger N application rates, the share of N leaching increases substantially. For all application rates, N leaching to groundwater constitutes at least 95% of the total N load to freshwater, and the N flux to surface water (N dissolved in runoff plus N in eroded sediments) 5% at most.

Crop yields increase with the N application rate as a result of reduced N stress. Yields stabilize at larger N application rates. The yield increase, however, comes at a price: the N load to freshwater, through leaching, runoff and eroded sediment, increases exponentially. As a result, large N-application rates result in a large grey WF (Figure 4.3). At lower N-application rates, crop yields decline as a consequence of N stress. While the grey WF in m<sup>3</sup> ha<sup>-1</sup> keeps on declining with lower N-application rates, the grey WF in m<sup>3</sup> t<sup>-1</sup> starts increasing again at very low N-application rate (in our case when the N-application rate drops below 50 kg N ha<sup>-1</sup>). The smallest grey WF per tonne can be found at an N-application rate of 50 kg N ha<sup>-1</sup>, where yield is substantially lower than the maximum, but where additional N

application goes along with increasing N load per unit of crop yield gain, thus with increasing grey WF per tonne.



**Figure 4.2** Nitrogen out-fluxes and yield for an irrigated maize field for a range of N-application rates under the reference management package (inorganic-N, conventional tillage, full irrigation).



**Figure 4.3** Grey WF of maize production in  $\text{m}^3 \text{t}^{-1}$  (left) and  $\text{m}^3 \text{ha}^{-1}$  (right) for a range of N-application rates under the reference management package.

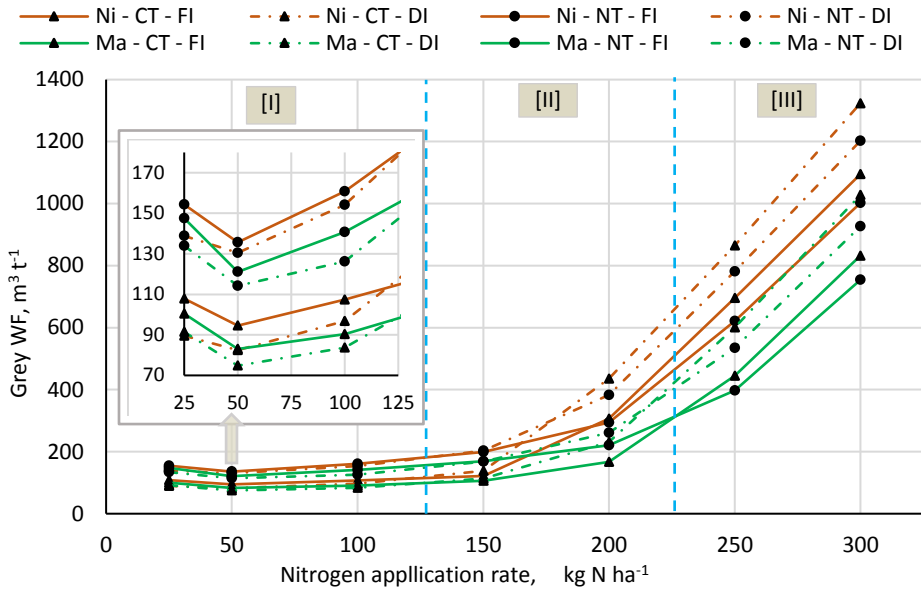
### 4.3.2 Effect of fertilizer form, tillage practice and irrigation strategy on grey WF

Figure 4.4 shows that, at a given N-application rate, the grey WF in  $\text{m}^3 \text{t}^{-1}$  can be higher or lower than for reference management package, by changing to manure, no-tillage or deficit irrigation, or a combination of those. Across the whole range of N application rates, the use of manure results in a smaller grey WF per tonne than the use of nitrate fertilizer. The effect of the tillage practice and irrigation strategy on the grey WF depends on the N-application rate. We can identify three ranges for the application rate, each with a different management package resulting in the smallest grey WF per tonne:

- I. Application rates up to  $125 \text{ kg N ha}^{-1}$ : the grey WF is smallest for manure with conventional tillage and deficit irrigation;
- II. Application rates between  $125$  and  $225 \text{ kg N ha}^{-1}$ : the grey WF is smallest for manure with conventional tillage and full irrigation;
- III. Application rates above  $225 \text{ kg N ha}^{-1}$ : the grey WF is smallest for manure with no-tillage and full irrigation.

At low and intermediate N-application rates (ranges I-II), the advantage of conventional tillage over no-tillage is that it decreases the hydraulic conductivity of the soil (because of the removal of fine cracks in the soil), which reduces percolation and thus N leaching. At high N-application rates (range III), no-tillage appears to be better. The disadvantage of increased hydraulic conductivity is now compensated by another effect: no-tillage results in improved soil texture: the soil remains intact, which in combination with the build-up of organic content creates favourable conditions for soil organisms that help to glue the soil particles and increase the number of micro-pores and macro-pores in the soil. This increases the soil water holding capacity and thus N holding capacity of the soil, resulting in lower N leaching (by 30%) and higher yield (by 3.6%).

At low application rates (range I), deficit irrigation decreases the amount of water available for percolation and thus reduces N leaching as well. At intermediate and higher N-application rates (ranges II-III), full irrigation has a smaller grey WF per tonne as compared to deficit irrigation because of the higher crop yield. With the absence of water stress and the higher yield, the N uptake by the crop is higher, resulting in a lower N surplus in the root zone and decreased N leaching.



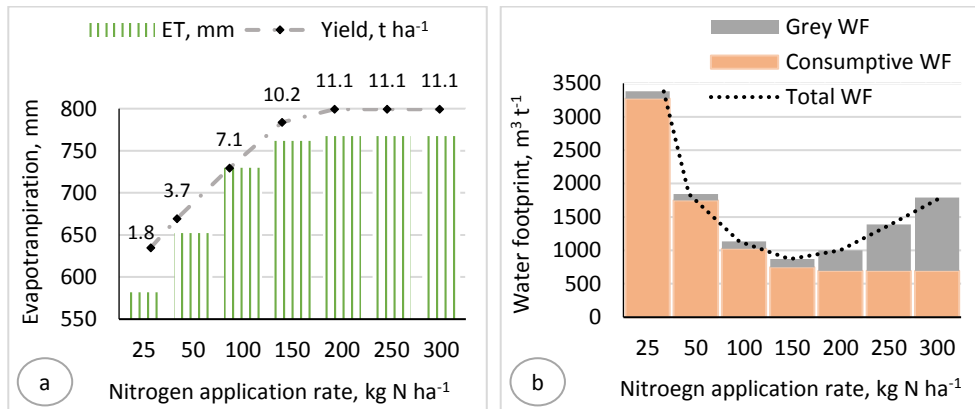
**Figure 4.4** The effect of N application rate, N form, tillage practice and irrigation strategy on grey WF per tonne. Considering which management package gives the lowest grey WF, three ranges can be distinguished: [I] N application rates up to 125 kg N ha<sup>-1</sup>, [II] N application rates between 125 and 225 kg N ha<sup>-1</sup>, [III] N application rates above 225 kg N ha<sup>-1</sup>. Red lines refer to nitrate (Ni); green lines refer to manure (Ma). Circular markers refer to no-tillage (NT); triangular markers refer to conventional tillage. Dashed lines refer to deficit irrigation (DI); solid lines refer to full irrigation (FI).

The smallest grey WF per tonne are found for an N application rate of 50 kg N ha<sup>-1</sup>. Taking the reference management package with an N application rate of 300 kg N ha<sup>-1</sup> as a starting point, one can reduce the grey WF per tonne of crop production by reducing the N application rate while keeping the management package fixed, by shifting the management package to one with a smaller grey WF, or both (Table 4A.1 in Appendix 4A). Reducing the N application rate from 300 kg N ha<sup>-1</sup> to the optimum of 50 kg N ha<sup>-1</sup> under the reference management package will reduce the grey WF by 91% (from around 1100 to 95 m<sup>3</sup> t<sup>-1</sup>), but the crop yield will reduce by two thirds (from 11.1 to 3.7 t ha<sup>-1</sup>). When, at the application rate of 50 kg N ha<sup>-1</sup>, shifting from the reference management package to organic N and deficit irrigation, one can further reduce the grey WF by 21% (from around 95 to 75 m<sup>3</sup> t<sup>-1</sup>), with a yield reduction of 5% (from 3.7 to 3.5 t ha<sup>-1</sup>).

### 4.3.3 Reducing grey WF vs consumptive WF

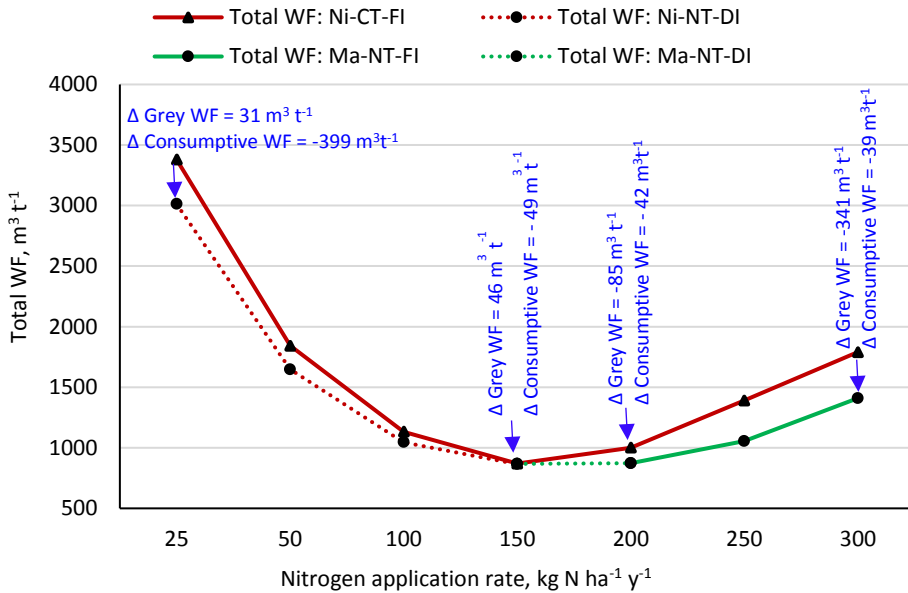
Both ET and yield increase with increasing N application rate, but level off at large N application rates (Figure 4.5a). Adding more N at relatively low application rates has a larger impact on Y increase than on ET increase. As a result, the consumptive WF per tonne, defined as ET over Y, decreases with increasing N application rate, levelling off at larger N

application rate (Figure 4.5b). The grey WF per tonne, however, exponentially increases with increasing N application rate. As a result, the sum of grey and consumptive WF has a minimum somewhere at intermediate N application rate, at 150 N ha<sup>-1</sup> in the case of our reference management package. The total WF is dominated by the consumptive WF for smaller N application rates and by the grey WF for larger N application rates.



**Figure 4.5** Evapotranspiration and crop yield (a) and consumptive WF and grey WF per tonne (b) for the reference management package.

Figure 4.6 shows the total (grey+consumptive) WF per tonne for the reference management package for different N application rates (the solid red line). For each given N application rate, shifting to another management package can reduce the total WF. At N application rates of 25, 50 and 100 kg N ha<sup>-1</sup>, the total WF can be reduced by shifting towards no-tillage and deficit irrigation. At N application rates of 150 kg N ha<sup>-1</sup>, the total WF can be reduced by shifting towards organic N, no-tillage and deficit irrigation. Finally, at N application rates of 200, 250 and 300 kg N ha<sup>-1</sup>, the total WF can be reduced by shifting towards organic N and no-tillage. The total WF reductions shown in the figure are the net effect of changes in the consumptive WF and grey WF; in some cases the total WF decrease is at the cost of some grey WF increase.

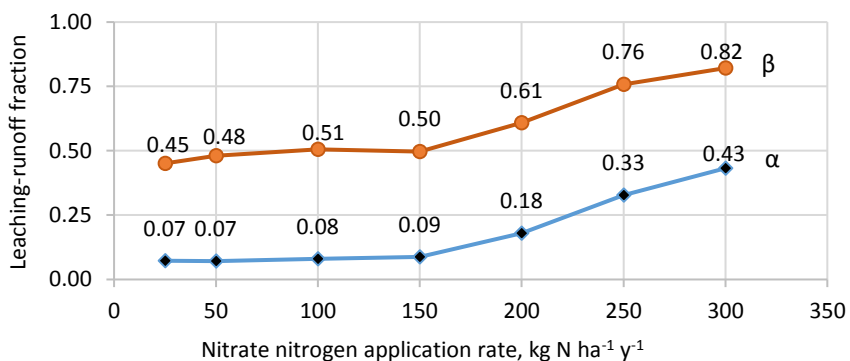


**Figure 4.6** The total (green, blue plus grey) WF per tonne for the reference management package and for a management package with the largest total WF reduction potential. Red lines refer to nitrate (Ni); green lines refer to manure (Ma). Circular markers refer to no-tillage (NT); triangular markers refer to conventional tillage. Dashed lines refer to deficit irrigation (DI); solid lines refer to full irrigation (FI).

#### 4.3.4 Resultant leaching-runoff fractions

The N leaching-runoff fractions  $\alpha$  and  $\beta$  for different N application rates for the reference management package, as calculated here with the tier-3 approach, are shown in Figure 4.7. The  $\alpha$  values, which show the ratio of the N load to fresh water to the N application rate are lower than the  $\beta$  values, which show the ratio of the N load to the N surplus in the soil. This can be logically understood, because the N load to freshwater (in the numerator of both ratios) is the same, while the  $\alpha$  ratio has the total N application rate in the denominator, while the  $\beta$  ratio has the relatively smaller N surplus (which is only a fraction of the N applied) in the denominator.

With increasing N application rate, both N surplus in the soil and the N load to freshwater increase exponentially (Figure 4.2). The  $\alpha$  values grow with increasing N application rate, because the N load to freshwater increases quicker with increasing N application rates than the application rate itself. The  $\beta$  values also grow with increasing N application rates, because denitrification and volatilization do not grow proportionally to the growth in N surplus, which leads to greater fractions of the surplus getting lost through leaching and runoff.

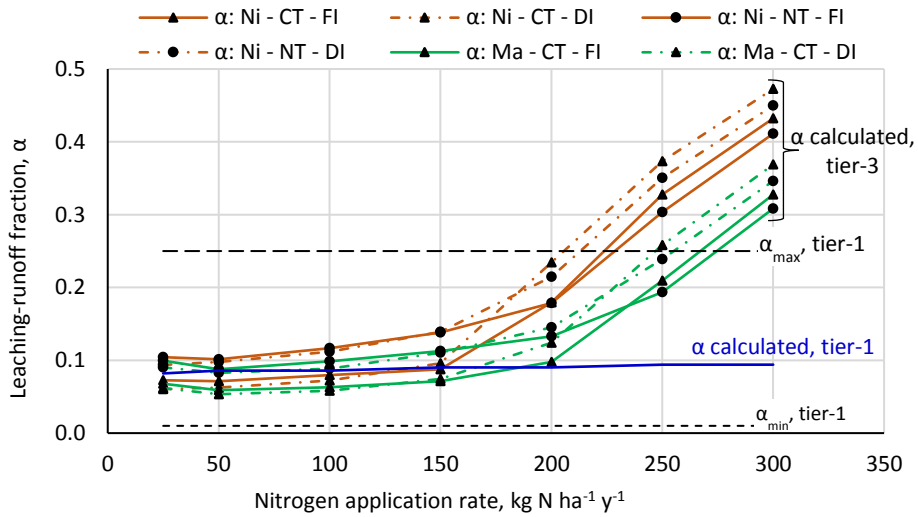


**Figure 4.7** The N leaching-runoff fractions  $\alpha$  and  $\beta$  calculated per N application rate for the reference management package.

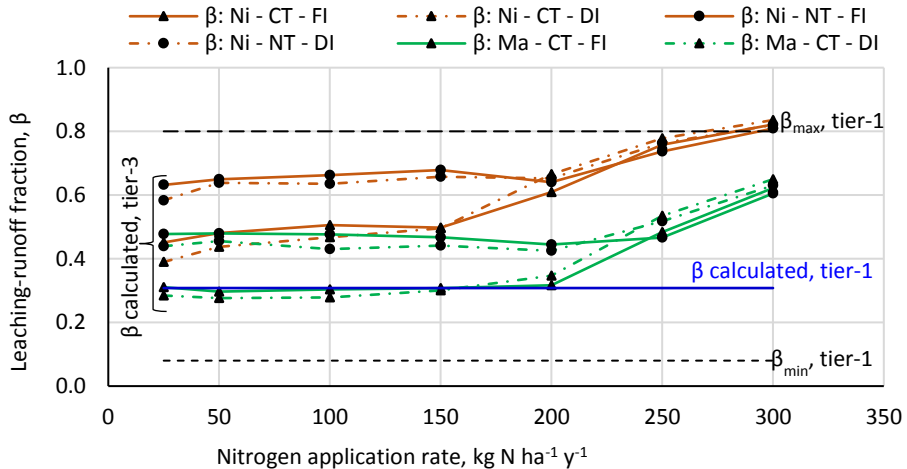
Figure 4.8 and Figure 4.9 show  $\alpha$  and  $\beta$  values for different management packages and N application rates. For comparison, the figures also show the  $\alpha$  and  $\beta$  values when estimated based on the simpler tier-1 approach (Tables 4A.2 and 4A.3 in Appendix 4A), which estimates  $\alpha$  and  $\beta$  within minimum and maximum values based on context-specific environmental and management factors (see section 4.2.3). The calculated leaching-runoff fractions based on the APEX model (tier-3 approach) for all management packages across the range of N application rates fall within the range set by the minimum and maximum leaching-runoff fractions margins as applied in the tier-1 approach (Franke et al., 2013), except for  $\alpha$  for very high N application rates.

For N applications rates in the range up to 150 kg ha<sup>-1</sup>, the tier-1 approach gives a good proxy for the  $\alpha$  value. For the reference management package, the most common practice, the tier-1 approach even yields nearly the same  $\alpha$  values as the more advanced tier-3 approach. For N applications rates exceeding about 150 kg ha<sup>-1</sup>, the tier-1 approach underestimates the leaching-runoff fraction and thus the grey WF. The  $\beta$  values estimated based on the tier-1 approach are comparable to the ones calculated at the tier-3 level for the management packages with manure and conventional tillage. For the other management packages,  $\beta$  is underestimated with the tier-1 approach. Also for N application rates of 250 kg ha<sup>-1</sup> and beyond, the tier-1 approach underestimates  $\beta$ .

The leaching-runoff fractions from the application of inorganic N (nitrate) calculated at the tier-3 level are larger than these for organic N (manure), a distinction that is not made in the tier-1 approach.



**Figure 4.8** N leaching-runoff fractions  $\alpha$  for different management packages and N application rates following from the tier-1 or tier-3 approach. Red lines refer to nitrate (Ni); green lines refer to manure (Ma). Circular markers refer to no-tillage (NT); triangular markers refer to conventional tillage. Dashed lines refer to deficit irrigation (DI); solid lines refer to full irrigation (FI).



**Figure 4.9** N leaching-runoff fractions  $\beta$  for different management packages and N application rates following from the tier-1 or tier-3 approach. Red lines refer to nitrate (Ni); green lines refer to manure (Ma). Circular markers refer to no-tillage (NT); triangular markers refer to conventional tillage. Dashed lines refer to deficit irrigation (DI); solid lines refer to full irrigation (FI).



## 4.4 Discussion

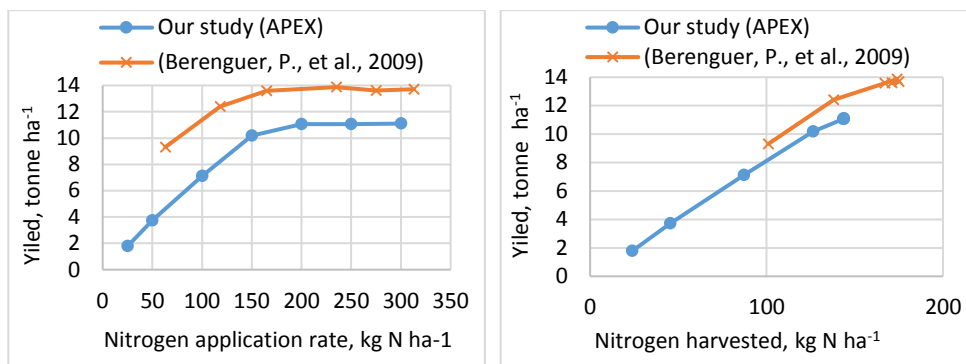
The study shows that there is not one combination of management practices that minimises grey WF or overall WF and maximises crop yield at the same time. Table 4.2 shows that the best combination of practices depends on what variable is optimised. Yield is optimal when there is neither nitrogen stress nor water stress, so at high N application rate and full irrigation. The highest yield (11.5 t/ha) is found for when N is applied in the form of manure and the case of no-tillage. The total WF per tonne (the sum of the green, blue and grey WF) is smallest at 150 kg N ha<sup>-1</sup>, manure application, no-tillage and deficit irrigation. The yield in this case, 9.3 t/ha, is below-optimum. There is both nitrogen and water stress, but the latter is more important. The grey WF per tonne is smallest at 50 kg N ha<sup>-1</sup>, manure application, conventional tillage and deficit irrigation. This, however, reduces the yield to 3.5 t/ha because of nitrogen stress. Deficit irrigation gives some water stress as well, but at such high nitrogen stress, it is the latter that constrains crop yield. Our results confirm the finding by (Mekonnen and Hoekstra, 2014) that there is a trade-off between consumptive WF per tonne and grey WF per tonne, i.e. a trade-off between reducing water consumption and water pollution.

**Table 4.2** The measures that give the optimum grey WF per tonne, total WF per tonne, or yield.

Indicator	Highest crop yield t ha <sup>-1</sup>	Smallest total WF* m <sup>3</sup> t <sup>-1</sup>	Smallest grey WF m <sup>3</sup> t <sup>-1</sup>
Management practice			
Nitrogen application rate	200 kg N ha <sup>-1</sup>	150 kg N ha <sup>-1</sup>	50 kg N ha <sup>-1</sup>
Nitrogen form	Manure	Manure	Manure
Tillage practice	No-tillage	No-tillage	Conventional tillage
Irrigation strategy	Full irrigation	Deficit irrigation	Deficit irrigation

\* Total WF refers to the sum of the green, blue and grey WF.

The response of maize yield to nitrogen input as simulated in this study with the APEX model is comparable with the shape of the N-response curves for a few crops, including maize, constructed for the EU based on field measurements from various earlier studies (Godard et al., 2008). Our finding is also consistent with the results presented by Berenguer et al. (2009), who carried out field experiments for maize for similar conditions in Spain (Figure 4.10). For every given N input, their yields are a bit higher than from our study, which may relate to the fact that Berenguer et al. (2009) used a high-yield maize variety.



**Figure 4.10** The maize yield simulated in our study in relation to N application rate (left) and N harvested with maize (right) in comparison to the maize yields from field experiments by Berenguer et al. (2009) when corrected for zero N build-up in the root zone.

An inter-model comparison for the case of no N stress and no water stress (taking optimal N application rate and full irrigation) for exactly the same growing conditions in Spain shows similar crop yields and net irrigation supply. The current study, using the APEX model, simulates a net irrigation supply of 638 mm and a maize yield of 11.1 t ha<sup>-1</sup>, while in an earlier study, employing the AquaCrop model (Steduto et al., 2011), we simulate an irrigation supply of 630 mm and a maize yield of 11.9 t ha<sup>-1</sup> (Chukalla et al., 2015).

Simulated yields, N loads to freshwater and grey WFs under different management packages are subject to the local environmental conditions of our case in Spain, which means that they cannot simply be transferred to other conditions. Besides, even for our specific case, the outcomes are subject to uncertainties inherent to any modelling effort (Kersebaum et al. (2016)). We have also excluded other factors relevant in crop production, like the effects of weeds, pests and diseases. Therefore, the precise values presented should be taken with caution; the value of our study rather lies in the understanding it provides on how different agricultural management practices can affect yield, N load and resultant grey WF of crop production, and how and why there are inevitable trade-offs between crop yield, water consumption and water pollution.

## 4.5 Conclusion

This paper provides the first detailed study on potential grey WF reduction of growing a crop by analysing the effect of a large number of combinations of different management practices. The paper shows that, when choosing a certain N application rate and when choosing between inorganic versus organic fertilizer, between conventional versus no tillage, and between full versus deficit irrigation, two inevitable trade-offs are made. The first trade-off is between crop yield and water pollution (grey WF). Whereas maximizing crop yields requires a relatively high N application rate and full irrigation, minimizing water pollution per unit of crop requires deficit irrigation and seeking a balance between N application rate (and associated water pollution) and the resultant yield. The second trade-

off is between reducing water pollution (grey WF) and water consumption (green and blue WF). Minimizing consumptive water use per tonne requires a higher N application rate (150 kg N ha<sup>-1</sup> in our case) than minimizing water pollution per tonne (50 kg N ha<sup>-1</sup> in our case). Applying manure instead of inorganic-N and deficit instead of full irrigation are measures that reduce both water pollution and water consumption per tonne. However, for minimizing water pollution per tonne one can better choose for conventional tillage, because that reduces leaching, whereas for minimizing water consumption per tonne the no-tillage practice is to be preferred, because that reduces soil evaporation.

The study gives some support to the simple tier-1 approach of estimating the grey WF of applying N fertilizer as proposed by Franke et al. (2013), but only for N application rates below 150 kg ha<sup>-1</sup>. Below that, the  $\alpha$  value is estimated in the proper range (in our specific case), but the  $\beta$  value is underestimated. Beyond the N application rate of 150 kg ha<sup>-1</sup>, the tier-1 approach underestimates the leaching-runoff fraction, by not accounting for the fact that N uptake by the crop is stabilizing and that denitrification and volatilization don't increase proportionally with growing N inputs, which results into an increasing fraction of the N surplus in the soil lost through leaching, runoff and erosion.

## Appendices 4A

**Table 4A.1** Grey WF per tonne of crop production for the different management packages.

Management packages			Nitrogen application rate						
	Tillage practice	Irrigation strategy	25	50	100	150	200	250	300
Nitrate	Conventional	Full irrigation	108	95	107	122	306	696	1095
Nitrate	Conventional	Deficit irrigation	90	82	97	138	436	865	1324
Nitrate	No-tillage	Full irrigation	154	136	161	199	294	621	1002
Nitrate	No-tillage	Deficit irrigation	139	130	154	203	383	781	1202
Manure	Conventional	Full irrigation	100	83	90	106	167	445	832
Manure	Conventional	Deficit irrigation	91	75	84	114	231	600	1028
Manure	No-tillage	Full irrigation	148	121	141	170	221	397	754
Manure	No-tillage	Deficit irrigation	134	114	126	168	261	534	927

**Table 4A.2** N leaching-runoff potential scores for environmental factors and agricultural practices, following the tier-1 approach (Franke et al., 2013).

Factors			Weight		Score (s)	Remark
			$\alpha$	$\beta$		
	Atmospheric	N-deposition	10	10	0	RFN=0.34 g m <sup>-2</sup> y <sup>-1</sup> less than 0.5
		Texture (for leaching)	15	15	0.67	Loam soil

		Texture (for runoff)	10	10	0.33	Loam soil
		Natural drainage (for leaching)	10	15	0.67	Assumed well drained
		Natural drainage (for runoff)	5	10	0.33	Assumed well drained
Climate	Precipitation (mm)	15	15	0	0-600 very low precipitation (450mm)	
	N-fixation (kg ha <sup>-1</sup> )	10	10	0	Non legume crops	
	Application rate	10	0	*		
	Plant uptake (crop yield)	5	0	*		
	Management practice	10	15	0.33	Assumed good management practices	

\* See Table 4A.3.

**Table 4A.3** N leaching-runoff potential scores based on fertilizer application rate and plant uptake, and calculated  $\alpha$  and  $\beta$  values following the tier-1 approach.

Fertilizer application kg ha <sup>-1</sup>	Categorized	Score for application rate	Score for plant uptake	Calculated $\alpha$ and $\beta$	
				$\alpha$	$\beta$
25	Very low	0	1	0.08	0.308
50	Low	0.33	0.67	0.09	0.308
100	Low	0.33	0.67	0.09	0.308
150	High	0.67	0.33	0.09	0.308
200	High	0.67	0.33	0.09	0.308
250	Very high	1	0	0.09	0.308
300	Very high	1	0	0.09	0.308

# 5 Trade-off between blue and grey water footprint of crop production at different nitrogen application rates under various field management practices<sup>4</sup>

## Abstract

In irrigated crop production, nitrogen (N) is often applied at high rates in order to maximize crop yield. With such high rates, the blue water footprint (WF) (the irrigation water volume consumed per unit of crop) is low, but the grey WF (the polluted water volume per unit of crop yield) is relatively high. This study explores the trade-off between blue and grey WF at different N-application rates (from 25 to 300 kg N ha<sup>-1</sup> y<sup>-1</sup>) under various field management practices. We first analyse this trade-off under a reference management package (applying inorganic-N, conventional tillage, full irrigation). Next, we estimate the economically optimal N-application rate when putting a price to pollution. Finally, we consider the blue-grey WF trade-off for other management packages, varying the form of N applied (inorganic-N or organic-N), the tillage practice (conventional tillage or no-tillage), and the irrigation strategy (full or deficit irrigation). We use the APEX model to simulate soil water and N balances and crop growth, and the Global Water Footprint Standard to calculate blue and grey WFs per unit of crop. As a case study, we consider irrigated maize on loam soil for the period 1998-2012 in a typical semi-arid environment, Badajoz in Spain. The results for the reference package show that increasing N application from 50 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, with crop yield growing by a factor 3, involves a trade-off, whereby the blue WF per tonne declines by 60% but the grey WF increases by 210%. Increasing N application from 25 to 50 kg N ha<sup>-1</sup> y<sup>-1</sup>, with yield increasing by a factor 2, is a no-regret move, because blue and grey WFs per tonne are reduced by 40% and 8%, respectively. Decreasing N application from 300 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup> is a no-regret move as well, with a grey WF per tonne reduced by 72% while the blue WF and yield remain the same. The minimum blue WF per tonne is found at N application of 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, while the minimum grey WF per tonne is at 50 kg N ha<sup>-1</sup> y<sup>-1</sup>. When we put a price to water pollution of 8 \$ kg<sup>-1</sup> of N load to water at least, the economically optimal N-application rate is 150 kg N ha<sup>-1</sup> y<sup>-1</sup>. The findings are similar for all other management packages. The study shows that shifting between different management practices with fixed N-application rate, is no-regret in some instances, but implies a blue-grey WF trade-off in other instances.

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<sup>4</sup> The Chapter has been submitted to *Science of the Total Environment*.

**Key words:** water pollution; nitrogen balance; soil water balance; irrigation; crop growth; APEX model.

## 5.1 Introduction

It has often been argued that increasing crop yield through increased use of inputs (intensification) is preferred over expanding the areal extent of less intensive production methods, in order to fulfil increasing global food demand, as it avoids disruption of the ecosystems and greenhouse gas emissions that come along with enlarging the agricultural area (Edgerton, 2009; Pradhan et al., 2015). In water-scarce areas, intensification is expected to be achieved on existing irrigated areas (Playán and Mateos, 2006). Research on 'closing the yield gap' tends to focus on maximizing land productivity through increasing the necessary inputs. Closing the yield gap, however, requires a careful balance between increasing land productivity and the efficient use of water and nutrients, because a focus on maximizing yields may come at the price of intensified resource use and pollution (Foley et al., 2011). With increasing inputs, the additional yield gain can be steep initially, but becomes less and less at higher input levels. This holds for adding more nutrients (Godard et al., 2008) as well as for adding more irrigation water (Steduto et al., 2012; Amarasinghe and Smakhtin, 2014). While intensification of agriculture comes along with widespread eutrophication of water (Carpenter et al., 1998), it also increasingly faces the problem of limitations in water availability (Davis et al., 2017). It is therefore relevant to consider not only crop yield, but also irrigation water consumption (blue water footprint) per tonne of crop produced and water pollution (grey water footprint) per tonne of crop (Hoekstra et al., 2011).

With increasing irrigation rate, the blue water footprint (WF) per tonne of crop will initially reduce, because of the high marginal yield gain per additional unit of water, but it will start to increase after the point of highest marginal water productivity (Chukalla et al., 2015). Similarly, with increasing N-application rate, the N load to fresh water per tonne of crop, and thus the grey WF per tonne, may initially decrease, but it will quickly increase at higher N-application rates (Valero et al., 2005; Zhou et al., 2011; Good and Beatty, 2011). Therefore, considerations on intensification are confronted with trade-offs between crop yield (and linked to it revenue per hectare) and environmental impacts (blue and grey WF).

The intensity of irrigation links to the blue WF and the intensity of N inputs to the grey WF. Crop yields depend on the combination of N and irrigation water inputs, however, so that the blue WF per tonne also depends on the N-application rate, and the grey WF per tonne also depends on the irrigation water volume applied. Previous studies show that increasing the rate of irrigation may increase nitrogen productivity and increasing the N-application rate may increase water productivity (Molden et al., 2010; Al-Kaisi and Yin, 2003). Other studies show that N leaching, and thus the grey WF per tonne, increases not only with N-application rate, but also with irrigation (Valero et al., 2005; Schröder et al., 2007; Al-Kaisi and Yin, 2003). A smart combination of management practices can increase the efficient use of both water and N fertiliser, by reducing unproductive losses like soil evaporation and N

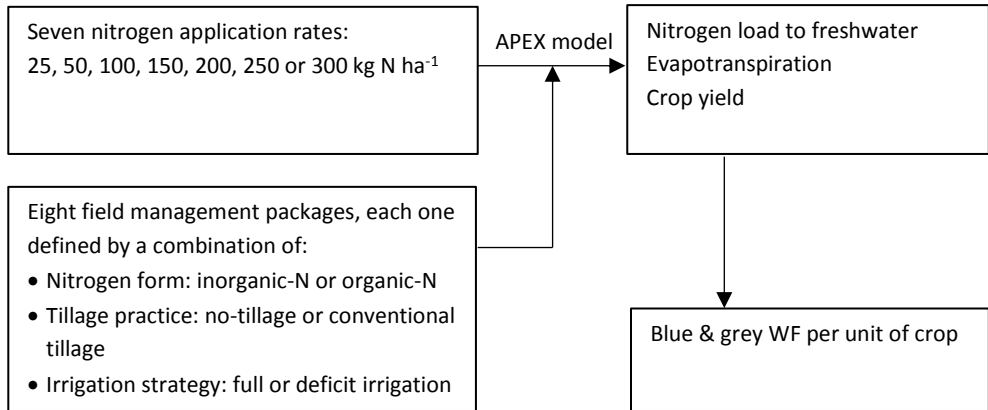
losses to freshwater and the atmosphere (Zhou et al., 2011;Carpenter et al., 1998). Important managerial factors include the irrigation technique and application strategy, the mulching practice and the tillage practice (Chukalla et al., 2015;Derpsch et al., 2010;Grandy et al., 2006;Huang et al., 2015). Some earlier studies provide insight in the effect of individual or combined management practices on the blue WF per tonne, or the N load to freshwater, but do not consider trade-offs that may occur between the blue and grey WF in crop production. The current study focuses on this blue-grey WF trade-off. Since experimental field studies are expensive in terms of the time and resources when one wants to study a wide variety of management conditions, we have chosen here a model-based approach to study water and nutrient balances and crop growth.

The objective of the current study is to explore the trade-off between the blue and grey WF per tonne of crop at different N-application rates, under various field management practices. As a reference, we consider the common combination of applying inorganic-N, conventional tillage and full irrigation. We study other management packages by changing the form of fertilizer (inorganic-N or organic-N), the tillage practice (conventional or no-tillage) and the irrigation strategy (full or deficit irrigation). As a case study, we consider irrigated maize over a 15-years period (1998-2012) on a loam soil in Badajoz, Spain, which is a semi-arid environment. We use the Agricultural Policy and Environmental eXtender (APEX) model, which simulates water and nutrient balances and crop growth (Williams and Izaurralde, 2006). This model is able to successfully simulate the effect of a wide array of field management practices (Wang et al., 2012;Gassman et al., 2010;Gaiser et al., 2010), and has been applied for a wide range of environments, including semi-arid conditions in Spain (Cavero et al., 2012).

## **5.2 Method and data**

### **5.2.1 Research set-up**

We use the APEX model to simulate the effect of seven nitrogen application rates on evapotranspiration, N load to freshwater, and crop yield, and subsequently compute the resultant blue and grey water footprints. We do this for eight field management packages, which results in 56 simulations altogether (Figure 5.1). Each management package constitutes of a combination of management practices: application of inorganic-N or organic-N, no-tillage or conventional tillage, and full or deficit irrigation. The combination of inorganic-N fertilizer with conventional tillage and full irrigation is assumed as a reference management package.



**Figure 5.1** Model experimental set-up: simulating the effect of seven nitrogen application rates on evapotranspiration, N load to freshwater, crop yield, and blue and grey water footprint, under eight field management packages.

The rate of N application in EU member states is legally restricted by the EU Nitrates Directive to  $170 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , or in case of derogation up to  $250 \text{ kg N ha}^{-1}$  (Van Grinsven et al., 2012; Amery and Schoumans, 2014). However, surveys in Spain show that application rates of  $300\text{-}350 \text{ kg N ha}^{-1} \text{ y}^{-1}$  are still common to cultivate maize in the Ebro Valley (Berenguer et al., 2009) and up to  $300 \text{ kg N ha}^{-1}$  in La Mancha (Valero et al., 2005). In our simulations, we therefore use  $300 \text{ kg N ha}^{-1}$  as an upper value for the N-application rate.

## 5.2.2 Soil water and nitrogen balances and crop growth simulation

The soil water and nitrogen balances and crop growth under different conditions are simulated with a daily time step using APEX, a dynamic, deterministic and physical-based model (Williams and Izaurralde, 2006). A brief summary of the processes simulated in the APEX model, provided in detail in the documentation of APEX (Williams et al., 2008), is given below.

In the water balance routines, the incoming rainfall or irrigation is partitioned between surface runoff and infiltration. Infiltrated water partly gets stored in the soil profile, partly gets lost via evapotranspiration (ET), partly percolates vertically to groundwater, and partly flows out laterally, eventually splitting up into quick return flow and lateral subsurface flow.

In the N balance calculation, APEX considers N addition to the soil in the form of anthropogenic N fertilizer and N manure addition, as well as atmospheric dry and wet N deposition. N out-fluxes from the root zone to the atmosphere included are denitrification and volatilization. Out-fluxes to the freshwater body concern N dissolved in runoff, quick return flow, lateral subsurface flow and percolation, and N adsorbed to sediments, while another out-flux describes N harvested with the crop. Simulated N transformations concern mineralization, immobilization, and nitrification.



APEX simulates the potential crop growth based on the interception of active radiation by the plant canopy, which is characterized by the leaf area index (Williams et al., 1989). Phenological development of the crop is based on daily heat unit accumulation from planting to harvest date, or until the accumulated heat units equal the potential heat units for the crop (Steduto, 1997;McMaster et al., 2005). Actual daily crop growth is constrained by the most limiting of four stress factors modelled (water, temperature, N-fertilizer, and aeration in the root zone). The marketable yield is obtained by multiplying the above-ground biomass with a harvest index, which may be affected by water stress and growing season length.

N application just before or during the growing season is done in two rounds. In the first round, 30% of the total is applied. Inorganic N is applied through broadcasting at planting; organic N (manure) is applied through injection 15 days before planting. In the second round, in which the remaining 70% of the total is put on the field, both forms of N fertilizer are applied as side-dressing one month after planting. The inorganic N is assumed to be in the form of nitrate. The manure composition is assumed as in the APEX database, as 91.7 % organic N and 8.3 % inorganic-N.

Conventional tillage is simulated as two times ploughing to a depth of 20 cm at thirty and fifteen days before sowing date, and one time harrowing following the emergence of the seed. The two times ploughing is in the range of the common one to three times tilling (Nagy and Rátonyi, 2013;FAO, 2016a); the ploughing depth of 20 cm is the average estimate reported by Townsend et al. (2015) and FAO (2016a). No-tillage, a form of conservation tillage encouraged by the EU agricultural policy (De Vita et al., 2007), is simulated as no soil disturbance; crop residues are kept on the field giving year-round soil cover.

Full irrigation is simulated by supplying irrigation water when the soil moisture content in the root zone would otherwise drop below a level at which water stress occurs, and irrigating a volume that raises the soil moisture content to field capacity. Deficit irrigation is simulated by allowing the soil moisture to drop to a level where the crop is moderately water-stressed (20% plant water stress level in APEX); when that level is reached, irrigation is done to bring the soil moisture to field capacity. In this manner, soil water deficits can reach up to 61-100% of total ET over the growing period (Feres and Soriano, 2007). We assume the use of furrow irrigation, the dominant irrigation technique in the EU in 2010, particularly in the Eastern and Mediterranean parts of Europe (EUROSTAT, 2016a).

### **5.2.3 Blue and grey water footprints of growing crops**

The blue and grey water footprint (WF) of crop production are indicators of the consumption and pollution, respectively, of groundwater or surface water (Hoekstra, 2017)The blue WF of crop production is defined as the volume of irrigation water consumed (evaporated or incorporated into the crop) in the process of growing crops (Hoekstra et al., 2011). The blue WF per area is calculated by accumulating the daily blue evapotranspiration

(ET) during the crop growing season, expressed as a volume per ha. The blue WF per unit of harvested crop is calculated as the ratio of accumulated blue ET to crop yield, expressed as a volume per tonne of crop. Blue ET is the ET from irrigation water, which is estimated at daily resolution by multiplying ET by the fraction of blue water in the total soil water content in the root zone (Chukalla et al., 2015).

The grey WF of crop production is defined as the volume of freshwater needed to assimilate the load of pollutants, emitted through the production process, based on natural background and existing ambient water quality standards. The grey WF per area (in volume per ha per year) is calculated by dividing the accumulated daily simulated N loads to freshwater by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration) and its natural concentration in the receiving water body (Hoekstra et al., 2011). The grey WF per unit of product is expressed in volume per tonne of crop by dividing the grey WF per area by the marketable crop yield (tonne). A maximum acceptable N concentration of 50 mg nitrate-N L<sup>-1</sup> (or 11.3 mg N L<sup>-1</sup>) is adopted, based on the EU Nitrates Directive (Monteny, 2001). The natural concentration was considered to be 0.5 mg N L<sup>-1</sup>, following for example (de Miguel et al., 2015).

#### **5.2.4 Benefit versus cost associated with increasing nitrogen application when putting a price to pollution**

We analyse when additional revenues of N application (because of increased crop yield) outweigh the cost associated with additional N application (because of increased N and irrigation water costs and because of increased water pollution). The gross revenue of crop production ( $\$ \text{ha}^{-1} \text{y}^{-1}$ ) is calculated at different N-application rates in case of the reference management package by multiplying crop yield (tonne  $\text{ha}^{-1} \text{y}^{-1}$ ) and the price of the crop ( $\$ \text{tonne}^{-1}$ ). The cost of N per ha for each N-application rate is calculated by multiplying the N-application rate (kg N  $\text{ha}^{-1} \text{y}^{-1}$ ) by the price of fertilizer ( $\$ \text{kg}^{-1}$ ). At increasing N-application rates, irrigation water application is higher as well, because of the better crop growth and associated additional transpiration of the plants; the cost of the irrigation water per ha for each N-application rate is calculated by multiplying the total volume of irrigation water used ( $\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$ ) by the price of water ( $\$ \text{m}^{-3}$ ). The cost of water pollution is expressed in terms of a price to the N load to water ( $\$ \text{kg}^{-1}$ ). We gradually increase this price, starting from zero, to find at what level, a price of water pollution will lower the economically optimum N-application rate.

#### **5.2.5 Data**

While we simulate the full consecutive period 1993-2012, we show results based on average values over the period 1998-2012, excluding the first five years of the simulation, which was identified as the warm-up period using graphical time-series inspection (Robinson, 2002). Climatic and soil data as input to the APEX model were collected for Badajoz in Spain (38.88° N, -6.83° E). Observed weather data that include daily minimum and maximum temperatures, and rainfall for 1993 to 2012 were extracted from the European Climate

Assessment and Dataset (Klein Tank et al., 2002). Mean monthly wind speed data were taken from FAO's CLIMWAT database (Smith, 1993). Physical and chemical characteristics of the soil used in APEX are extracted from the European Soil Database (ESD) (Hannam et al., 2009). Soil texture at our study site is classified as loam soil, based on the relative fractions of sand, silt and clay in the soil and using the Soil Texture Triangle Calculator (Saxton et al., 1986). A loam soil albedo of 0.13, at field capacity, is used in APEX (Sumner, 1999). Soil moisture content is initialised using the standard procedure in APEX, based on average annual rainfall within the simulation period. Soil nutrient content (nitrogen, phosphorus, carbon) is initialised in APEX using the data extracted from the ESD. We adjusted the initial organic-N content for each simulation so that there is zero N build-up in the root zone over the simulation period of twenty years. We use default values for the crop parameters in the APEX model (Fader et al., 2015; Davis et al., 1988). The cost of irrigation water is assumed at 0.05 \$ m<sup>-3</sup>, which is within the range of 0.01 to 0.11 \$ m<sup>-3</sup> reported by Gómez-Limón and Riesgo (2004) for Spain. The cost of N fertilizer is assumed 0.09 \$ kg<sup>-1</sup> (Martínez and Albiac, 2006). We use a price of harvested maize of 264 \$ tonne<sup>-1</sup>, which is the average of the reported annual prices over the period 2010-2015 in Spain (FAOSTAT, 2017).

## 5.3 Results

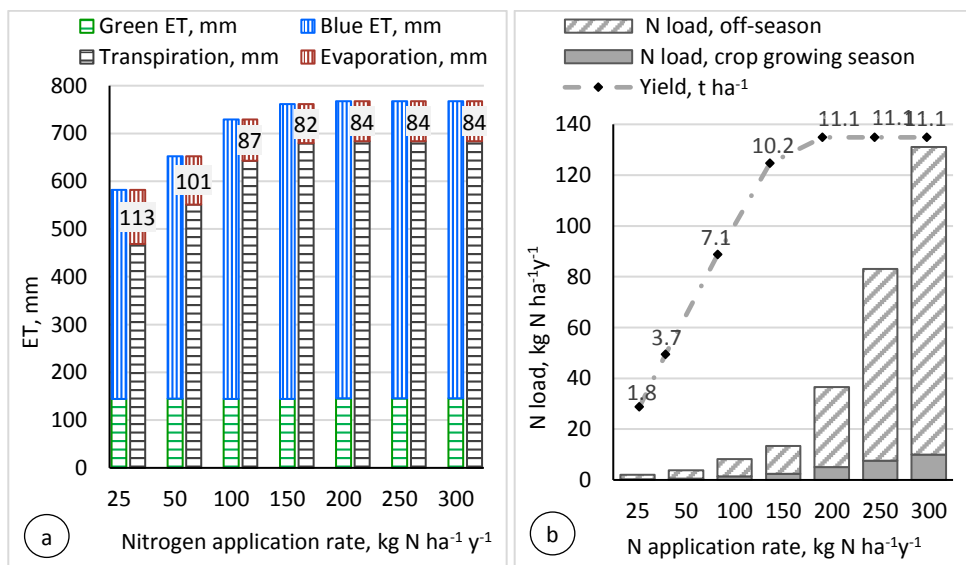
### 5.3.1 Trade-off between blue and grey WF under the reference management package

Figure 5.2 shows evapotranspiration (ET) from the crop field, N load to groundwater and surface water, and maize yield as a function of the N-application rate for the reference management package (inorganic-N; conventional tillage; full irrigation). As shown, total ET is the sum of green and blue ET, as well as the sum of (unproductive) evaporation (E) and (productive) transpiration (T). Blue ET makes up 75-81% of ET (with the larger share at higher N-application rates), and T amounts to 81-89% of ET (again with the larger share at higher N-application rates). Green ET has a constant value of 144 mm along the range of N applications considered. E decreases as a result of increased canopy cover from 113 mm (19% of ET) at 25 kg-N ha<sup>-1</sup> to 82 mm (11% of ET) at 150 kg-N ha<sup>-1</sup>. The N load to groundwater and surface water consists of two components: the load during the crop growing season and the off-season load. For all N-application rates the off-season load is the main share (87%±3.5%) of the annual load, due to the absence of N uptake by the crop in that season.

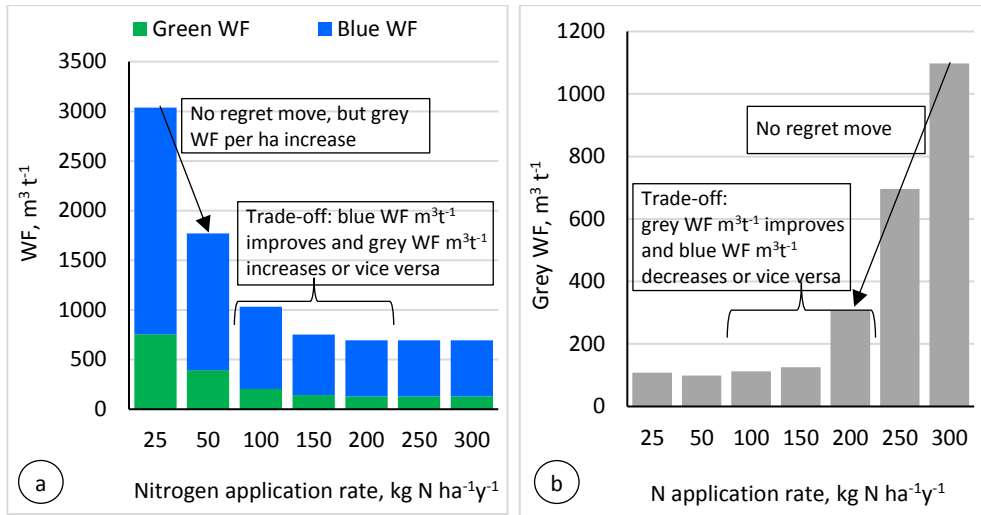
Figure 5.3 shows the green, blue and grey WF per tonne as a function of the N-application rate. At low to intermediate N application, both green and blue WF per tonne reduce at increasing N-application rates. The green WF per tonne (green ET divided by crop yield) decreases because green ET remains constant while crop yield increases with increasing N application. The blue WF per tonne (blue ET divided by crop yield) decreases because crop yield increases faster with increasing N application than blue ET. At high N application, green and blue ET and yield remain constant, and so do the green and blue WF per tonne.

When increasing the N-application rate while the application rate is still very low (from 25 to 50 kg N ha<sup>-1</sup> y<sup>-1</sup>), crop yield increases at a bit faster rate than leaching and runoff of N, so that the grey WF per tonne slightly decreases. At higher N application, the grey WF per tonne will increase, because the N load to freshwater increases at a faster rate with increasing N application than the crop yield. This is particularly the case from 150 kg N ha<sup>-1</sup> y<sup>-1</sup> onwards. At the higher N-application rates the fraction of applied N that is taken up by the crop diminishes, while fraction that leaches to groundwater or runs off to surface water increases.

Increasing N application from 25 to 50 kg N ha<sup>-1</sup> y<sup>-1</sup>, with yield increasing by a factor 2, is a no-regret move, because blue and grey WFs per tonne are reduced by 40% and 8%, respectively. Decreasing N application from 300 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup> is a no-regret move as well, with a grey WF per tonne reduced by 72% while the blue WF and yield remain the same. The intermediate N-application range inevitably involves a trade-off between the blue and grey WF per tonne. When N application increases from 50 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, crop yield grows by a factor 3 and the blue WF per tonne declines by 60%, but the grey WF increases by 210%. The minimum blue WF per tonne is found at the N application 200 kg N ha<sup>-1</sup> y<sup>-1</sup>, while the minimum grey WF per tonne is at 50 kg N ha<sup>-1</sup> y<sup>-1</sup>.



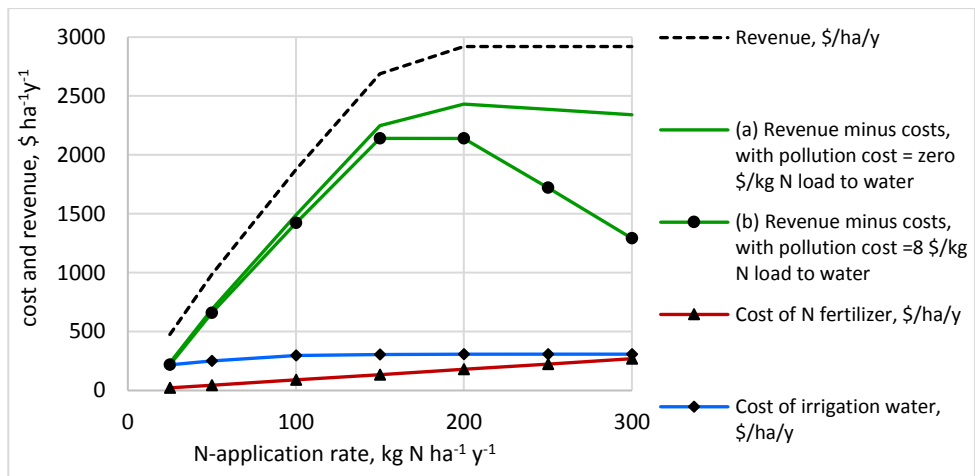
**Figure 5.2** Total evapotranspiration (ET), subdivided into green and blue ET, and subdivided into transpiration and evaporation (a); and N load to freshwater during the crop growing season and off-season and crop yield (b) for an irrigated maize field at different N-application rates for the reference management package.



**Figure 5.3** Green and blue WF per tonne (a) and grey WF per tonne (b) at different N-application rates for the reference management package.

### 5.3.2 Economic optimal nitrogen application rate when including cost of pollution

For the reference management package, Figure 5.4 shows the revenue at increasing N-application rate, as well as the costs of additional inputs (N-fertilizer and irrigation water). The revenue stabilizes beyond an N-application rate of 200 kg N ha<sup>-1</sup>y<sup>-1</sup>, because yields don't increase beyond that rate. When we look at the gross revenue minus the cost of N and additional irrigation water, we can see that applying more than 200 kg N ha<sup>-1</sup>y<sup>-1</sup> is not economical, because net revenue will diminish. When putting a price to water pollution, by introducing a gradually increasing cost per kg of N load to freshwater, we find that when the cost reaches 8 \$ per kg of N load to water, the economically optimal N load shifts from 200 to 150 kg N ha<sup>-1</sup>y<sup>-1</sup>. The shift will take place at a lower price of pollution if we assume higher prices of N fertilizer and water than we did (see Section 2.5). These findings appear to be insensitive to the prices of N fertilizer and irrigation water assumed. The largest uncertainty is with the cost of irrigation water, but even if we vary the water price within the broad range of 0.01 to 0.11 \$ m<sup>-3</sup> as reported by Gómez-Limón and Riesgo (2004) for Spain, the tipping points will not change from what is presented here.



**Figure 5.4** Revenue with increasing N-application rate, costs of inputs (N-fertilizer and irrigation water) at increasing N-application rate, and revenue minus those input costs (for the reference management package). An additional line shows revenue minus input costs when also subtracting a cost of pollution of 8 \$ per kg of N load to water.

### 5.3.3 Trade-off between blue and grey WF under different management packages

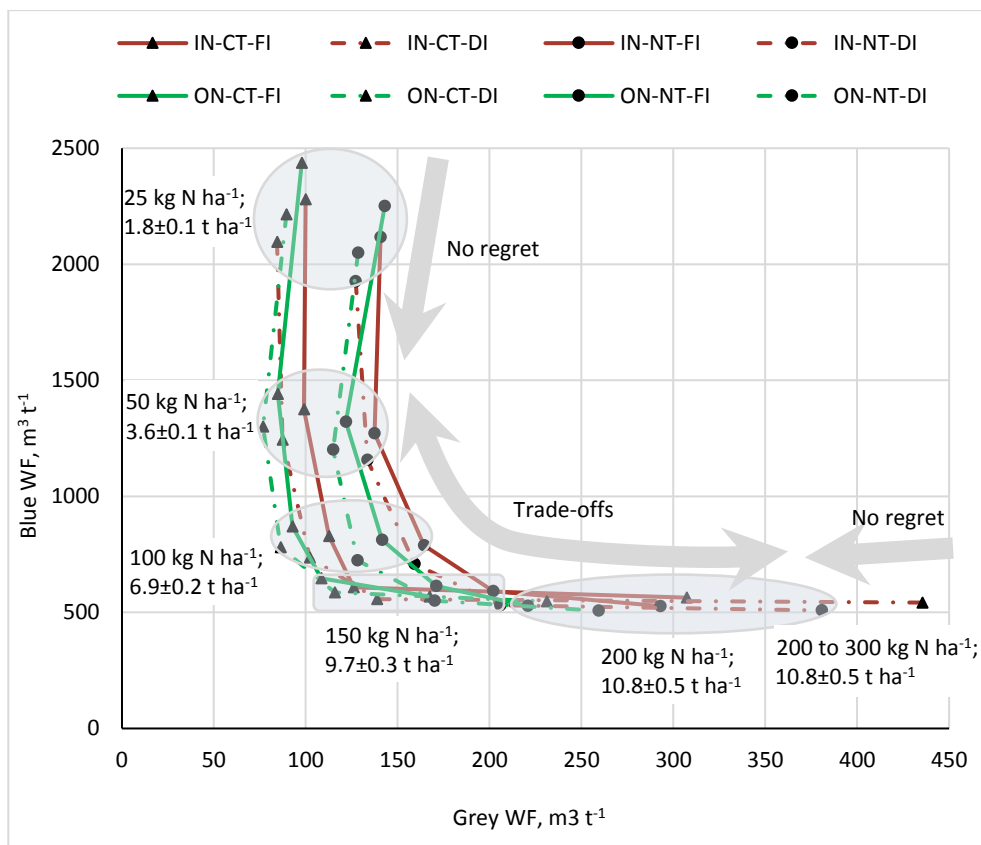
Figure 5.5 shows the blue versus grey WF per tonne of crop for different N-application rates and field management packages. The figure shows the results of 56 simulations (seven N-application rates  $\times$  two forms of N  $\times$  two tillage practices  $\times$  two irrigation strategies). The points that have the same combination of N form, tillage practice and irrigation strategy are connected in the figure by a solid or dashed line. Each line thus shows the effect of a changing N-application rate in case of a fixed management package. The figure demonstrates that the effect of increasing the N-application rate on the blue and grey WF per tonne is similar for all management packages: increasing the rate from 25 to 50 kg N ha<sup>-1</sup> y<sup>-1</sup> or reducing the rate from 300 to 200 kg N ha<sup>-1</sup> y<sup>-1</sup> are no-regret moves, as they reduce both blue and grey WF per tonne or just one of them without worsening the other. Changing N-application rates between 50 and 200 kg N ha<sup>-1</sup> y<sup>-1</sup> always involves a trade-off, reducing blue WF per tonne and increasing grey WF, or vice versa.

The oval shapes in the figure encircle points with a certain fixed N-application rate. Within each oval, crop yields may differ slightly (as indicated), depending on the precise management package, but yield differences at fixed N-application rate are small. Shifting from one management package to another within an oval (a given N-application rate) may lead to a reduction of both blue and grey WF per tonne (no regret), an increase of both (no go), or a decrease in one and increase in the other (trade-off).

There are numerous no-regret moves (relative to the reference package). Most important, for all N-application rates, shifting from the reference package to the combination of organic-N and deficit irrigation (staying with conventional tillage), will result in a blue WF decrease of by  $4\pm 1\%$  and a grey WF decrease of  $17\pm 7\%$ . For N-application rates up to  $100 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , shifting from the reference to deficit irrigation (staying with inorganic-N and conventional tillage) will reduce the blue WF by  $10\pm 1\%$  and the grey WF by  $14\pm 5\%$ . The same move for N-application rates from  $150 \text{ kg N ha}^{-1} \text{ y}^{-1}$  or higher involves a trade-off, however: the blue WF per tonne will still reduce (by  $5\pm 2\%$ ) but the grey WF per tonne will significantly increase (by  $24\pm 12\%$ ). For N application rates of 200 to  $300 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , there are different possible no-regret moves. Moving from the reference to no-tillage will reduce the blue WF by  $6\pm 0\%$  and the grey WF by  $8\pm 2\%$ . Moving from the reference to organic-N and no-tillage will reduce the blue WF by the same percentage, but the grey WF by  $34\pm 6\%$ . Finally, moving from the reference to the combination of organic-N, no-tillage, and deficit irrigation will reduce the blue WF by  $10\pm 0\%$  and the grey WF by  $18\pm 4\%$ .

A number of moves will reduce the blue WF per tonne but increase the grey WF per tonne. For all N-application rates, moving from the reference to no-tillage and deficit irrigation (staying with inorganic-N) will reduce the blue WF by  $13\pm 3\%$  and increase the grey WF by  $29\pm 18\%$ . For N-application rates up to  $150 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , moving from the reference to organic-N, no-tillage and deficit irrigation will reduce the blue WF by  $11\pm 1\%$  and increase the grey WF by  $21\pm 8\%$ . For N-application rates from 150 to  $300 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , moving from the reference to deficit irrigation will reduce the blue WF by  $5\pm 2\%$  and increase the grey WF by  $24\pm 12\%$ .

The opposite, reducing the grey WF per tonne at the cost of a blue WF increase can occur as well. For all N-application rates, moving from the reference to organic-N (staying with conventional tillage and full irrigation) will reduce the grey WF per tonne by  $4\pm 3\%$  and increase the blue WF by  $23\pm 12\%$ .



**Figure 5.5** Blue versus grey WF per tonne of maize production for different N-application rates and field management packages. The oval shapes encircle points with a certain fixed N-application rate. The two no-regret arrows indicate how both blue WF can be reduced without increasing grey WF or vice versa. In the trade-off range, changing the N-application rate will result in a trade-off between blue and grey WF. Red lines refer to inorganic-N (IN); green lines refer to organic-N (ON). Circular markers refer to no-tillage (NT); triangular markers refer to conventional tillage. Dashed lines refer to deficit irrigation (DI); solid lines refer to full irrigation (FI).

## 5.4 Discussion

The current study shows how increasing N-application rates in maize production may lead to trade-offs between water consumption (blue WF), water pollution (grey WF) and between WFs and crop yield as well. The optimal level at N application is different: the minimum water pollution per unit of crop is achieved at an N-application rate of  $50 \text{ kg N ha}^{-1} \text{ y}^{-1}$ ; the minimum blue water consumption per unit of crop and maximum yield are at  $200 \text{ kg N ha}^{-1} \text{ y}^{-1}$ . When water pollution costs are considered, the economically optimum N



application is  $200 \text{ kg N ha}^{-1} \text{ y}^{-1}$  when the pollution costs are lower than 8\$ per kg of N load and  $150 \text{ kg N ha}^{-1} \text{ y}^{-1}$  when the pollution cost equals or is larger than 8\$ per kg of N load.

The results can be understood by considering N uptake by the crop and N surplus in the soil (N application minus N uptake by the crop), the two central variables determining blue and grey WFs in crop production, respectively. N uptake is important for the development of the plant, which determines ET and crop yield, and thus the blue WF. N surplus determines N leaching and runoff, and thus the grey WF. At low N-application rates, most N is taken up by the plant, so that the N surplus and thus leaching is small, resulting in a small grey WF. However, at low N application, nitrogen stress to the plants results in a low crop yield, and thus a large blue WF per tonne. At intermediate N-application rates, the N surplus and thus grey WF is increased, but increased N uptake also results in a better development of the crop and an increased crop yield, thus a smaller blue WF. At high N-application rates, N uptake, ET and crop yield have reached their maximum levels and the blue WF per tonne is at its minimum level. Adding more N in the range of high N-application rates, however, will still increase N leaching, which results in increasing a grey WF per tonne.

Effects of field management practices on the N and water balances and crop production, as simulated here using APEX, have been discussed extensively in literature. Changes in the form of N applied, the tillage practice or the irrigation strategy will alter the moisture and nutrient holding capacities of the soil, the rate of soil water movement, and the soil surface cover (crop residue, and crop canopy cover). As a result, the N load to freshwater (through leaching, runoff and erosion) will be affected, and thus the grey WF per hectare. ET, including the blue ET component, will change as well, and thus the blue WF per hectare. Since also crop yield will be affected, blue and grey WFs per tonne of crop will change as well. Applying organic-N instead of inorganic-N improves the water holding capacity of the soil (Hudson, 1994;Sommerfeldt et al., 1988) and the nutrient retention capacity of the soil as well, which facilitates crop growth and results in increasing ET and blue WF, while N-leaching and thus the grey WF is reduced as a result of the increased nutrient retention capacity. Compared to conventional tillage, no-tillage facilitates the crop residue to remain as a soil cover (mulch) and to reduce unproductive evaporation (De Vita et al., 2007;Mitchell et al., 2012); as a result the blue WF is reduced for all N-application rates. No-tillage enhances nitrogen leaching (Azooz and Arshad, 1996;Triplett and Dick, 2008;Constantin et al., 2010); as a result the grey WF is increased at low N-application rates, where the crop residue is small. At high N-application rates, when the biomass and crop residue are large, no-tillage facilitates the accumulation of soil organic matter that helps to improve the water holding and nutrient retention capacities of the soil; as a result, leaching and grey WF are reduced at high N-application rates. Deficit irrigation instead of full irrigation maintains smaller soil moisture content, which helps to reduce ET and blue WF for all N-application rates. Deficit irrigation reduces percolation (Igbadun, 2012) and N-leaching (Carpenter et al., 1998); as a result the grey WF per tonne is smaller at low N-application rates. At high N-application rates, however, the water stress that comes along with deficit irrigation, hampers N uptake by the crop; this results in a higher N surplus in the soil, which increases leaching and the grey WF per tonne.

There is a comparable crop yield response to N uptake by the crop between our model study with APEX and the field study by Berenguer et al. (2009), both of which are for maize and for similar conditions in Spain. The crop yield response for a given N input in our study is 25% less than the yield response in the study by Berenguer et al. (2009), which may be due to the high yielding maize variety used in their study.

The WF estimates presented and the N-application rates at which we find minimum water consumption and pollution per tonne of crop depend on the climate, soil, crop type and crop variety assumed in this study, as well on the model used. Similarly, the assumed market value of the crop, costs of N and irrigation water, and the price put to water pollution all affect the calculated economically optimum N-application rate. Furthermore, the grey WF of growing maize, based in this study on the N load to freshwater, may increase if other pollutants such as phosphorous and pesticides are considered as well. Therefore, the precise values presented should be taken with caution; the reported values are rather to be understood as illustrative of how different nitrogen application rates and field management practices can affect the trade-offs between water consumption and water pollution.

## 5.5 Conclusion

This paper explores the trade-offs involved at different N-application rates in a case of maize production at a selected site in Spain. For the reference management package (inorganic N fertilizer, conventional tillage and full irrigation), different optimum N-application rates are identified. Water pollution (grey WF) per tonne of crop is lowest at  $50 \text{ kg N ha}^{-1} \text{ y}^{-1}$ . Irrigation water consumption (blue WF) per tonne is lowest at  $200 \text{ kg N ha}^{-1} \text{ y}^{-1}$ . The economically optimal N-application rate is at  $200 \text{ kg N ha}^{-1} \text{ y}^{-1}$  as well, but only if the cost of water pollution resulting from N leaching and runoff is not included in the calculation. When water pollution is included in the computation and when the cost of the N load to freshwater exceeds  $8 \text{ \$ ha}^{-1} \text{ y}^{-1}$ , the optimal N-application rate is reduced to  $150 \text{ kg N ha}^{-1} \text{ y}^{-1}$ . If we consider water pollution and water consumption per hectare rather than per unit of crop produced, we find yet other optimum N-application rates. Water pollution (grey WF) per hectare is lowest at  $0 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , while irrigation water consumption (blue WF) per hectare does not depend much on the N-application rate. The additional blue WF per hectare slightly increases with increasing N-application rate, because of the improved growing conditions and the resultant increased transpiration. However, lowering the blue WF per hectare is done more effectively (and without so much impact on the yield) by improved the irrigation technology and irrigation water application strategy (Chukalla et al., 2015).

No single optimal N-application rate can be identified. It depends on the crop, the local environmental conditions, the management practice (e.g. nitrogen form, tillage practice, and irrigation strategy) and what variable is considered: blue or grey WF, per tonne or per hectare, or the economic optimum. In the latter case, it depends on whether the environmental cost of water pollution is included in the computation and, if so, what price

is assumed. Local considerations on water pollution and water scarcity levels may influence how the different variables are weighted.

Considering the trade-off between blue and grey WF per tonne of crop associated with choosing an N-application rate, we have identified three typical cases: the no-regret move when increasing N application at very low rates, the no-regret move when decreasing N application at very high rates, and case where a trade-off is inevitable, at intermediate N-application rates.

Changing the form of N applied, the tillage practice or the irrigation strategy, at a given fixed N-application rate, may imply a trade-off between blue and grey WF per tonne of crop as well. However, there are also no-regret moves. Moving from the reference to deficit irrigation is a no-regret move for N-application rates up to  $100 \text{ kg N ha}^{-1} \text{ y}^{-1}$ , but involves a trade-off for N-application rates from 150 to  $300 \text{ kg N ha}^{-1} \text{ y}^{-1}$ : the blue WF per tonne will reduce but the grey WF per tonne will significantly increase. Moving from the reference to organic-N involves a trade-off, for all N-application rates: the grey WF per tonne will get reduced, but (particularly at N-application rates up to  $150 \text{ kg N ha}^{-1} \text{ y}^{-1}$ ) the blue WF per tonne will increase. Moving from the reference package towards a combination of organic-N and deficit irrigation is a no-regret move, for all N-application rates, as it reduces both blue and grey WF per tonne. Shifting from the reference package towards no-tillage at high N-application rates of  $200\text{-}300 \text{ kg N ha}^{-1} \text{ y}^{-1}$  is a no-regret move, since it reduces both blue and grey WF per tonne. Shifting from the reference to no-tillage at all other N-application rates, however, implies a trade-off, whereby the blue WF per tonne is reduced, but the grey WF per tonne increased.



# 6 Conclusions

The field of water footprint assessment has gradually evolved over the past fifteen years (Hoekstra, 2017) and has attracted an increasing number of researchers worldwide (Zhang et al., 2017). This thesis contributes to the advancement of the field in several ways as will be summarized in this chapter. I will conclude with reflecting on interesting focus areas for future study.

## 6.1 Contributions to scientific advancement

First, a shadow water-balance method was developed and implemented in all chapters to calculate the green and blue ET and thus green and blue WF of crop production, based on a daily accounting of the green-blue water composition of the soil moisture, whereby infiltrating rainwater is recorded as green water added, and whereby infiltration of irrigation water and capillary rise of groundwater are recorded as blue water added. The two types of blue water are distinguished explicitly. The colour composition of outgoing fluxes is determined based on the colour composition of the soil moisture at a daily basis. The current work is the first time that the contribution of groundwater through capillary rise is explicitly distinguished as a form of blue water consumption, which is mainly relevant in the case of shallow groundwater tables. The shadow water-balance accounting approach to estimate green and blue ET is better than the approach followed earlier, by for instance Mekonnen and Hoekstra (2011), which was based on making two simulations, one rain-fed and one irrigated, and the estimation of blue ET as the difference in ET in the two simulations. That approach neglects the difference in the development of the plant (root-system and canopy) in both cases and thus the difference in the ability of plants to grow and take up and transpire water. Explicitly addressing green water consumption in addition to blue water consumption is relevant because green water consumption in agriculture is much bigger than blue water consumption, and its productive use therefore relevant as well, as explained for example by Falkenmark and Rockström (2006).

Second, for the first time, in Chapters 4 and 5, the APEX model was applied to estimate the grey WF of crop production by tracking the pollutant load to surface water and groundwater. Given that the earlier studies were based on an annual mass balance approach (Mekonnen and Hoekstra, 2015; Liu et al., 2012), this is also the first time that the grey WF related to nitrogen application in crop production has been estimated on the basis of a crop growth model with a daily time step. Furthermore, the earlier studies ignore soil organic matter build-up and decomposition, and nitrogen transformations such as mineralization, immobilization and nitrification, which all affect the N uptake and N load to freshwater.

Third, the thesis offers the first comprehensive assessment on the potential for reducing green, blue and grey WF per unit of crop by changing field management practices (in Chapter 2 for green-blue WF reduction and Chapter 4 for grey WF reduction). The field management practices considered in this thesis are: four different irrigation techniques, four irrigation strategies, three mulching practices, different nitrogen-application rates, two forms of nitrogen, and two tillage practices. We analysed various cases, including three crops, four different environments, different hydrologic years (dry to wet), and different soil types. We made transient simulations, for periods covering multiple subsequent years, to capture inter-annual variability as well. We ordered the field management practices in terms of their effectiveness to reduce WFs. The results are summarized as follows:

- The blue or consumptive WF per tonne can be reduced most by improving the mulching practice first, next the irrigation technique and finally the irrigation strategy. Under all cases, the WF in case of mulching is much smaller than in case of no mulching. The ranking of irrigation techniques in terms of the blue or consumptive WF per tonne of crop production is as follows: drip or subsurface drip irrigation have the smallest WF, then furrow irrigation, and finally sprinkler irrigation. Irrigation strategies are ranked from deficit irrigation (smallest WF), to full irrigation, supplementary irrigation, and finally no-irrigation (rain-fed).
- Compared to the reference of furrow and full irrigation without mulching, the maximum reduction in the blue and consumptive WF of crop production can be achieved by practicing drip or subsurface drip with deficit irrigation and synthetic mulching.
- Reducing the N-application rate will generally result in a higher reduction of the grey WF per tonne of crop production than changing the form of N applied, the tillage practice or the irrigation strategy.
- For reducing both consumptive WF and grey WF per tonne, one can best apply manure-N instead of inorganic-N, and deficit instead of full irrigation. No-tillage generally results in a smaller consumptive WF per tonne, while conventional tillage result in a smaller grey WF per tonne.

Fourth, the study identifies and quantifies trade-offs between irrigation water consumption (blue WF) and water pollution (grey WF), and between WFs and crop yield at different N-application rates and under various field management practices (N-forms, tillage practices and irrigation strategies). This is exemplified in a case study for maize production in semi-arid environment and on loam soil in Chapter 5. At low N-application rate, the blue WF per tonne is high due to low crop yield and the grey WF is low due to the low N load to freshwater. When increasing the N-application rate, both blue WF and grey WF drop due to increased crop yield. The grey WF per tonne declines despite the higher N-application rate, because at low N-application rate the crop yield increases faster than the N load to fresh water, when marginally adding N. Further increase of the N-application rate increases the crop yield to its maximum, which further decreases the blue WF per tonne, but increases the grey WF per tonne.

Finally, the thesis shows how one can develop a marginal cost curves (MCCs) for WF reduction in crop production. This is done in Chapter 3 for the case of consumptive WF reduction, for three crops cultivated under different environments, in different hydrologic years and on different soils. The tool introduced provides information on the cost-effectiveness of alternative field management practices for WF reduction, and the cost of WF reduction to achieve a certain reduction target, for instance to stay within a certain WF permit or below a certain WF benchmark. We found that aiming at cost-effective consumptive WF reduction, one can best improve the irrigation strategy first. The WF reduction will not be much, but some water is saved while saving money. Next the mulching practice can best be changed from no mulching to organic mulching, and finally the irrigation technique from furrow or sprinkler to drip irrigation.

## 6.2 Future outlook

Future study can focus on (1) the better modelling of the processes in the soil, (2) the capturing of uncertainties involved and possibly reduce them, (3) the assessment of more specific combinations of field management practices, and (4) the scaling up of the learnings in the current thesis from field to catchment scale.

First, by enhancing the modelling of the processes in the root zone, the green-blue ET separation in the shadow water-balance method can be improved. In the thesis, in every single time step, the colour compositions of ET and percolation (green from rain, blue from irrigation, and blue from capillary water) are taken equal to the colour composition of the soil moisture. Even though the AquaCrop and APEX models that we use distinguish multiple soil moisture layers, in the shadow accounting we consider soil moisture as a whole, with one overall colour composition. Since the colour composition may vary between the soil moisture layers, the approach taken may be too simplistic. For example, when over time there has been a period of rain first and a period of irrigation later on, the blue-green ratio of the soil moisture in the upper soil layer is likely to be higher than in the lower soil layer. Another example is that the fraction of blue water from capillary rise is likely to be higher in the lower than in the higher soil layer.

Second, future studies are required to better understand the uncertainties (in input data, model parameters, equations and the model structure) and include uncertainty analysis in WF estimation. We did not perform sensitivity analyses for input data used or carry out full uncertainty analyses, which both would be interesting. Also, we did not conduct field experiments, which would be relevant to validate the simulated results with field data, and could be instrumental in calibrating the models.

Third, exploring the potential reduction of the green, blue and grey WF of crop production can be extended by assessing the effect of a wider range of existing and innovative management practices, including for instance crop rotation, intercropping, the application of improved crop varieties, the use of cover crops following harvest, the use of precision irrigation and fertilizer application methods (supply according to the real-time crop demand

considering expected weather and mineralization), and cultivating crops under controlled conditions (e.g. greenhouse or aquaponics, hydroponics or aeroponics system).

Fourth, the field level accounting can be extended to larger spatial (farm and basin level) and temporal (current and future) dimensions so that efficiency improvements at field scale can be translated into aggregated results at basin scale. At basin scale we can explore the effect of measures outside crop fields as well, like water saving in the irrigation water storage and conveyance system, water savings in other agricultural production systems, like animal farming and pastures, and water savings in the domestic and industrial sectors. In future studies, one can also extend the application of the MCCs for WF reduction beyond field level.



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## About the author

Abebe D. Chukalla was born in Dera (precisely in a village called Borera Derbo), Arsi Zone, Oromia regional state, Ethiopia. He studied his elementary and high school in Dera and Adama towns. He obtained his BSc in (Water resources and) Irrigation engineering in 2005 from Arbaminch University, Ethiopia. After working for three years, he moved to the Netherland to study his MSc and he obtained his MSc in Hydraulic engineering - Land and water development in 2010 from UNESCO-IHE, Delft, the Netherlands. After working for three years in Ethiopia, he started his PhD in 2013 in Water Management and Engineering group, University of Twente, the Netherlands. His PhD study feeds into the EU project called FIGARO, which aims to facilitate significant reductions in freshwater, fertilizer and energy use at farm level and develop a management platform for cost-effective precision irrigation and fertigation. From 1<sup>st</sup> of July 2017, Abebe has been working as a postdoc on a project 'Checks and Balances for resources use efficiency assessment: reducing yield gaps while accounting for nutrient- and water fluxes across spatiotemporal scales' with four groups (Water Resources Management, Water Systems and Global Change, Plant Production Systems and Business Economics) in the department of Environmental Science, Wageningen University, the Netherlands.

Abebe has worked as technical engineer, lecturer, researcher, and coordinator of projects and researches in the area of water resources management and development for domestic and irrigation purposes. Teaching is, and always has been his passionate work that motivates him to query and keep learning!





## List of publications

- Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, *Hydrol. Earth Syst. Sci.*, 19, 4877-4891, 2015.
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How to reduce water footprint. U-Today Science Magazine, issue #1 - 2017, University of Twente.

## Conference abstracts

- Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y. (2014): Effect of irrigation techniques and strategies on water footprint of growing crops, American Geophysical Union, Fall Meeting 2014, abstract #H43E-0999. San Francisco, U.S.A.
- Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y. (2014): Marginal cost curves for water footprint reduction in irrigated agriculture: a policy and decision making guide for efficient water use in crop production, SAO/NASA ADS Physics Abstract Service, 2016EGUGA..18.3050C. EGU General Assembly 2016, held 17-22 April, 2016 in Vienna Austria, p.3050.

## Presentation at conferences and project meetings

- Oral presentation on Marginal Cost Curves for water footprint reduction in irrigated agriculture: a policy and decision making guide for efficient water use in crop production. EGU General Assembly 2016 in Vienna, Austria (17-22 April, 2016).
- Oral presentation on Marginal Cost Curves for water footprint reduction in irrigated agriculture: a policy and decision making guide for efficient water use in crop production. FiGARO –project meeting in Haifa, Israel (7-9 September, 2016).
- Oral presentation on effect of fertilizer strategies on the grey water footprint of irrigated crop production. Euro-AGRIWAT conference: Water Footprint of agricultural products: progress, challenges and solutions. Wageningen University, The Netherlands (7-9 March, 2016).

Oral presentation on water footprint benchmarks of crop production. FiGARO – project meeting in Bologna University, Italy (25-27 January, 2016).

Oral presentation on linking the green-blue soil water distinction to AquaCrop. FiGARO – project meeting in Valencia, Spain (20-24 January, 2014).

### **Teachings and supervisions**

Daily supervision of three MSc graduation projects, and supervision of five pre MSc projects, three BSc graduation projects

Lecture on 'Estimating blue & green WFs in agriculture or industry' to MSc students following Master Programme in Civil Engineering and Management (2017)

Teach E-learning course on Water Footprint Assessment: concept and application (2016 and 2017)

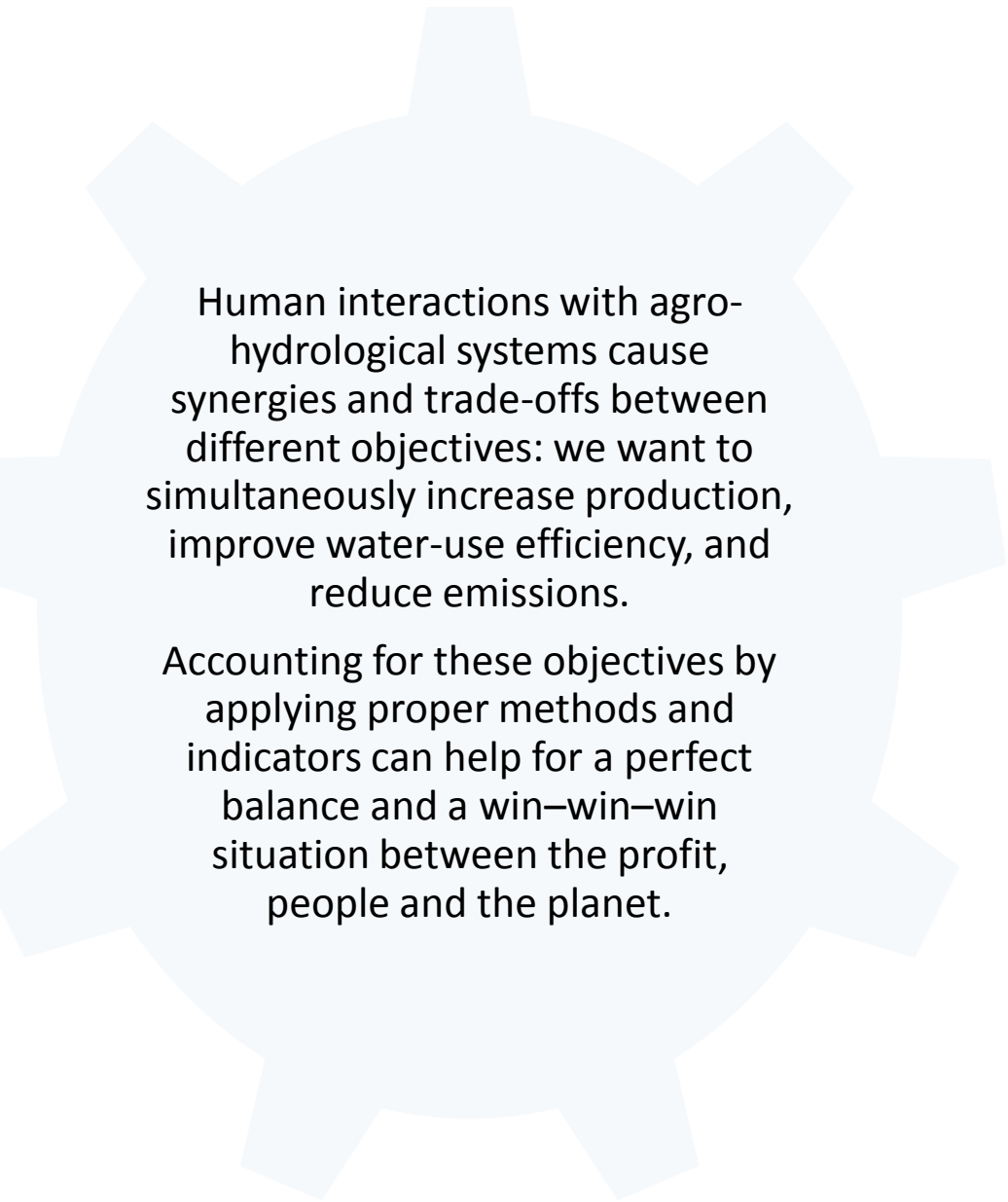
Teach in the water track of CuriousU, summer school festival in Europe: River basin game. University of Twente (August, 2015/2016)

### **Award**

Nominated for Twente Water Centre 'Best PhD paper of the year', 2016







Human interactions with agro-hydrological systems cause synergies and trade-offs between different objectives: we want to simultaneously increase production, improve water-use efficiency, and reduce emissions.

Accounting for these objectives by applying proper methods and indicators can help for a perfect balance and a win–win–win situation between the profit, people and the planet.