INTEGRATING BIOTREATED WASTEWATER REUSE AND VALORIZATION WITH ENHANCED WATER USE EFFICIENCY TO SUPPORT THE GREEN ECONOMY IN EU AND INDIA

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Selection of the most efficient irrigation scheme

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Selection of the most efficient irrigation scheme

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Abbreviations

RDI: Regulated Deficit Irrigation

PRD: Partial Root-zone Drying

SW: Surface Water

TWW: Treated Waste-water

RMSE: Root Mean Square Error

Introduction

Good management will be required to double food production by 2050. Agriculture would have to use the natural resources more efficiently, which means produce more crop per drop and more crop per unit area.

The main resources limiting food production are fertile land, mined fertilizers (phosphorus and potassium) and water. At present, agricultural water use accounts for about 70% of the world's fresh water use and this percentage is bound to increase if the growing food demand is to be met. In some parts of the world this has already led to significant overexploitation of conventional water resources and more use of alternative water resources. Even in humid regions, drought events have increased in frequency and the rainfed agriculture regularly has to be supported by supplemental irrigation.

The use of non-conventional water resources (e.g. reused agricultural drainage water, treated waste water, brackish groundwater, seawater) requires a great deal of care in order to avoid negative impact on the environment or causing soil degradation. In addition deficit irrigation, where the plant is subjected to mild stress in the less sensitive growth stages is being adopted (Hirich *et al*., 2012; Silva *et al*., 2013). Water previously classified as too saline for conventional agriculture is now being used in irrigation. Pulvento *et al.* (2013) showed that, under an appropriate management system, saline water can be used to irrigate quinoa and amaranth. As salt and water movements are intimately tied, salinity management is dependent on irrigation water management. With the increased use of poor quality water for irrigation an integrated approach is required to minimise drainage disposal problems and optimise the combined use of multiple water sources. As the effect of the use of poor quality water on soil salinity and crop yield only becomes clear after a prolonged period of time, short term experiments are not adequate for studying its long term impact and the use of models can be helpful. Models can also help in irrigation scheduling, estimation of crop water requirements, prediction of soil moisture deficit, soil salinity, soil nutrient status, dry matter production and crop yield.

The SALTMED model (Ragab, 2002, 2005a,b, 2015) was developed to predict final yield, dry matter, soil moisture and soil salinity profiles, plant water and nitrogen uptake, soil nitrogen transformation and content, drainage flow and evapotranspiration. The model can be used for rainfed and irrigated agriculture, as well as for different irrigation systems and irrigation strategies, it also accounts for the presence of drainage systems and shallow groundwater. Moreover, the model can handle different crops, soil types and N-fertilizer applications. SALTMED is a physically based model, user friendly (Windows^{TM} environment) and, together with the user guide and related documents, is freely downloadable from the Water4Crops project at the following link:

http://www.water4crops.org/saltmed-2015-integrated-management-tool-water-crop-soil-n-fertilizers/

The model description, processes and equations have been delivered as Deliverable 3.4.

Experiment Site

The three selected crops, potato, maize and tomato are selected as typical crops for the Mediterranean region. They were grown on silty-clay soil at Consorzio Bonifica CER' experimental farm "Azienda Marsili", located in Mezzolara di Budrio (Bologna, Italy), Po valley (Figure 1). In 2013, potato crop was grown first as it is less tolerant to salinity and in the following year, maize was grown in 2104 followed by tomato in 2015 (Figure 2). In this study only drip irrigation was used with two irrigation strategies either as regulated deficit irrigation (RDI) or partial root drying (PRD) strategy with fresh water (surface water, SW) and treated waste water (TWW). The latter was spiked with salts to increase its salinity to study the soil salinity distribution and its impact on growth and yield. All the samples required for the model calibration and validation were taken over the crop growing seasons during each growing phase. The soil moisture and salinity were measured continuously using sensors at two depths 25-35 cm and 55-65 cm.

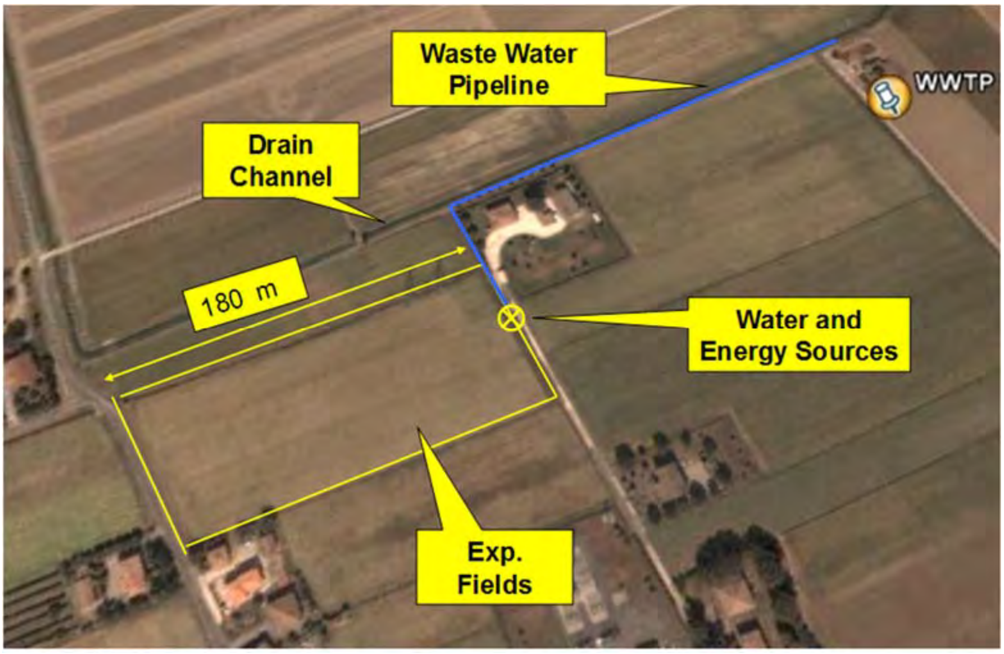

Figure 1. Experimental site at CER (Bologna, Italy)

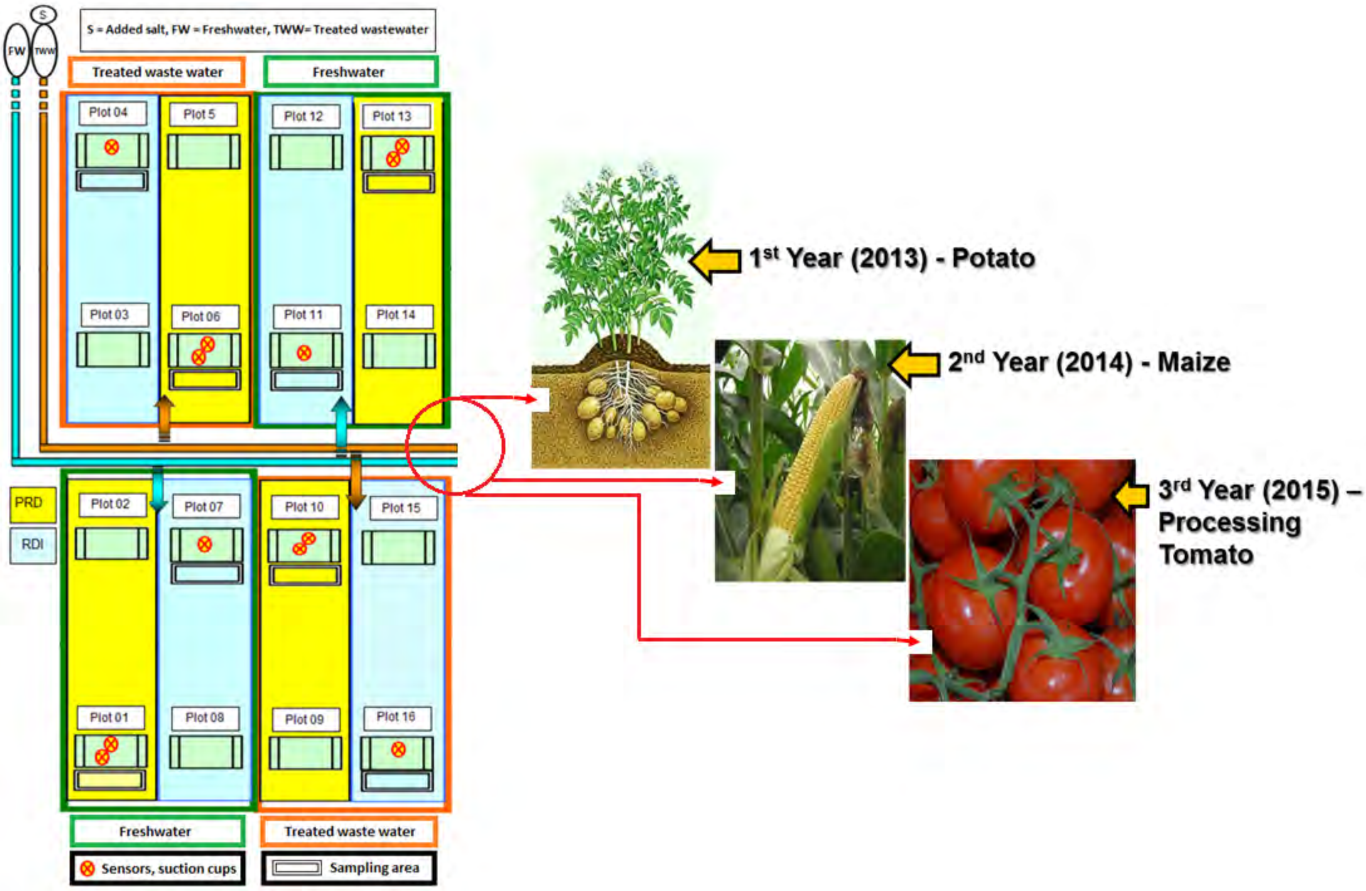

Figure 2: W4Cs crop rotation 2013-2015

Irrigation strategies and field measurements

For the three crops, drip irrigation system was applied as shown in the plot layout (Figure 3). The total number of plots were 16 with each has an area of 600 m^2. The size of the harvest sub-plot was 10 m^2. The drip line has emitters with a nominal flow of 0.8 l h^{-1}. The sensors and the suction cups (to collect the soil solution) were placed in each plot to measure the soil moisture and the soil salinity. For the RDI irrigation strategy the drippers were placed next to the plant; whereas, for the PRD double lines were used, with drippers placed in the mid-point between two plants. The soil moisture and salinity sensors and suction cups installation is shown in Figure 4 for the potato crop as an example.

In addition, dry matter and total leaf area, which were required to calculate the Leaf Area Index (LAI), were obtained in situ at regular intervals. Total yield was measured during the harvesting period. Other plant parameters such as plant height, root depth, length of each growth stage and harvest index were also based on field measurements. Fertirrigere DSS was utilized to manage Irrigation and Fertigation scheduling (Battilani, A, www.water4crops.org). In this study Naan Dan Jain drip system was applied for irrigation. Figure 5 shows the example of drip irrigated potato crop. PRD-irrigated plots were managed as for RDI plots, with a reduction of the calculated irrigation depth during the PRD-treatment period as shown for potato crop in Figure 6 as an example : in the early growth stage, from emergence to 80% of tuber > 2 cm in diameter, potato is very sensitive to water and nutrient stresses. Furthermore, the variety used (Agata) has a tendency to rapidly reduce both growth and yield if subjected to water and nitrogen stresses at the early growth stage. Therefore, available water at field capacity, AW_{FC} and soil water potential (in kPa) were used to determine the suitable level of water stress/deficit for each growth stage and irrigation strategy as shown in Figure 6.

All the required climatic variables data were collected on site from the available weather station. The soil moisture and soil salinity were also observed using the gravimetric and suction cup methods. The observed data obtained from more than one source helped in data quality control.

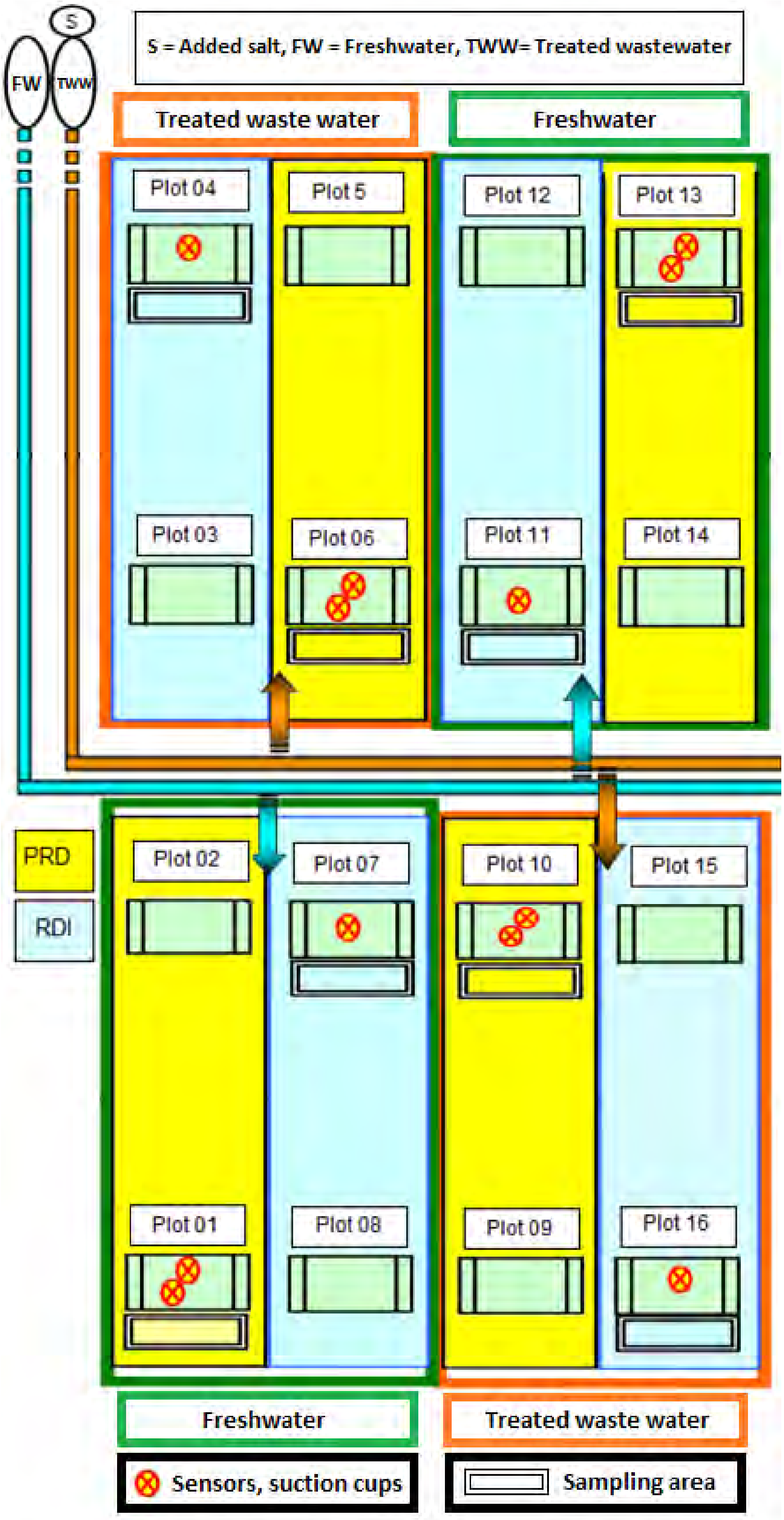

Figure 3. Plot layout of the irrigation treatments, plot area is 600 m^2.

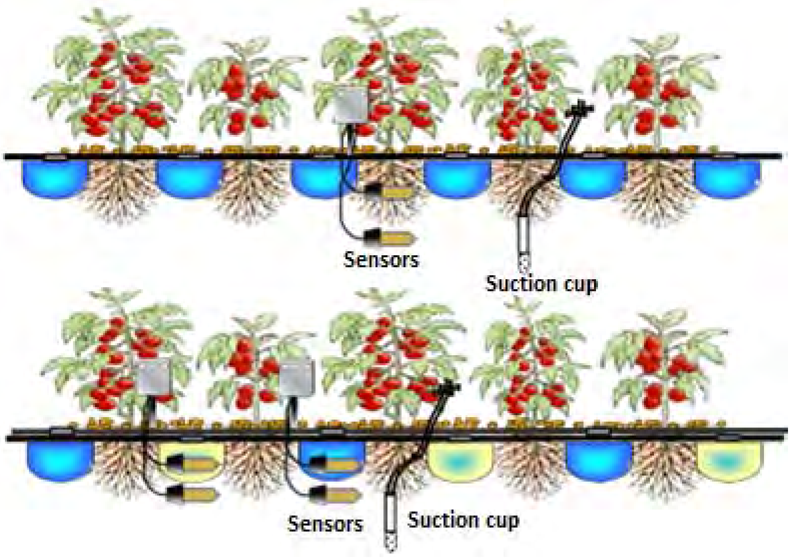

Figure 4. Sensors and suction cups installation scheme. In the upper part is the RDI treatment, in the bottom part are the PRD plots.

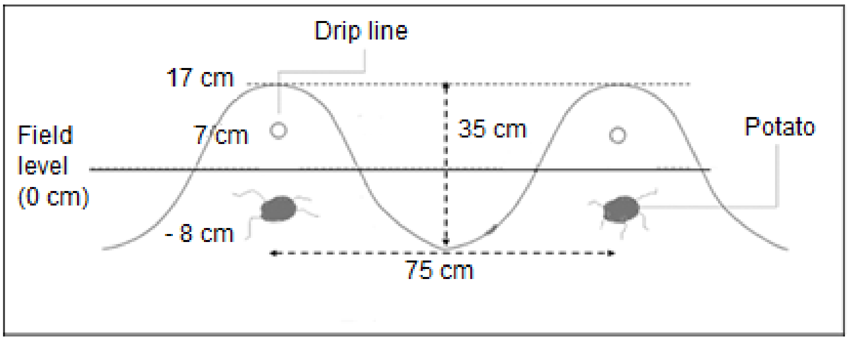

Figure 5. Drip line placement in potato ridges

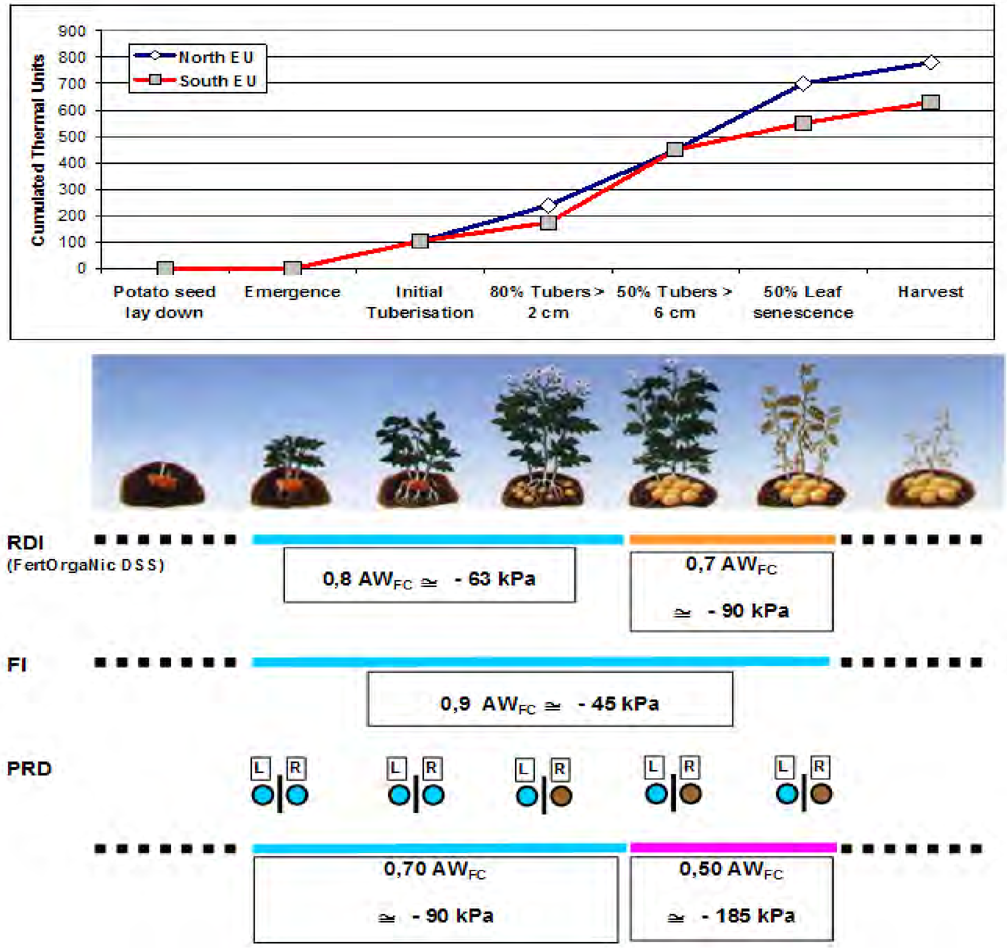

Figure 6. Example of potato water management scheme based on crop growth stages, tuber diameter and irrigation strategies. Stress levels expressed by the available water at field capacity, AW_{FC} and soil water potential (in kPa)

Results

Soil moisture

Soil moisture is essential parameter to determine the water stress level and the need to irrigate. It will also highlight the difference between the different irrigation strategies. Measurements combined with modelling are helpful for future work as successful simulation of soil moisture and salinity will lead to a reliance on model future prediction of soil moisture and salinity without the need to install sensors in the future in this particular site. The same principal applies to Yield. Once the model successfully simulated the yield, it can be used to predict future yields under different strategies without the need for conducting expensive and labour intensive field experiment. This is the main reason to combine modelling with field experiment and measurement in this project.

Initially the soil moisture was calibrated with RDI with fresh water in 2013 and validated against all other treatments. The model has shown a good fit for both layers (25-35 and 55-65 cm depth) of the simulated soil moisture when compared with the observed soil moisture Figures 7, 8 and 9 for potato 2013, maize 2014 and tomato 2015, respectively. Overall the model showed a good fit against the observed data both during the calibration and validation processes. These result are consistent with those obtained by (Pulvento et al., 2013, Pulvento et al., 2015a), Hirich et al. (2012), Silva, et al. (2013) Ragab et al.(2015), Fghire et al. (2015) and Rameshwaren et al.(2015).

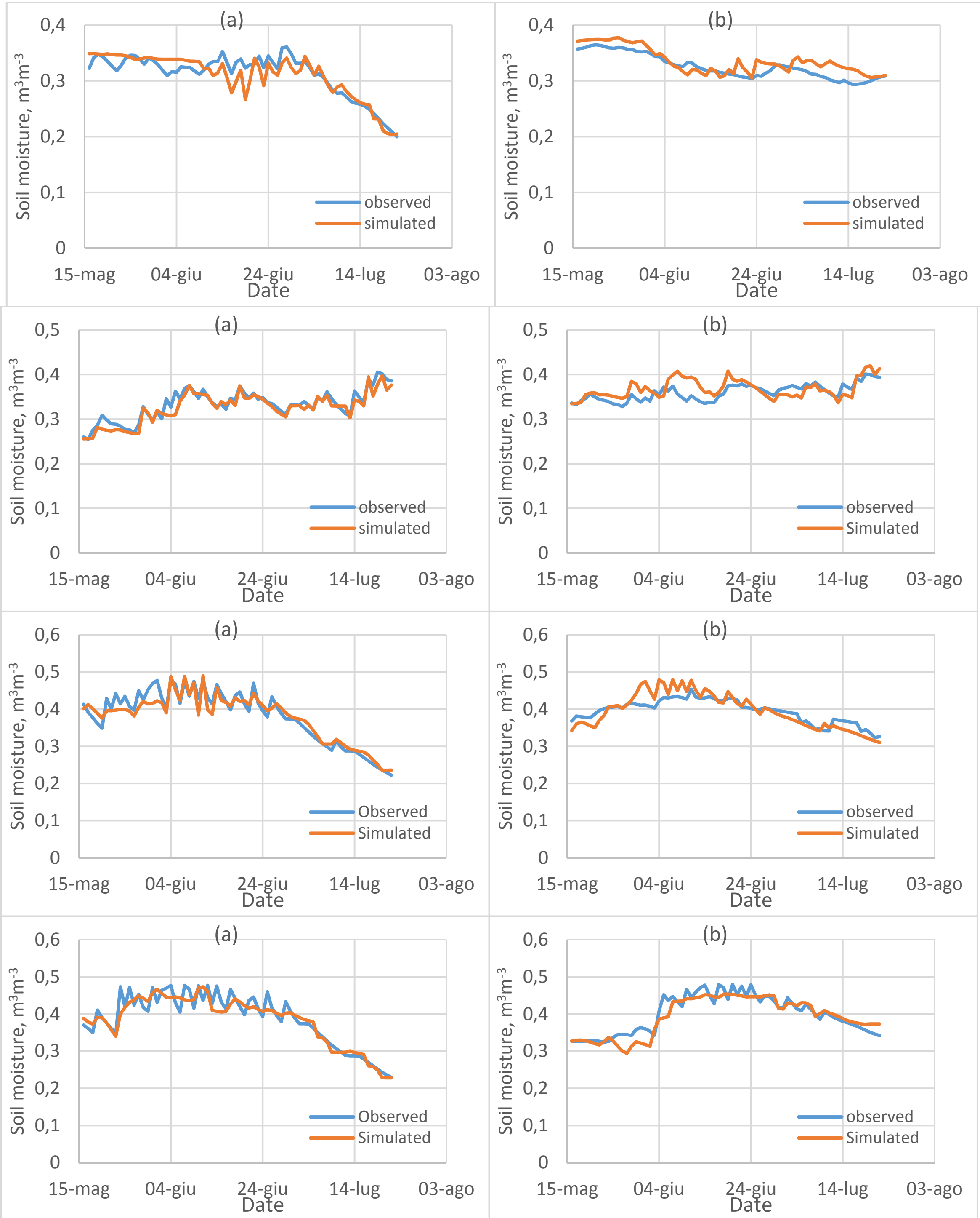

Figure 7. Observed and simulated soil moisture for potato 2013 in Bologna, Italy where figure (a) refers to the layer-1 and (b) refers to the second layer for all irrigation strategy (RDI Surface fresh water, SW, RDI, Treated waste Water, TWW, PRD SW and PRD TWW) from the top to bottom. The model was calibrated for the RDI SW (top figures a & b) and validated against the other irrigation time series.

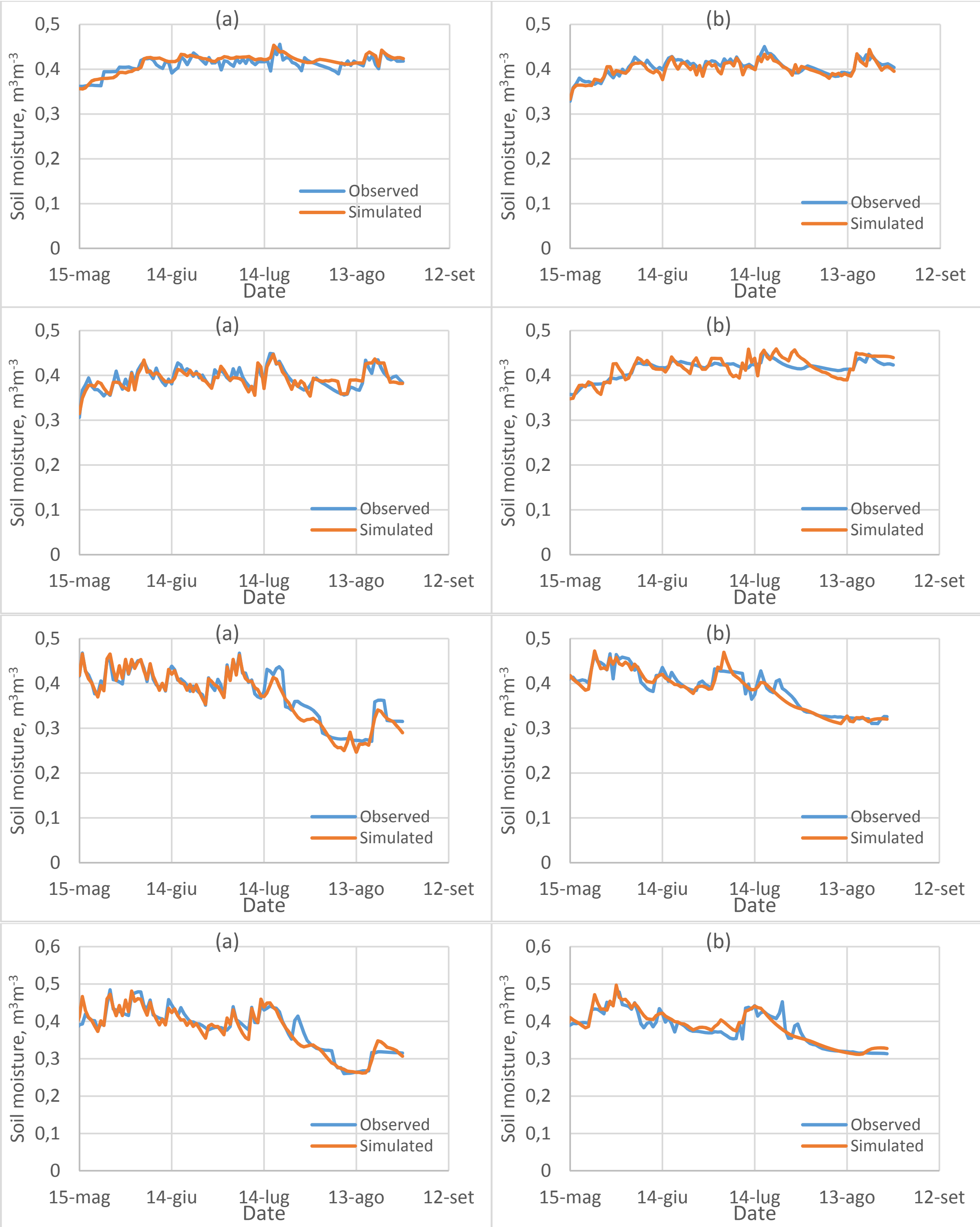

Figure 8. Observed and simulated soil moisture for maize 2014 in Bologna, Italy where figure (a) refers to the layer-1 and (b) refers to the second layer for all irrigation strategy (RDI surface fresh water, SW, RDI, Treated waste Water, TWW, PRD SW and PRD TWW) from the top to bottom. The model was calibrated for the RDI SW (top figures a & b) and validated against the other irrigation time series.

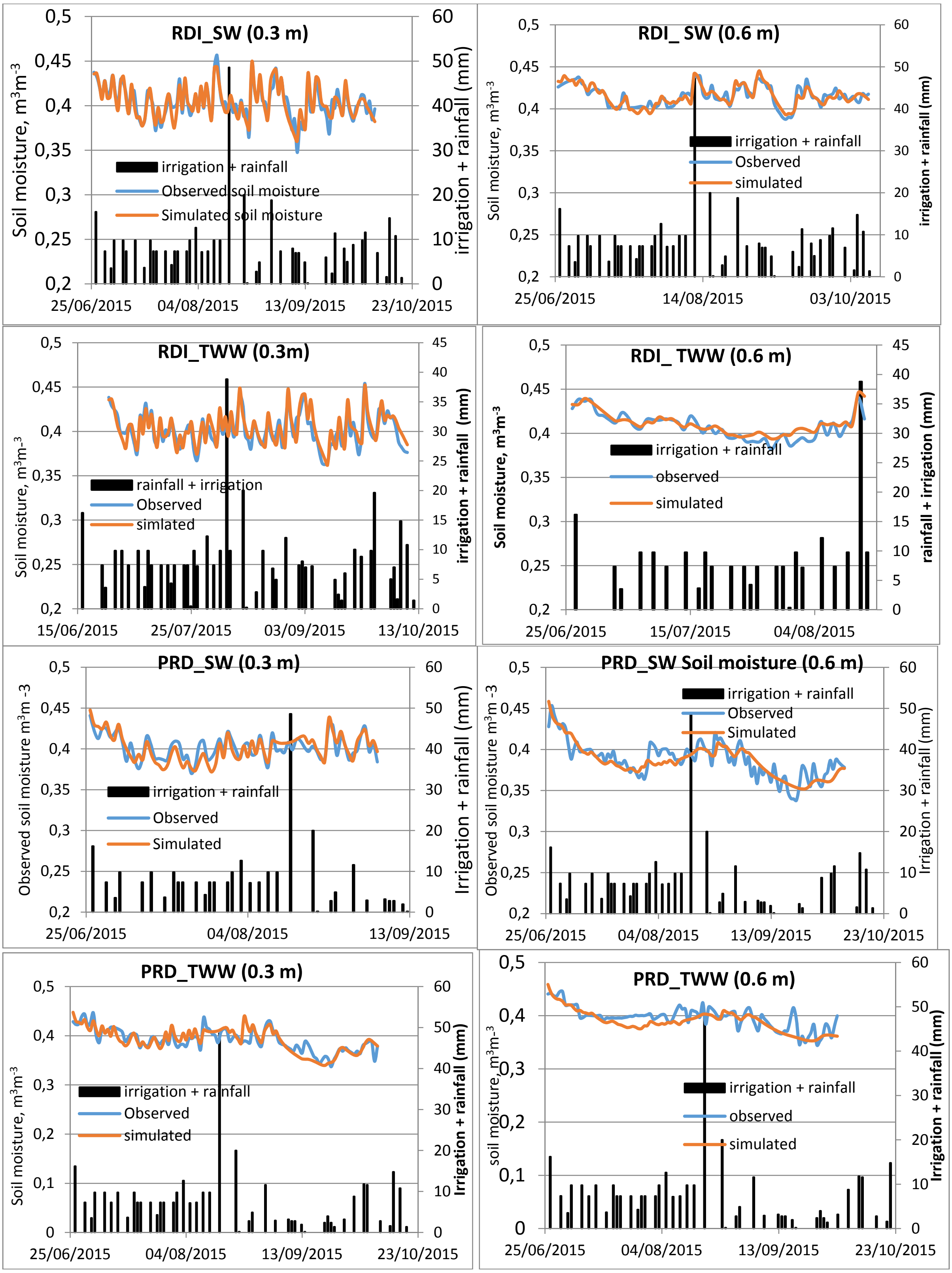

Figure 9: Observed and simulated soil moisture for tomato in 2015, where model was calibrated for the RDI with freshwater at 0.3 m depth and validated against other types at both 0.3 m and 0.6 m depth.

The model showed strong correlation between the observed the simulated soil moisture. With higher values for the R^2 and reasonable Root Mean Square Error, RMSE (Table 1).

Table 1. Soil moisture correlation and root mean square error for the model calibration and validation

Irrigation strategy	Year	Layer-1(0.3 m)		Layer-2 (0.6 m)		Average 2-layers	
		RMSE (%)	R^2	RMSE (%)	R^2	RMSE (%)	R^2
RDI-SW*	2013	1.76	0.84	1.53	0.82	1.25	0.92
	2014	1.28	0.88	1.488	0.87	1.07	0.91
	2015	1.4	0.82	4.0	0.79	0.14	0.88
PRD-SW	2013	1.18	0.89	1.21	0.90	1.29	0.92
	2014	1.77	0.96	2.164	0.91	1.59	0.98
	2015	1.12	0.67	1.61	0.71	1.72	0.79
PRD-TWW	2013	2.33	0.88	2.04	0.93	1.62	0.93
	2014	2.57	0.90	3.159	0.88	1.75	0.93
	2015	1.01	0.92	1.94	0.80	1.86	0.79
RDI-TWW	2013	2.76	0.86	2.65	0.85	2.10	1.87
	2014	1.17	0.87	1.464	0.83	0.90	0.91
	2015	1.79	0.72	1.2	0.79	1.54	0.81

* calibration treatment

Soil salinity

The soil salinity was also simulated for all irrigation strategies RDI and PRD for both fresh water and treated- waste water. In this study the simulated soil salinity was compared with the observed soil salinity measured in the field with suction cups and the sensors (both at depth 55-65 cm). The suction cups were used in calibrating the soil salinity sensors. The simulated results for both calibration and validation were close to the observed soil salinity (Figure 10,11 and 12).

At the early start, the simulated soil salinity was slightly lower than the observed soil salinity more particularly for the PRD treatment with the treated wastewater.

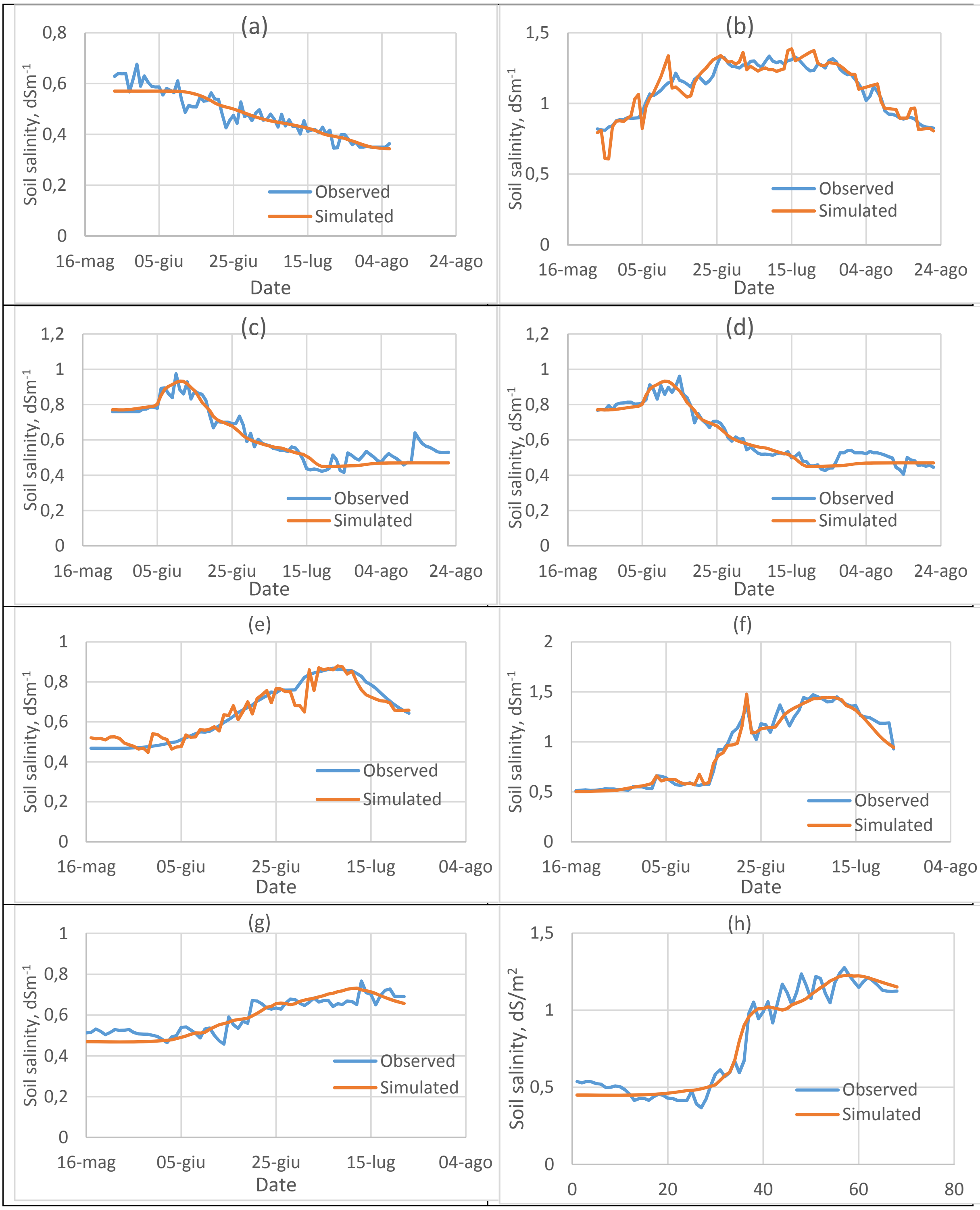

Figure 10. The observed and simulated soil salinity for the both RDI-SW (a & e), RDI-TWW (b & f), PRD-SW (c & g) and PRD-TWW (d & h) for the both maize (a-d) and potato (e-h) crops.

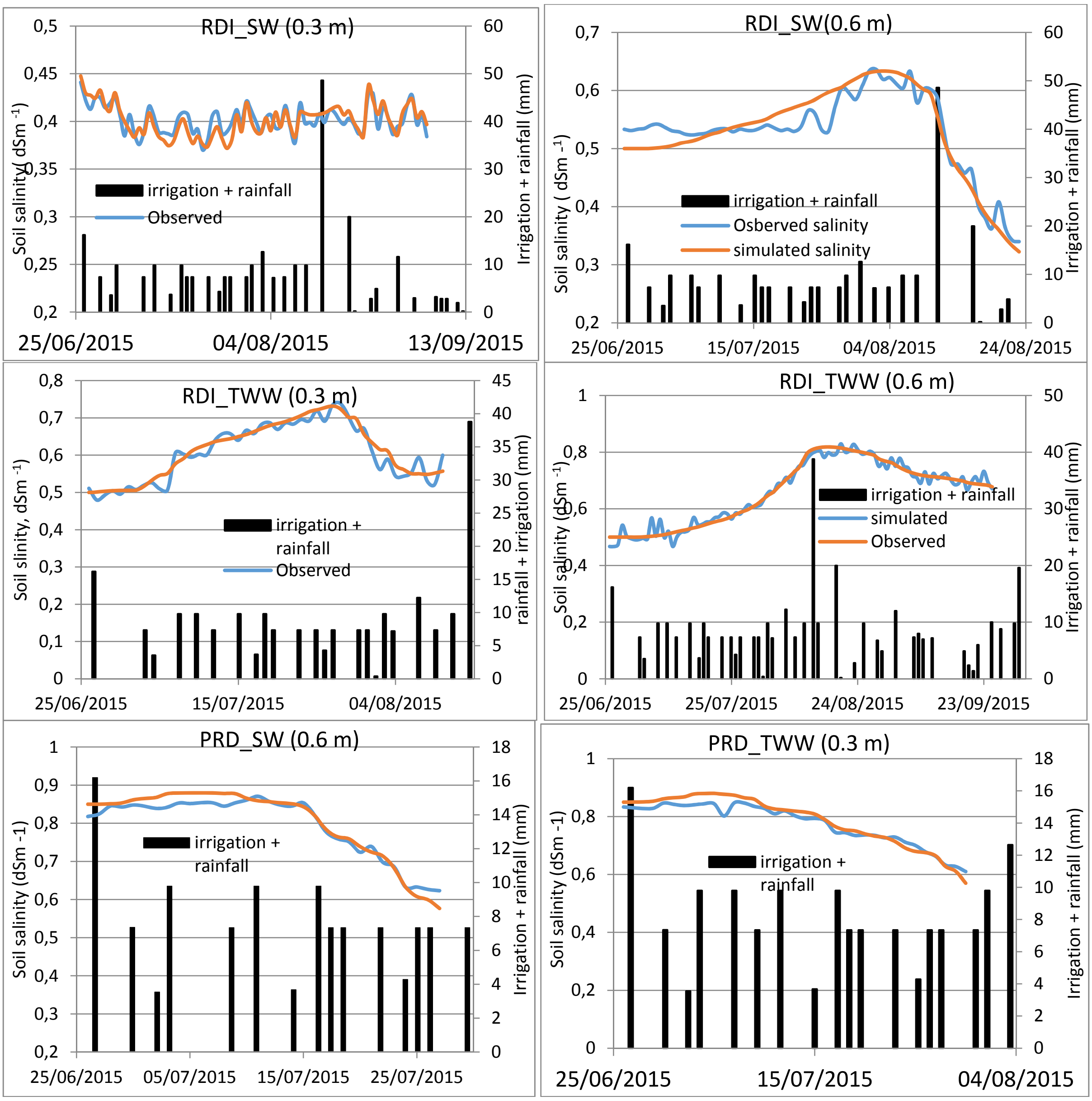

Figure 11: Observed and simulated soil salinity for tomato in 2015, where model was calibrated for the RDI with freshwater at 0.3 m depth and validated against other strategies at both 0.3 and 0.6 m depth.

The observed and simulated soil salinity was lower for the treatments with the freshwater and slightly higher for those irrigated with the treated waste water. Overall the observed and simulated soil salinity values are showing good fit for all treatments with the freshwater but the simulated values are slightly under-estimated with the treated waste water possibly due to accumulation of the salt in the top layers by evaporation. An overall strong correlation was obtained between the observed and simulated soil salinities.

Crop yield and Water productivity

Figures 12, 13 and 14 are showing the observed and simulated total yield for the potato, maize and tomato crops, respectively under different irrigation strategies.
When considering only irrigation amount for potato (excluding the rainfall), the PRD-SW received 15% less irrigation water than RDI-SW and produced a yield only 6% less than RDI-SW while RDI-TWW received similar amount of irrigation and produced equal yield to RDI-SW. Moreover, PRD-TWW used 12% less irrigation amount and produced a yield only 6% less than RDI-SW. This indicates that the treated waste water with salinity of 4 dSm^{-1} is as good as the fresh water for potato production and could be a good alternative to the river water for that site. In addition, PRD seems to be a good water saving strategy in this case.

For maize 2014, RDI-SW and RDI-TWW received the same amount of irrigation (but different qualities) and produced similar yields. Moreover, PRD-SW received 17% less irrigation water but produced similar yield to RDI-SW. In addition, PRD-TWW received 15% less irrigation water but produced similar yield to RDI-SW. Once again this confirms the results of potato that the treated waste water with salinity of 4 dSm^{-1} is as good as the fresh water for maize production and could be a good alternative to the river water for that site. In addition, PRD seems to be a good water saving strategy also in this second case.

For Tomato 2015, RDI-SW and RDI-TWW received similar irrigation water (but different qualities) and produced similar yields. Meanwhile, PRD-SW received 28% less irrigation water and produced yield only 9% less than the RDI-SW. Another confirmation that the treated waste water with salinity of 4 dSm^{-1} is as good as the fresh water for tomato production and could be a good alternative to the river water for that site. In addition, PRD seems to be a good water saving strategy also in this third case.

One should note here that, Irrigation water amount used for TWW was slightly higher in both RDI and PRD when using treated waste water as this treatment requires application of extra water for leaching of salts from the root zone to prevent excessive accumulation as shown in Table 2-4. For 2013, 2014, and 2015.
The model showed a good fit for the total yield over three years period for the potato, maize and tomato crops (Tables 2-4).

The water productivity was calculated as amount of yield produced in kg per cubic meter of water (including rainfall and irrigation) used. The field and modelling results show that the water productivity in was generally slightly high in PRD for potato, maize and tomato crops during the years 2013, 2014 and 2015, respectively. (Figures 15-17). Overall high water productivity was observed for the PRD with surface water for potato, maize and tomato (2.27 kg m^{-3} 3.56 kg m^{-3}, 2.29 kg m^{-3}), respectively. Similar results were also observed for the total dry matter for the three crops. In most cases, the lowest productivity was observed for the RDI with treated waste water. These findings are consistent with the studies carried out in other parts of the world (Liu et al., 2006, Shahnazari et al., 2008).

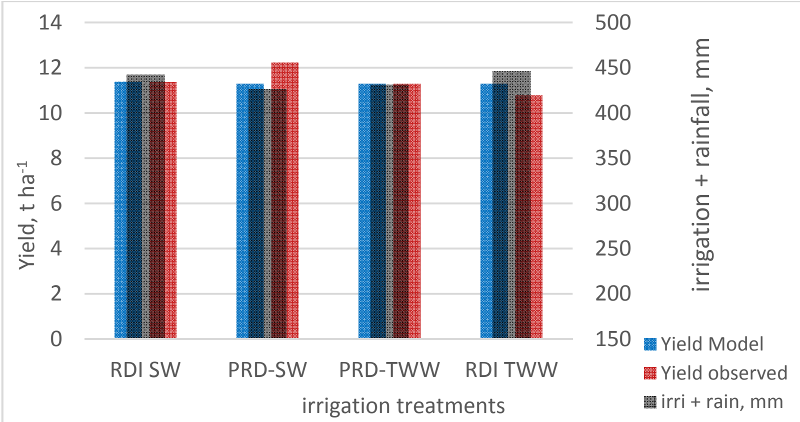

Figure 12. Observed and simulated potato yield under different irrigation strategies in Bologna, Italy for the year 2013.

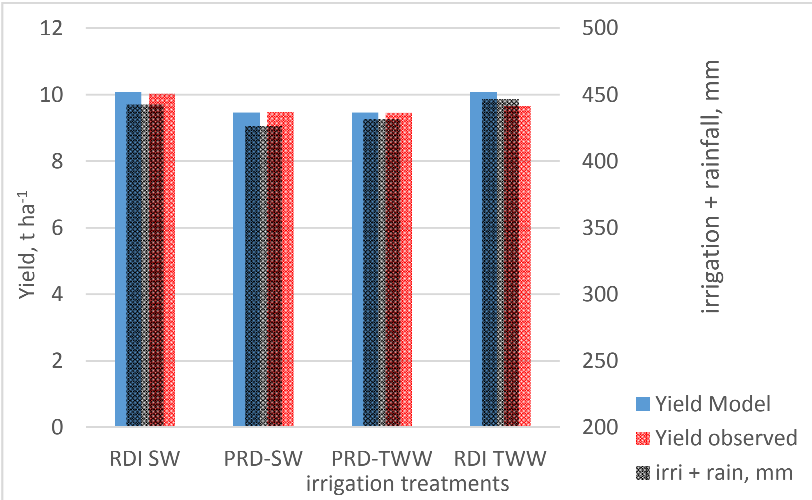

Figure 13. Observed and simulated maize yield under different irrigation strategies in Bologna, Italy for the year 2014.

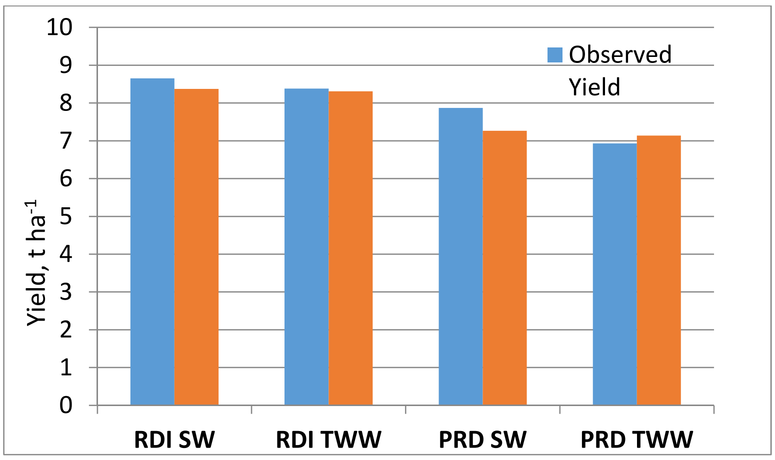

Figure 14: Simulated and observed tomato yield for all irrigation strategies in Bologna, Italy for the year 2015.

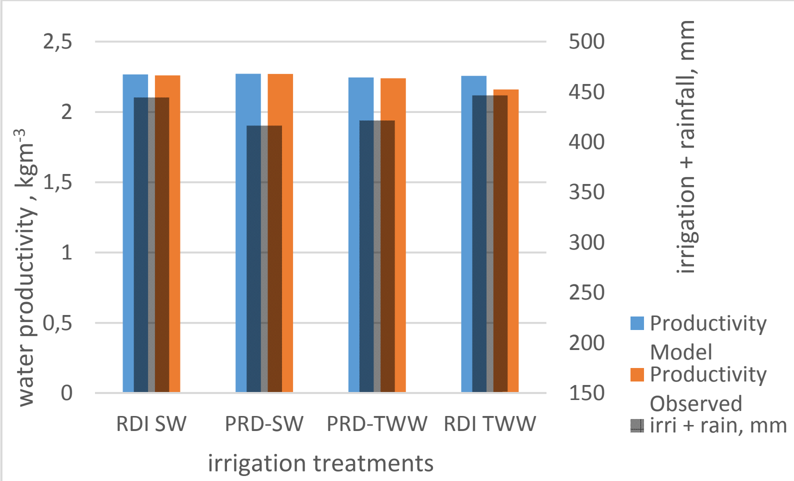

Figure 15. Observed and simulated water productivity for the potato yield (2013) and the amount of water supplied.

Table 2. Observed and simulated potato yield and water productivity for the year 2013 in Bologna, Italy

Irrigation Treatment	Yield t ha^{-1}		Difference *	Irrigation	Rain	Irrigation + rain	Water Productivity Kg m^{-3}	
	Observed	Simulated	%	mm	mm	mm	Observed	Simulated
RDI SW	10.08	10.03	-0.47	186.49	258	444.49	2.26	2.267
RDI TWW	10.08	9.85	-2.29	188.49	258	446.49	2.16	2.257
PRD-SW	9.46	9.47	0.09	158.49	258	416.49	2.27	2.272
PRD-TWW	9.46	9.46	-0.07	163.49	258	421.49	2.24	2.245

* Means % difference between observed and simulated

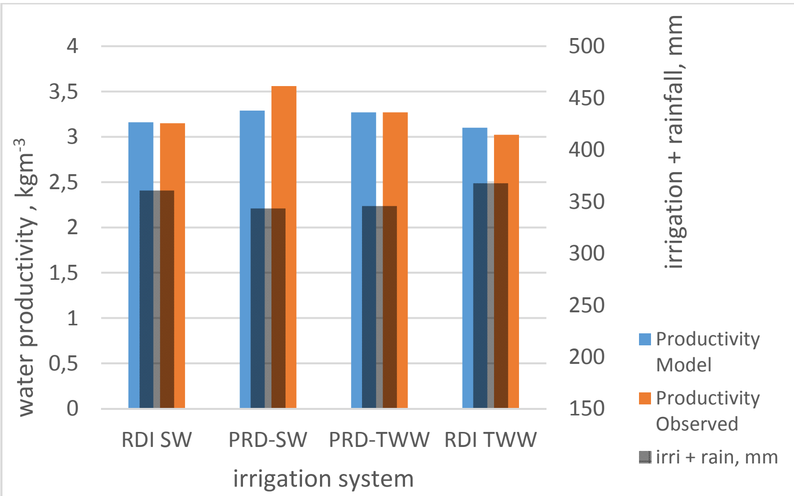

Figure 16. Observed and simulated water productivity for maize (2014) and the amount of water supplied.

Table 3. Observed and simulated Maize yield for and water productivity for the year 2014 in Bologna, Italy

Irrigation Treatment	Yield t ha^{-1}		Difference *	Irrigation	Rain	Irrigation + rain	Water Productivity Kg m^{-3}	
	Observed	Simulated	%	mm	mm	mm	Observed	Simulated
RDI SW	11.39	11.36	0.37	101.0	259	360.0	3.15	3.16
RDI TWW	11.35	11.26	0.03	103.5	259	363.0	3.02	3.11
PRD-SW	11.29	11.33	0.06	83.8	259	343.0	3.56	3.29
PRD-TWW	11.29	11.28	-1.10	86.1	259	345.0	3.27	3.27

* Means % difference between observed and simulated

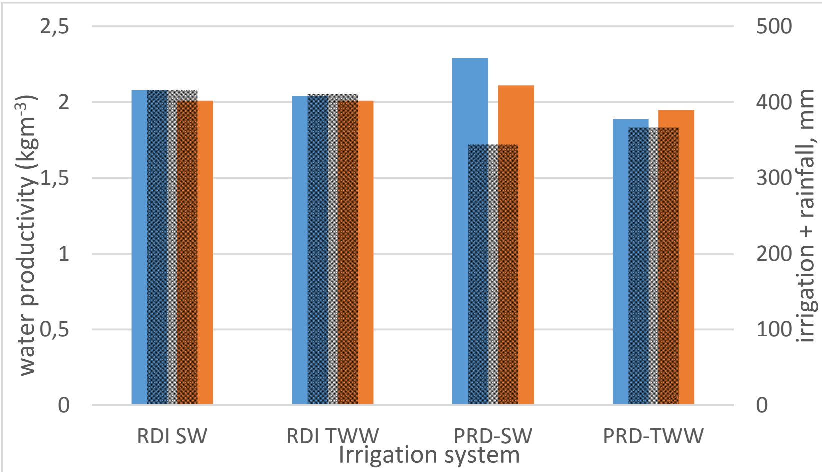

Figure 17. Observed and simulated water productivity for tomato (2015) yield and the amount of water supplied.

Table 4. Observed and simulated tomato yield for and water productivity for the year 2015 in Bologna, Italy

Irrigation Treatment	Yield t ha^{-1}		Difference *	Irrigation	Rain	Irrigation + rain	Water Productivity Kg m^{-3}	
	Observed	Simulated	%	mm	mm	mm	Observed	Simulated
RDI SW	8.65	8.37	3.37	255.47	160.4	415.87	2.08	2.01
RDI TWW	8.38	8.31	0.86	250.27	160.4	410.67	2.04	2.01
PRD-SW	7.86	7.46	5.41	183.8	160.4	344.20	2.29	2.11
PRD-TWW	6.93	7.14	2.92	206.13	160.4	366.53	1.89	1.95

* Means % difference between observed and simulated

Discussion

Although, the two strategies of irrigation application are based on the concept of deficit irrigation, one can see from the results that the PRD with 12 to 28% less water than the RDI, produced similar or close amount of yield. In addition, using different water qualities did not seem to have a large impact on crop yield and the biomass. The model not only showed a good correlation with the observed soil moisture, soil salinity and the crop yield but also the intermediate values of biomass during the growth stages. The field experiment and the modelling study suggest that the partial root drying (PRD) and regular deficit irrigation (RDI) irrigation strategies have a huge potential to save irrigation water in comparison to the full irrigation. The finding of this study suggests that the treated wastewater produced similar amount of crop yield as was produced by the freshwater. The outcome of this study also suggest that crop water productivity could be increased by implementing more innovative irrigation systems and proper irrigation strategies like partial root drying.

Concluding remarks

The field and modelling study revealed that the PRD irrigation strategy during the year 2013 for the potato crop used almost 15% less irrigation water, produced only 6% less yield than RDI and it gave equal water productivity to RDI. Similarly in the year 2014, maize PRD strategy received 17% less irrigation water but produced the same amount of crop yield as produced by the RDI. In 2015, PRD received 28% less water but produced a yield of tomato only 9% less than RDI. Given that the two water irrigation strategies received the same amount of rainfall, the results favour the PRD over RDI. The study also confirm the potential possible use of treated waste water for that site as alternative to the fresh river water resource.

Overall the modelling results are good and the model has shown a strong relationship between the observed the simulated soil moisture and salinity profiles, total dry matter and final crop yield. This illustrates the model ability to simulate the biomass and the crop yield of C3 and C4 crops as well as to simulate different water qualities and different irrigation strategies. Considering this, the model can run now with “what if” scenarios depicting several water qualities, crops and irrigation system strategies without the need to try them all in the field. It has the potential to reduce the cost and the labour.

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