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# **DEFICIT IRRIGATION TOOLBOX (DIT)**

## **User Guide**

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# 1. Introduction

## *Problem definition*

In response to the global population growth, the demand for food and water is expected to increase by more than 50% by 2050 (Valin et al. 2014; OECD 2012). Consequently, farmers will need to increase crop production worldwide. This can be done either by increasing the arable area or by enhancing crop productivity. However, clearing the land for agricultural needs brings high ecological and social trade-offs. Moreover, crop yields are highly affected by climate change, water availability and soil conditions. Therefore, there is a need for *sustainable intensification* of agriculture. It can be done through the application of organic fertilizers, better soil and water management, and modern technology such as remote sensing and artificial intelligence.

## *What is Deficit Irrigation Toolbox?*

**Deficit Irrigation Toolbox (DIT)** is an open-source software to simulate crop-water productivity. Written in MATLAB language, the toolbox allows you to perform the complex analysis of crop yield response to climate change, soil variability, and water management practices. The toolbox includes several crop models and various irrigation strategies which allow you to make a comprehensive assessment of crop yields in variable environments. Moreover, with an application of artificial intelligence, DIT brings water management options to the whole new level.

You can find the latest information and release notes on the official website: <http://bit.ly/TUD-DIT>.

## *About developers*

DIT is developed by Chair of Hydrology at TU Dresden (Germany) in 2019. At various stages, the next people participated in building and designing the code:

- **Prof. Dr. Niels Schütze** – Supervisor and Chair Holder
- **Oleksandr Mialyk** – Lead developer and Research Assistant

If you have any problems with running the code, please don't hesitate to contact us by writing an email to [hydrologie@tu-dresden.de](mailto:hydrologie@tu-dresden.de) with subject: "[DIT] Help request".

## *Acknowledgments*

We would like to thank Dr. Timothy Foster and the rest of his team for developing AquaCrop-OS, which is the main crop model of DIT. We would also like to acknowledge MSc and PhD students for testing and providing feedback for developers. We must also express a profound thankfulness to the staff of Chair of Hydrology at TU Dresden for providing resources and support in technical issues.

## 2. Installation

### *How to download?*

If you don't have your DIT copy, please follow the download procedure on the official website: <http://bit.ly/TUD-DIT>. The download package includes the latest DIT version with complete MATLAB code, simulation examples, instructions, and related literature.

### *Technical requirements*

Because the code was written for MATLAB R2017a, it may not be compiled with the previous versions. Therefore, we recommend getting the same or newer version of MATLAB which you can download at <https://www.mathworks.com>.

### *Test the code*

Once you have downloaded the toolbox, simply unzip the contents in a chosen location on your computer. The final structure of the folder should consist of 4 subfolders and the main script DIT.m:

- **Add-ins** - additional tools that we've created in the process of DIT development: Converter from AquaCrop to AquaCrop-OS (AOS) and Converter of the climatic database into DIT format;
- **Instructions** - here you can find the complete user guide and other related literature;
- **Projects** - here the inputs, configurations, and results of your projects are stored;
- **Scripts** - storage of all DIT scripts;
- **DIT.m** - script to run the simulation(s).

To check whether everything is properly installed, open *DIT.m* in MATLAB and click Run button. If you see some outputs and don't see any errors in Command Window, you are ready to start with simulations.

**For Beginners:** */Projects* folder has a subfolder with examples which you can follow to get familiar with DIT. The stepwise process of how to run those projects is explained in **Quick Start Guide** which you can find in */Instructions* folder.

### 3. Simulation procedure

#### 3.1. Project preparation

To run DIT you need to have your project first. In order to create it, copy */Projects/Project\_Template* and give it a new name (a single word, e.g. MaizeOman).

##### *Project structure*

Every DIT project has 2 subfolders and configuration file:

- **Data** - location of input files for Climate, Soil, and Crop data;
- **Results** - here the outputs will be saved;
- **Config.m** - configurations of your DIT project.

##### *Input data*

Depending on the crop model you select in the configuration file, the input files may be different.

List of files for **Soil-Water Balance Model (SWB)** (all in .txt format):

- *Climate* subfolder: Daily climatic data (Min Temp [°C], Max Temp [°C], Precipitation [mm], Reference ET [mm]);
- *Soil* subfolder: Root depth [mm];

List of files for **AquaCrop-OS (AOS)** (all in .txt format):

- *Climate* subfolder: 1) CO2 projection, 2) Daily climatic data (same as for SWB);
- *Crop* subfolder: 1) Crop mix, 2) Crop, 3) Field management, 4) Irrigation management, 5) Irrigation schedule (optional);
- *Soil* subfolder: 1) Soil, 2) Soil hydrology, 3) Soil texture (optional), 4) Initial water content, 5) Soil profile, 6) Water table.

If you are using AOS, you can refer to */Instructions/Literature/AquaCropOSv50a\_Reference Manual(2017).pdf* where more information about inputs is provided.

##### *Configuration file*

The complete configuration file is divided into 4 parts. Each of them has a set of parameters to set up:

1. **Scenario** settings:
  - *General* – names and time frame of your project;
  - *Visualization* – user control of output graphs.

## 2. Calculation settings:

- *Calculation mode* – run type in MATLAB. Can be standard or in parallel. The latter is used to run several iterations at the same time which can significantly decrease the overall computational period. However, this process requires high-performance characteristics of your computer. Browse [Parallel Computing Toolbox](#) for more information.

## 3. Crop Model settings:

- *Crop model selector* – selector of available DIT crop models. In DIT v1.0, two models are available:

- Soil-Water Balance Model (SWB) (Rao et al. 1988) - a simple solution to calculate crop-water productivity. It is calculated as a ratio of the potential yield  $Y$  to the maximum obtainable crop yield  $Y_m$  when the source of water is not limited. Crop growing season is divided into  $N$  growth stages (vegetative, flowering, grain-formation and maturity). Each stage has a corresponded yield response factor  $K$ :

$$Y/Y_m = 1 - \sum_{i=1}^N K_i \left(1 - \frac{AET}{PET}\right) \quad \%$$

- AquaCrop-OS (AOS) (Foster et al. 2017) - an open-source solution of PC software AquaCrop version 5.0a ([official website](#)). A crop yield  $Y$  is estimated as a harvestable fraction  $HI$  of a potential biomass  $B$  which reflects climate, soil and water management conditions on a daily time step. The biomass is calculated as a function of water productivity  $WP$  and daily transpiration  $Tr$ :

$$Y = HI * B = HI * WP * \sum Tr \quad [ton/ha]$$

If you want to convert your AquaCrop project into AOS format, find the instruction in Annex.

**Extra:** In order to understand AOS better, we recommend to read the official user manual [/Instructions/Literature/AquaCropOSv50a\\_Reference Manual\(2017\).pdf](#).

- *Common settings* – parameters which are the same for all crop models: crop name, growing season, and link to the climate input file.
- *SWB settings* – unique parameters of SWB model: soil data and link to root depth time series.
- *AOS settings* – unique parameters of AOS model: links to crop, soil, CO2 input files.
- *Multiple input files* – special feature for AOS model which allows you to iterate several input files in the same simulation process, e.g. different soil hydrology files (soil variability analysis).

4. **Irrigation** settings:

- *Irrigation limits* – available water storage and limits for a single irrigation event.
- *Irrigation strategy* – The toolbox allows you to choose one of the irrigation strategies below:
  - 1) No irrigation – whole growing season is under rainfed conditions;

$$\sum Irr = 0 \quad [mm]$$

- 2) Full irrigation – during the growing season  $gs$ , the crop is irrigated when the soil water content  $WC$  is less than 90% of the field capacity  $FC$ ;

$$\sum Irr = \sum_{i=1}^{gs} \begin{cases} (FC - WC_i) & \text{if } WC_i < 90\% \\ 0 & \text{if } WC_i > 90\% \end{cases} \quad [mm]$$

- 3) Full irrigation with thresholds – crop is irrigated when the soil water content is less than a defined threshold  $K_{WC}$  with the amount of water controlled by an irrigation threshold  $K_{Irr}$ ;

$$\sum Irr = \sum_{i=1}^{gs} \begin{cases} (FC - WC_i) * K_{Irr} & \text{if } WC_i < K_{WC} \\ 0 & \text{if } WC_i > K_{WC} \end{cases} \quad [mm]$$

- 4) Constant irrigation – crop is irrigated every  $X$  days with the amount of water  $Q_N$  coming from the water storage  $Q_{tot}$ . In other words, all irrigation events  $N_{Irr}$  are the same in time and volume;

$$\sum Irr = \sum_{i=1}^{N_{Irr}} Q_N \quad [mm], \quad \begin{cases} Q_N = \frac{Q_{tot}}{N_{Irr}} \\ N_{Irr} = \frac{gs}{X} \end{cases} \quad [mm]$$

- 5) Optimized irrigation with Decision Table (DT) – algorithm optimizes six decision variables using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) proposed by Hansen et al. (2003). The algorithm has six decision variables. The soil moisture fraction  $X_1$  divides soil conditions into two groups – dry and wet. Similarly, the available water fraction  $Y_1$  divides the irrigation storage into two groups – few and much water. Each of these four sections has an irrigation limit ( $L_1, L_2, L_3, L_4$ ) which is the fraction of the maximum irrigation. As a result, a farmer is provided with recommendations for crop watering according to the current soil moisture and available water storage.

$$\sum Irr = \sum_{i=1}^{gs} \left\{ \begin{array}{l} \text{Wet soil and Few Water} \\ (FC - WC_i) * L_1 \quad \text{if } FC * X_1 \leq WC_i \leq FC * X_2 \text{ and } Q_{tot} * Y_0 \leq Q_i \leq Q_{tot} * Y_1 \\ \text{Dry soil and Few Water} \\ (FC - WC_i) * L_2 \quad \text{if } FC * X_0 \leq WC_i \leq FC * X_1 \text{ and } Q_{tot} * Y_0 \leq Q_i \leq Q_{tot} * Y_1 \\ \text{Wet soil and Much Water} \\ (FC - WC_i) * L_3 \quad \text{if } FC * X_1 \leq WC_i \leq FC * X_2 \text{ and } Q_{tot} * Y_1 \leq Q_i \leq Q_{tot} * Y_2 \\ \text{Dry soil and Much Water} \\ (FC - WC_i) * L_4 \quad \text{if } FC * X_0 \leq WC_i \leq FC * X_1 \text{ and } Q_{tot} * Y_1 \leq Q_i \leq Q_{tot} * Y_2 \end{array} \right.$$

- 6) Optimized irrigation with Decision Table (4 phenological stages) – same principle as for the strategy 5 but, here, each crop development stage (Germination, Flowering, Grain-formation, Maturity) has own set of decision variables making in total  $6 \times 4 = 24$  variables. This strategy is the most computationally demanding and may take several hours to complete.
  - 7) Optimized irrigation with GET-OPTIS – Global Evolutionary Technique for Optimal Irrigation Scheduling (GET-OPTIS) is an evolutionary optimization of random irrigation events throughout the crop cycle (Schütze et al. 2012). This technique applies selection, crossover, mutation, and reconstruction in order to maximize crop yields. As a result, the optimal irrigation schedule is produced.  
GET-OPTIS was modified in order to be used in DIT and, currently, has 3 modes which you can select at the end of the configuration file.
  - 8) Defined irrigation schedule – you can use your own irrigation schedule for DIT. It can be either the schedule created by some of the previously described strategies or it can be a new one. In the latter case, make sure to follow the same format as in the example file `/Projects/ProjectTemplate/Data/Crop/Irrigation/200_irr_schedule.txt`.
  - 9) Defined Decision Table – you can use your own decision variables for DIT. They can be either created by strategies 5 and 6 or they can be user-defined. In the latter case, make sure to follow the same format as in the example file `/Projects/Example/Data/Crop/Irrigation/ DecisionTable_24.txt`.
- *Irrigation optimization* – optimization parameters of irrigation strategies (currently 5-7).

You can find available options for all parameters and default values in the comments to the code lines.

**Extra:** In `/Scripts` folder there is a master configuration file `DIT_ConfigFull.m`. you can add it to the beginning of the configuration file of your project which allows you to remove unnecessary for you parameters and shorten the file. However, make sure that the default parameters from `DIT_ConfigFull.m` don't compromise the goal of your simulation. You can also look how it is working by opening one of the examples in `/Projects/Examples`.



In DIT, we don't consider the irrigation efficiency  $E_{irr}$  by intention. It is easier for a user to correct the simulated values of water storage  $Q_{tot}$  rather than recalculate the crop yield for every new value of  $E_{irr}$ . According to FAO (2017), water loss is controlled by two values:

- *Conveyance efficiency*  $E_c$  (the efficiency of water transport): 60...90% - Earthen canals; 90...95% - Lined canals; 95...100% - Pipes.
- *Field application efficiency*  $E_a$ : 60% - Surface irrigation (border, furrow, basin); 75% - Sprinkler irrigation; 90% - Drip irrigation.

Consequently, the final required water storage can be calculated as follows:

$$Q_{final} = Q_{tot} / E_{irr} = Q_{tot} / \frac{E_c * E_a}{100} \quad [\%]$$

The final irrigation efficiency  $E_{irr}$  of > 50% is good; 30-50% is reasonable, while < 30% is poor.

Notice that in AquaCrop-OS, the irrigation efficiency is defined in the irrigation management input file. We recommend to use 100% and then correct the final results using the methodology above.

## 3.2. Simulation run

### *General process*

The simulation process consists of 3 stages (Figure 1):

1. After preparing the configurations, you need to run *DIT.m*. First, the script reads default configurations and saves them into **conf** structure. Then, it overwrites them with the ones you define in *Config.m* of your project.
2. *DIT.m* calls the script */Scripts/RunDITProject.m* for every project run. This script makes all hard work. First, it runs initialization where the input data is validated and read. Afterwards, according to the crop model you have defined, the script reads the climatic data. If the irrigation strategy is 5...7, the next step is **optimization**. Otherwise, the script will directly start with crop modeling. Each growing season is calculated separately either in *for* or in *parfor* loop. In the latter case, MATLAB runs several iterations in parallel which can significantly decrease the overall computational time. However, this process requires high computational characteristics of your computer. Search for "Parallel Computing Toolbox" in web for more information. Finally, *RunDITProject.m* prepares and saves the results of DIT run.
3. Once *DIT.m* finishes its work, the results are available for you. Some of them you can see in MATLAB Command Window and some pop up. However, the reports you need to open by yourself in */Projects/Your\_Name/Results*. Find more information in Section 3.3.

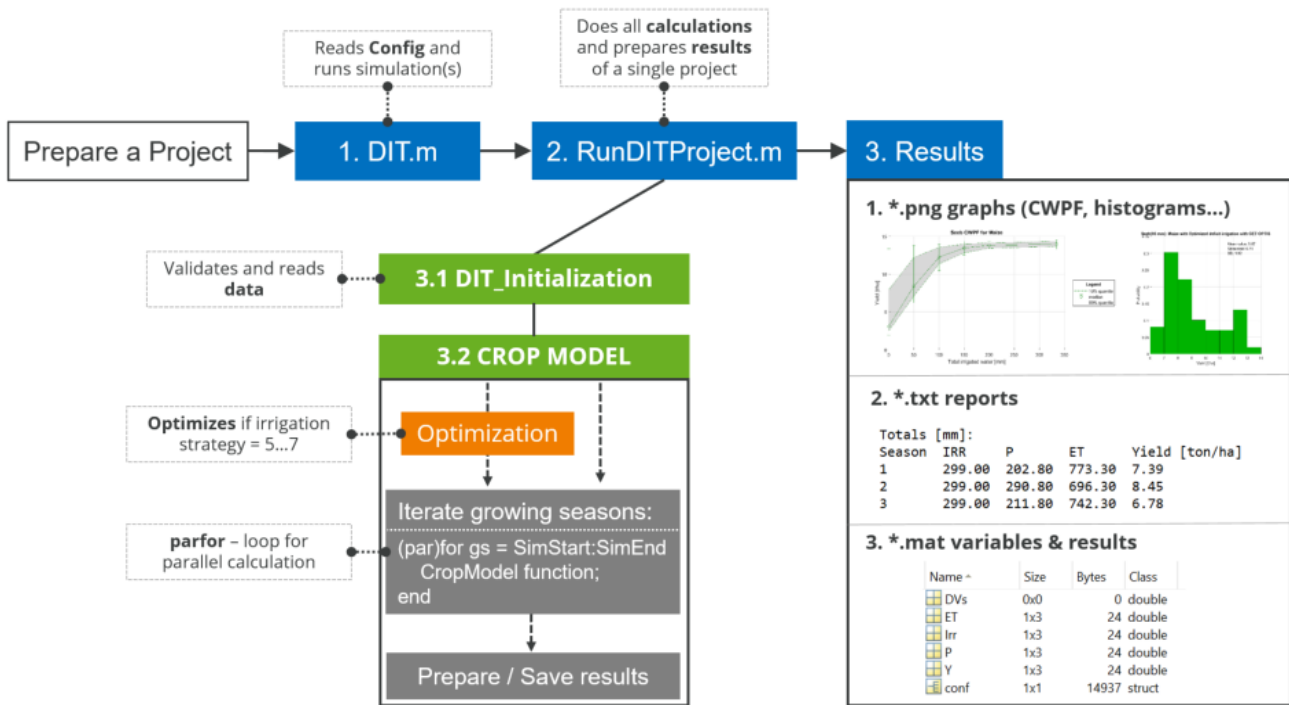


Figure 1. General process of DIT run.

### Crop-Water Production Function (CWWPF)

If you want to build a **Crop-Water Production Function (CWWPF)**, you need to set irrigation storage in the configuration file as an array, e.g. [0 100 300 500]. DIT runs for each water storage sequentially in a for loop. Please notice that the empty water storage (0mm) provides you the range of crop yields under the rainfed conditions. You can see how CWWPF looks in Section 3.3.

**Extra:** It is possible to run several simulations simultaneously. For instance, analyze different crops using the same climate and soil data. For more information read the comments in the DIT.m.

### 3.3. Output analysis

#### MATLAB Command Window

The most important information of your DIT run is shown directly in MATLAB Command Window. Apart from the simulation settings, you can also see the results. Furthermore, DIT has an error support system for the most common errors, so you can easily fix them by following the instructions in error messages.

```

>> DIT
===== DIT START =====
Project: ProjectTemplate
Number of simulations: 4
Simulation period: 2000-2010 (10 y)
Calculation mode: Standard
Crop model: AquaCrop-OS v5.0a
Crop name: Maize
Irrigation strategy: Constant irrigation

Progress:
- Simulation 1:
  ~ Calculating crop yields...
  ~ Max/Mean/Min crop yields = 3.36/0.45/0 ton/ha, with irrigation ~0 out of 0 mm
- Simulation 2:
  ~ Calculating crop yields...
  ~ Max/Mean/Min crop yields = 4.42/0.81/0.05 ton/ha, with irrigation ~107 out of 200 mm
- Simulation 3:
  ~ Calculating crop yields...
  ~ Max/Mean/Min crop yields = 11.4/10/8.49 ton/ha, with irrigation ~319 out of 400 mm
- Simulation 4:
  ~ Calculating crop yields...
  ~ Max/Mean/Min crop yields = 13.7/13.5/13.3 ton/ha, with irrigation ~480 out of 600 mm
- Plotting figures...
- Saving results...
- Successful finish (21.2 sec)

You can find results in DIT/Projects/ProjectTemplate/Results/Test_05-04-2019_114739/
===== DIT END =====

```

Figure 2. DIT results in MATLAB Command Window.

### *Output folder*

The toolbox provides you with different kinds of results: graphs, reports, and MATLAB databases. These results are saved only if you define so in the configuration file. The name of the output files is generated according to the next methodology:

Your Project / Results / conf.saveas + current datetime / (CWPF / conf.irr.storage) / conf.saveas + (conf.irr.storage) + conf.crop.model + Type of an output

For example:

/Projects/ProjectTemplate/Results/Test\_05-04-  
2019\_114739/CWPF/400/Test\_400\_AOS\_Historgam.png

**(CWPF / conf.irr.storage)** and **(conf.irr. storage)** are added only if CWPF is activated. In this case, most of the results will be distributed between different output folders according to the water volumes (Figure 3).

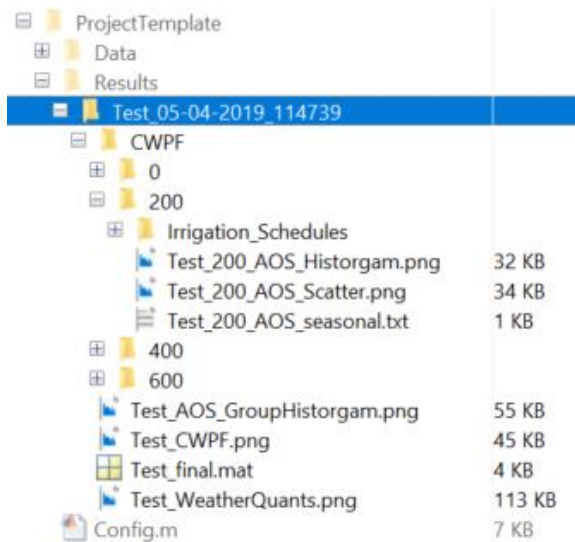


Figure 3. Structure of the results folder.

## Graphs

There are several types of graphs available:

- Statistical analysis of climatic data;
- Scatter plot of crop yields;
- Histogram of crop yields;
- Crop-Water Production Function (CWPF) if activated.

Depending on your project, they may be distributed among different result folders. You can perform some basic visualization set up directly by using available parameters of the configuration file or by changing manually the code in */Scripts/Visualization*.

## Reports and Irrigation Schedules

DIT provides you with seasonal reports of each simulation where you can see the water balance and crop yield summary for each growing season (Figure 4).

For some strategies, DIT also generates the irrigation schedules which you can later reuse by applying irrigation strategy 8. Find more in Section 3.1.

```

Project:      ProjectTemplate
Crop model:  AquaCrop-OS
Seeding date: 01/11
Harvest date: 01/04
Strategy:    Constant irrigation
Irrigation storage: 600.0 mm

Crop yields [ton/ha]:
mean - 13.46; 10% quantile - 13.3
|
Totals [mm]:
Season  IRR      P      ET      Yield [ton/ha]
1       480.00  47.90  494.10  13.28
2       480.00   0.80  517.80  13.69
3       480.00  47.50  495.10  13.44
4       480.00  23.20  503.00  13.32
5       480.00  27.50  514.80  13.36

```

Figure 4. Example of a seasonal report.

*IRR* – total amount of irrigated water, *P* – total precipitation, *ET* – total evaporation

### *MATLAB databases*

All results are also stored in MATLAB format, so you are able to manipulate them and reuse for external scripts.

## 4. Simulation Example

### *Maize under climate variability in Oman*

In the Projects folder, you can find a case study project: */Projects//Oman*. The location of input data is a small arid region in the eastern seaside of Oman and the task was to analyze the crop-water requirement under climate variability according to IPCC A2 scenario (stochastically generated 100 years of the year 2080).

You can run it by following the next procedure:

- Open *DIT.m*;
- Provide the path of your DIT to *DIT\_path* variable or leave as "" if it is the current MATLAB folder;
- Provide the path of your configuration file to *config\_path* variable. In our case: 'Projects/Oman/Config\_Oman.m';
- Click Run button.

As you can see, due to the dry conditions, the water requirement to get reasonable yields is quite high. However, you can try to run it with optimization strategies and see how much water you can save by using 'smart' DIT strategies.

Explore more about this project by analyzing the configuration file and input files.

## References

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