APPLICATION OF COMPUTER MODELS IN IRRIGATION MANAGEMENT

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1.

Introdcution

Several key factors such as population growth, climate change, rising food prices, declining natural resources call for more efficient management in crops as well as in water management. Good water management maximizes the water use efficiency and preserves water resources. The implementation of **ICT (information and communication technology)** in water management improves efficiency by introducing different tools, devices, software, remote sensors, and applications into the management. It enables engineers, scientists, farmers, and policymakers to increase productivity with improved planning and management of the production system. Furthermore, the implementation of ICT in water management has improved the data storage capacity, exchange of information, and ability to access data remotely. ICT can help to prevent and reduce water losses through well-planned irrigation schedules which is crucial to increased productivity. ICT is now being used in irrigation projects to improve water management in a variety of ways: planning, data collecting, storage, and sharing. Furthermore, it is used for weather forecasting, and to improve water efficiency with the introduction of hardware, software, models, and remote sensors. Such innovative water management is helping to improve and expand intensive irrigation facilities.

Irrigation is the application of water to meet the crop water demand at the proper time in the proper way (Ali, 2010). Crop water demand in arid and humid regions are not the same, i.e. in arid regions irrigation water is the main source of water for crop production while in humid areas the crops are irrigated only during the period of drought. Nevertheless, irrigated agriculture is one of the major consumers of freshwater resources. Therefore, proper irrigation scheduling is required for better and more efficient irrigation systems. The purpose of **irrigation scheduling** is to calculate net irrigation, irrigation rate, crop water demands (CWD), and irrigation time. Different methods could be used for the determination of irrigation scheduling, i.e. calculation method, observation method, estimation method, and measuring of soil moisture content. Each of these methods has its advantages and limitations, which indicate the fact that irrigation scheduling is a demanding and time-consuming process. However, the **introduction of computer models, instrumentations, and techniques for computerized irrigation** has made it easier since it provides irrigation scheduling exactly according to the water needs of the crops.

1.1.   Computer models

Some of the computer models that are used in irrigation scheduling as well as in crop production are APSIM, CROPWAT, AQUACROP, and DSSAT. Dynamic simulation models of soil-plant systems are powerful tools which combined with automated weather station networks, soil, and plant measurement systems are increasing the efficiency of decision making. No matter which computer model is used for irrigation scheduling, a basic understanding of **soil – water - plant** interactions is obligatory for achieving efficient crop production. Also, it must be stated that the model to be as efficient as possible it is necessary to calibrate and validate the model for specific crops as well as for specific growing conditions.

1.2.   Wireless sensors

One of the developing sectors in irrigation management is the implementation of **wireless sensor networks (WSN)**. Sensors can provide real-time weather, soil, and crop data which considerably simplifies the decision-making in irrigation scheduling (Figure 1). In such a form, irrigation scheduling becomes **smart irrigation technology**. Due to the latest technological advances, sensors have become more efficient, reliable, and less expensive. Sensors are set up in a field, i.e. soil sensors, canopy sensors, or compact weather sensors to collect (usually periodically) and send data to the end-user in a short period of time, ending with efficient temporal and spatial data network. Of course, no matter what type of sensor is used, experts in soil, climate, or crop science are required so that the sensor's maximum efficiency would be achieved.

The introduction of sensors to irrigation management is one of the latest technological innovations for improving irrigation efficiency.
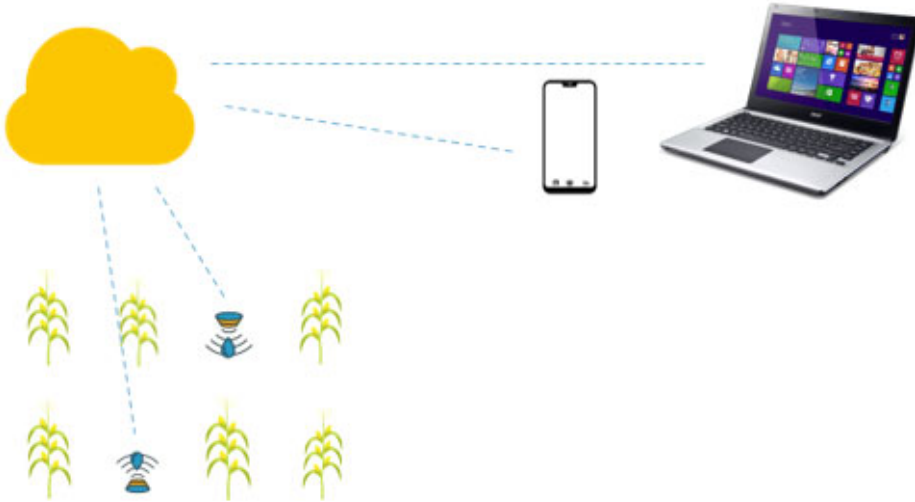
Figure 1. Wireless sensors in smart irrigation

1.3. GIS (Geographic Information System)

Some of the GIS functions that are related to crop production can successfully be used to monitor and improve water management in irrigated agriculture. Of course, the use of sensors for collecting temporal and spatial data that are mentioned in the previous section is obligatory. Some of the GIS software that can be used in irrigation management are ESRI, ArcPAD, ArcGIS, etc. One of the GIS features is Digital orthophoto quads (DOQs), digital maps that provide spatial illustra- tions of terrain, including elevation and property boundaries, which can help delineate irrigation canals and drainage systems. Laser scanning (LiDAR) is a technology for obtaining a highly detailed digital terrain model that can be used more broadly in water management. It works similar to radar but it uses the beaming light pulses instead of the radio waves for identification of areas with the slope and elevation, water flow and catchments maps as well as erosion control.

1.4.   Remote sensing in irrigation management

A large scale of crop production justifies the implementation of remote sensing, i.e. satellite data. Precision irrigation mostly uses data that are part of hydrology and of course meteorology and collected data are used to improve water management in irrigated agriculture. Satellite imagery has wide-ranging applications in agriculture, for example, early identification of plant stress caused by pests and diseases, lack of water, or monitoring of weeds.

2.

CropWat MODEL

2.1. About CropWat model

CropWat 8.0 is a computer model designed by experts from the Land and water development division of the Food and Agricultural Organization (FAO).

CropWat model calculates **Crop water requirements (CWR)** and irrigation water requirements (IWR) from climate, soil, and crop data (Figure 2).
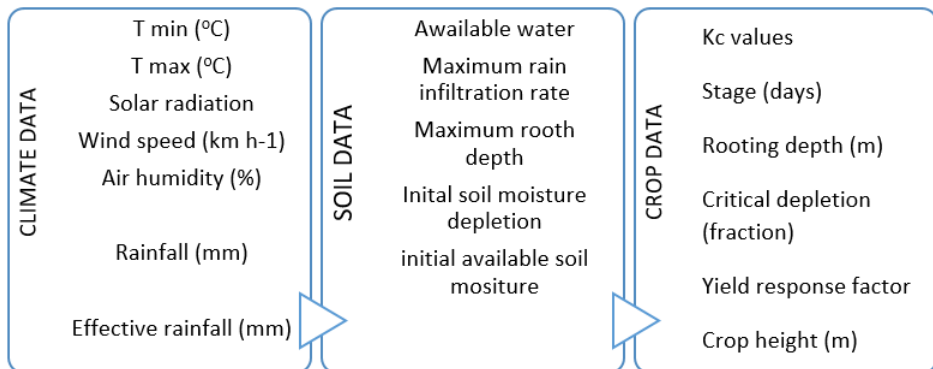

Figure 2. Climate, soil, and crop data used for calculation of irrigation scheduling and crop water requirements

The CropWat 8.0 model provides calculation of irrigation schedules for different irrigation management conditions as well for different crops. For example, if irrigation has a full or supplemental (regulated deficit) character. Full irrigation will provide the total amount of water needed for crops to avoid water deficit. Opposite to full irrigation, deficit irrigation aims to reduce water demands with optimization of economic output. CropWat model is available on the following link, where also installation guide

can be found: http://www.fao.org/land-water/databases-and-software/CropWat/en/. Procedures for calculation of the CWR and IWR are mainly based on methodologies presented in FAO Irrigation and Drainage Papers No. 24 "Crop water requirements". It would be the best if climate, soil, and crop data are collected in the field or at least in the local area. If not, CropWat 8.0 program includes standard crop and soil data that are integrated into the model.

2.2. Step by step procedure

A step-by-step procedure for the CWR calculation and irrigation scheduling is explained below. The chosen crop is maize (*Zea mays* L.) grown and irrigated in the Osijek region. Each step is briefly described as well as the main definitions that are related to the model.

2.2.1. Station and climate data

CropWat computer program allows calculation of the CWR and IWR for different agro-ecological zones with the assumption that at the very beginning of the analysis the exact geo-coordinates and altitude of the selected area are given. The accurate geolocation and climate data are needed to calculate the crop water requirements that are environment-dependent.

Crop yield is highly dependent on weather conditions during the growing season, these are rainfall, air temperature, and humidity, wind speed, etc. The primary source of water, that is available water for crop production for most of the world is rainfall. In crop production, rainfall is observed through three aspects, quantity, distribution, and intensity. The amount of water that crop uses for the evapotranspiration process can be observed as "lost" water that should be compensated with irrigation. The process of evapotranspiration depends on the amount of energy available for water evaporation, while the largest source of energy is solar radiation. Due to differences in the position of the Sun, the potential amount of solar radiation that can reach the surface from which water evaporates depends on the geographical position and the season. On the other hand, the actual amount of solar radiation reaching the surface from which water evaporates depends on the atmosphere, i.e. on the presence of clouds that absorb and reflect the main parts of the solar radiation. Also, when assessing the impact of solar radiation on evapotranspiration, it should be noted that all available energy is not only used to evaporate water but part of the solar energy is spent on warming the atmosphere and soil. Solar radiation that is absorbed into the atmosphere increases the air temperature which in turn affects the ETo process.

Solar radiation absorbed by the atmosphere and heat emitted by the Earth increases the air temperature. The heat of the surrounding air transfers energy and thus affects the rate of evapotranspiration. Thus, during sunny, warm days, the loss of water from the soil surface and plants by the process of evapotranspiration is higher compared to the evaporation of water from them during cold and cloudy weather. From this, it can be concluded that the higher the air temperature, the more water will evaporate into the atmosphere from the surface of the soil and plants. The consequence is a higher crop for water requirement, which in case of lack of rainfall must be compensated by irrigation.

Relative air humidity is the ratio of air vapor pressure to its saturation vapor pressure. It shows how much vapor is in the air according to the maximum amount of water vapor that the air could contain at the same temperature. As the air temperature changes, so does the relative humidity. If the amount of vapor in the air remains unchanged and the air temperature rises, the relative humidity decreases as warm air may contain a larger amount of water vapor compared to cold air. In arid areas, relative humidity is low and evapotranspiration is more intense, so crops in such conditions have a greater need for water. On the other hand, in rainy, tropical conditions, high relative humidity reduces the loss of water from the soil surface and plants by the process of evapotranspiration.

The process of removing vapor from the air largely depends on the wind and turbulence of the air above the surface from which the water evaporates. When water evaporates from plants and soil, the air above the surface from which the water evaporates becomes saturated with water vapor. If such air is not constantly replaced by dry air, the process of evapotranspiration weakens. In other words, continuous airflow contributes to increased evapotranspiration. Thus, the higher the wind speed in hot and dry conditions, the more water will be released into the atmosphere from the surface of plants and soil.

Two main weather-related variables that determine IWR are the amount and timing of rainfall, and evapotranspiration. CropWat gives the opportunity to choose, how different types of climatic data will be entered

into the model. The air temperature can be provided as T_{min} and T_{max}, or as an average air temperature (T_{avg}). Air humidity can be given as air relative humidity (%) or as a vapour pressure (kPa). Daily sunshine data can be given as hours of sunshine, as a % of daylength, and as a fraction of daylength. Wind speed data can be given as km/day or m/sec. It would be best to collect data from a weather station that is located on the field. If that is not the case, the weather data can be obtained from the Croatian Meteorological and Hydrological Service.

At the very beginning, it is necessary to enter the basic location data (Figure 3), such as Country and station data (altitude, longitude, and latitude), and afterward the climate data so that the ETo could be calculated. The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation, and on the other hand from the crop by transpiration is referred to as evapotranspiration (ET).

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m2/day	mm/day
January	-14.4	14.0	92	2	0.9	3.7	0.28
February	-7.6	17.0	83	2	1.7	5.8	0.50
March	-3.8	20.5	76	2	3.8	10.4	1.12
April	4.4	25.5	68	2	7.6	17.8	2.45
May	3.8	31.3	69	2	8.8	21.6	3.54
June	7.6	33.0	76	2	7.4	20.5	3.67
July	11.2	36.6	64	2	11.8	25.9	4.72
August	11.2	36.2	67	2	9.4	20.8	3.82
September	8.5	33.1	66	2	7.9	15.8	2.63
October	-1.0	29.6	79	2	4.3	8.8	1.34
November	-2.4	20.4	85	2	3.0	5.5	0.63
December	-17.5	21.3	88	2	1.3	3.5	0.42
Average	0.0	26.5	76	2	5.7	13.3	2.09

Monthly ETo Penman-Monteith - C:\ProgramData\CROPWAT\data\climate\Osijek 2009.PEM

Country: Croatia Station: Osijek
Altitude: 90 m. Latitude: 45.00 °N Longitude: 18.00 °E

Figure 3. Station and climate data

Simply said, ET is the amount of water that is lost and should be compensated with irrigation water. In the CropWat model, the ETo calculation is based upon the Penman-Monteith equation (Allen et al., 1998) which is the established method for determining the ET of major herbaceous crops with sufficient precision for management purposes (Fereres and Soriano, 2007).

As presented in figure 3., climate data include monthly data for minimum and maximum air temperature (or average), air humidity (%), sunshine hours, and wind speed (km/day). Mentioned climate data are used for the calculation of **reference evapotranspiration** (ETo, mm/day).

ETo is the evapotranspiration rate from the reference surface (grass) that represents the evaporative demand of the atmosphere regardless of crop or agricultural practices. As can be seen from figure 2, the only factors affecting ET_o are climatic parameters.

2.2.2. Effective rainfall

Before the calculation of Crop evapotranspiration under standard conditions (ETc) the effective rainfall is to be calculated. This is an important step since part of the rainfall is not effective for the plant. Part of the rainfall percolates below the plant root zone (deep percolation) and other parts of the rainfall flow away over the soil surface (run-off). Deep percolation water and run-off water cannot be used by the plants. So, part of the rainfall is not effective but the remaining part is stored in the root zone and can be used by the plants and that is so-called effective rainfall. In general, the efficiency of rainfall will decrease with increasing rainfall.

For most rainfall events below 100 mm/month, the efficiency will be approximately 80%. The factors which influence which part is effective and which part is not effective include the climate, the soil texture, the soil structure, and the depth of the root zone, and these factors have been discussed in previous studies of Dastane (1978). There are different methodologies for the calculation of effective rainfall and a few of them are integrated into the Crop-Wat model (Figure 4), a fixed percentage (usually 80%), FAO/AGWL formula, empirical formula, and USDA method. In our example, the effective rainfall is calculated with the use of the FAO/AGWL methodology.
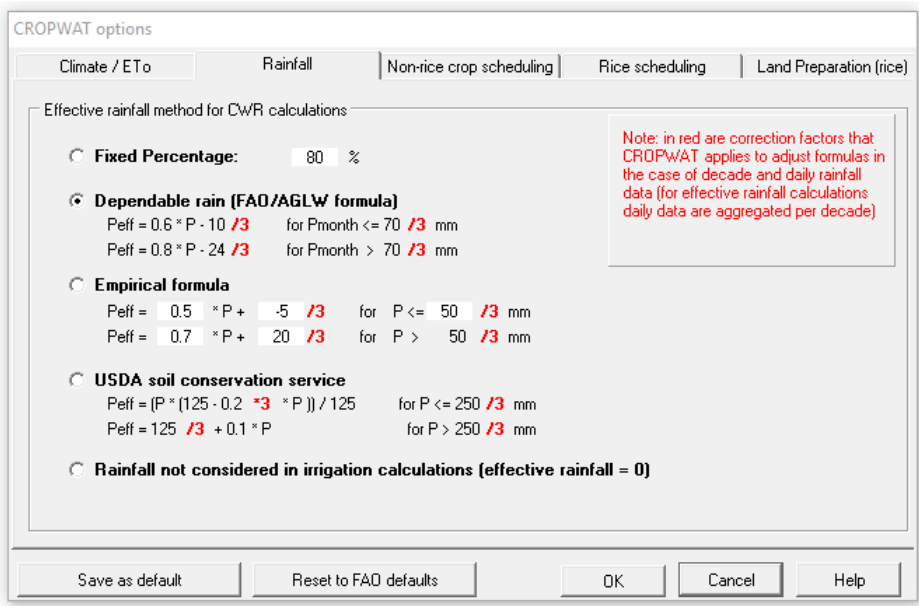
Figure 4. Effective rainfall calculation methodologies

After the rainfall data are entered, the model calculates effective rainfall which in our example is 59.9% lower than total rainfall (Figure 5). This significant reduction of available water for the plants is important for the irrigation scheduling of CWR.

Figure 5. Effective rainfall calculation

2.2.3. ETc calculation

After the ETo and effective rainfall calculation is done, the model moves to the calculation of ETc. The crop evapotranspiration under standard conditions, denoted as ETc, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions (Allen et al., 1998). Crop water requirements (ETc) over the growing season are determined from ETo and estimates of crop evaporation rates, expressed as crop coefficients (Kc), based on well-established procedures (FAO, 1977), according to the following equation:

ETc=Kc x ET

The crop coefficient varies thru the growth period because of changes in vegetation and ground cover. In the CropWat model, the trends in Kc during the growing period are represented in the crop coefficient curve. Single (time-averaged) crop coefficients, Kc, and mean maximum plant heights for non-stressed, well-managed crops in sub-humid climates for use with the FAO Penman-Monteith ETo are presented in FAO publication (FAO, 1998). Next, the following data must be entered to calculate the ETc (Figure 6):

• **planting date** (the harvest date is calculated by the model according to used crop data);
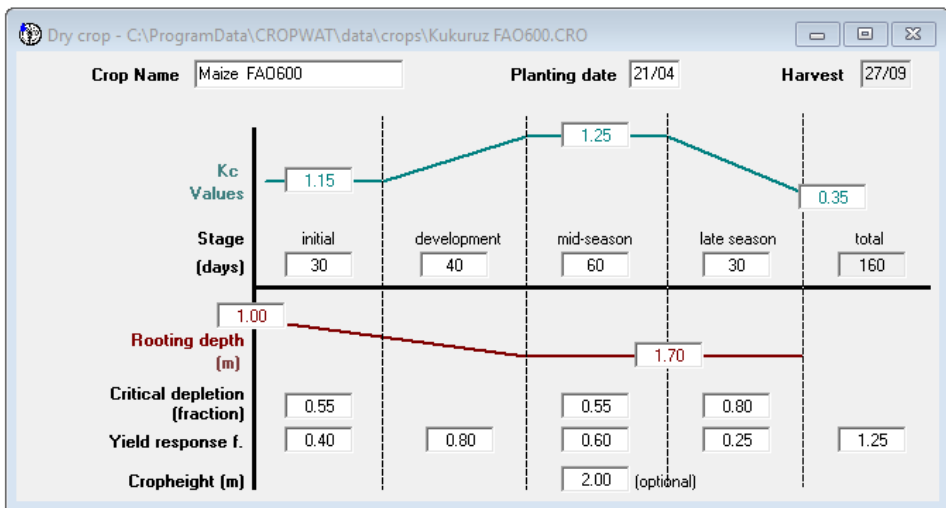
Figure 6. Crop data

- **Kc values** - Only three values for Kc (Figure 7) are required to describe and construct the crop coefficient curve: those during the initial stage (Kc ini), the mid-season stage (Kc mid), and at the end of the late-season stage (Kc end).
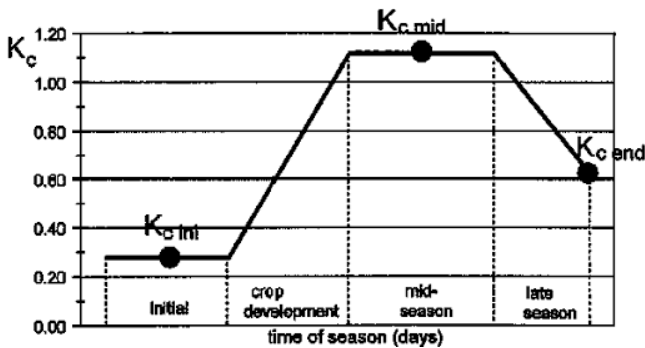

Figure 7. Single crop coefficient (Kc) (Allen et al., 1998)

- **Crop development stage** – refers to the duration (in days) of specific crop growth stage; initial, development, mid-season, and late season. Of course, the duration of a specific growth stage is climate and crop-dependent.
- **Rooting depth** – refers to the depth of the rooting system at the beginning and the end of the growing season. Effective root depth is the upper soil layer from which the plants can take 80 % of water. Rooting depth is soil type and crop dependent. Vegetables are shallow-rooted (< 60 cm), while for example, maize shas deeper rooting depth > 120 cm.

- **Critical depletion fraction** - is the critical soil moisture level where the first drought stress occurs affecting crop ETo and yield. It is a fraction of Total Available Water (TAW) that usually ranges from 0.4 to 0.6. Sensitive crops with limited rooting systems under high evaporative conditions have lower values, while the higher values are for deep and densely rooting crops and low evaporation rates.
- **The yield response factor** – is the crop yield response to the water supply. It relates relative yield decrease to relative evapotranspiration deficit.

Critical depletion fraction and Yield response data are available on: http://www.fao.org/3/x0490e/x0490e0e.htm.

2.2.4. General soil data

The next step is to enter soil data. It is first necessary to enter the data on **Total available water (TAW)**. Simply said, TAW (Figure 7) is the difference in soil water content between **Field water capacity (FWC)** and Wilting point (WP). FWC is defined as the content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible (Soil Science Glossary Terms Committee, 2008).

FWC as a soil moisture content comes after the drainage has stopped and it represents the upper limit of the available water or the maximum amount of water that soil can hold. This indicates, of course, that the FWC is soil type dependent.

FWC = FIELD WATER CAPACITY
MAD = MAXIMUM ALLOWABLE DEPLETION
WP = WILTING POINT
RAW = READILY AVAILABLE WATER
TAW = TOTAL AVAILABLE WATER
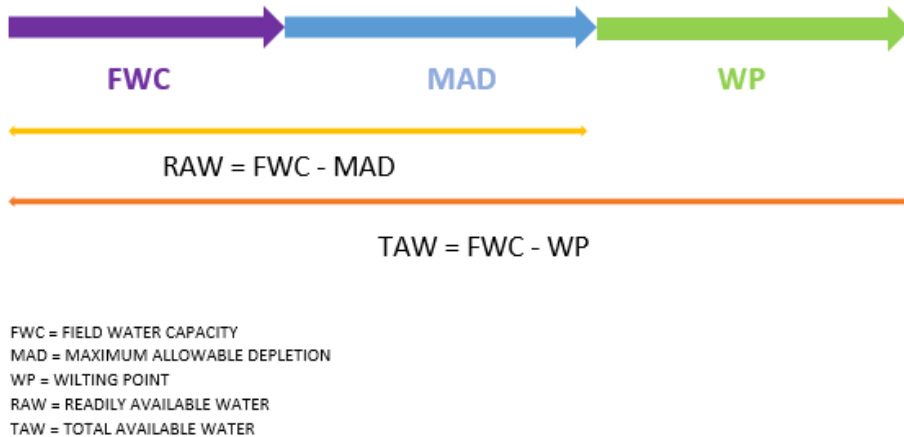
Figure 8. Soil water content

Total available water differs from **Readily available water (RAW)** which is the SWC that could be easily taken by the plants. RAW is the difference in SWC from FC and **Management allowable depletion (MAD)**, the desired soil-water deficit at the time of irrigation, and It can be expressed as the percentage of available soil-water capacity or as the depth of water that has been depleted in the root zone (USDA, 1997). When the MAD is reached, the lack of water in the soil should be compensated with irrigation water to prevent crop stress. This means that the RAW is equal to MAD. As the SWC decreases, it is more difficult for the plants to extract the water from the soil because water be-

comes more strongly bonded to soil particles. Afterward, in the case of drought and dry farming the **Wilting point (WP)** is reached. At this point SWC is low and plants cannot extract water so at the end they are wilting. This process is mainly influenced by soil texture (Rai et al., 2017).

As presented in Figure 9. **the maximum rain infiltration rate** must be entered. Infiltration refers to soil ability to enable the water movement into and through the soil profile. It is a measure of how fast the water enters the soil (mm/day, mm/hour) and it greatly affects irrigation scheduling. In case of low infiltration rate the ponding or waterlogging can occur while in a case of high infiltration rate, an excessive amount of rainfall or irrigation water can cause nitrogen losses and contamination of aquafers with pesticide.
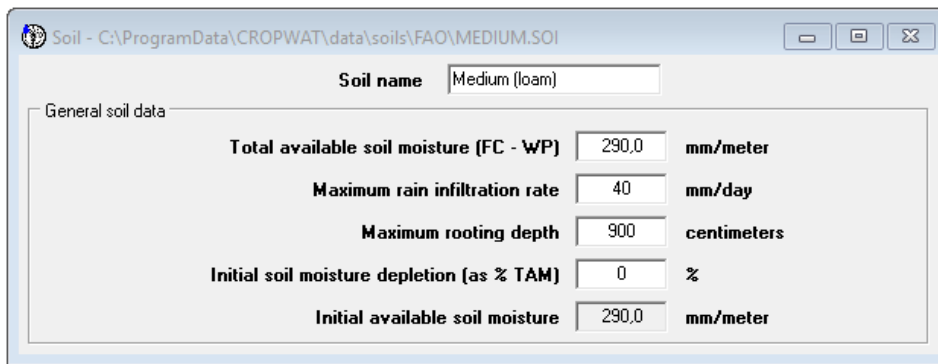
Figure 9. Soil properties

Basic infiltration rates for various soil types (Table 1) are presented by Brouwer et al. (1985) and could be used in the CropWat model as reference data.

Table 1. Infiltration rates for various soil types

Soil type	Infiltration rate (mm/hour)
Sand	< 30
Sandy loam	20 - 30
Loam	10 - 20
Clay loam	5 - 10
Clay	1 - 5

Then the **Maximum rooting depth (MRD)** is to be entered in the model. MRD is one of the factors that determine TAW. Values of MAD can be found at: http://www.fao.org/3/x0490e/x0490e0.htm.

The next step is to enter the **initial Soil moisture depletion (SMD)** which is expressed as % of TAW. SMD is a measure of soil moisture between field capacity and existing moisture content and multiplied by the root depth (Walker, 1989), and basically, it represents the lack of soil water content at the beginning of irrigation.

At the end of the soil data, the value of **Initially available soil moisture** is to be entered. This value represents the SWC at the beginning of irrigation (mm/m).

As it can be seen, the irrigation practice is highly dependent on soil science. Therefore, the efficiency of irrigation scheduling requires a thorough evaluation of the soil properties.

2.3. Analysis of Crop Water Requirements (CWR)

Crop water requirements (CWR) refer to the amount of water required to compensate for the evapotranspiration losses from a cropped field during a specified period of time. Given that it is important to know the difference between Net irrigation and Irrigation rate. **Net irrigation** is the amount of water needed to meet the crop water loss through evapotranspiration (ETo) during the growing season. This means that the net irrigation is mainly rainfall and ETo dependent. **Irrigation rate** is the amount of water added in one irrigation event, and it depends on soil properties (soil bulk density (g cm^{-3}), field water capacity (FWC, %), and soil moisture (%)) and root depth (cm). **Irrigation time** has the most significant impact on the yield and quality of the crops because if too early or too late irrigation events can cause overirrigation, or it could cause drought stress. That is why the growing competition for water, especially in the agricultural sector demands the correct time for the application of irrigation water. Furthermore, it is important to maximize the **efficiency of crop water productivity (CWP)** and to find a strategy for saving water and better use of irrigation water.

In the CropWat model decadal CWR are presented according to growth stages, i.e. initial, development, middle, and late. As it can be seen from Figure 10, in this example the kc values range from 1.15 to 0.44, while the ETc ranges from 0.97 at the end of the growing season (September) to 6.21 mm/day during the summer month July.

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	3	Init	1.15	3.23	32.3	1.0	31.3
May	1	Init	1.15	3.72	37.2	3.1	34.2
May	2	Init	1.15	4.18	41.8	4.4	37.4
May	3	Deve	1.17	4.26	46.8	6.0	40.8
Jun	1	Deve	1.20	4.26	42.6	9.0	33.6
Jun	2	Deve	1.22	4.38	43.8	11.2	32.5
Jun	3	Mid	1.25	4.95	49.5	7.5	42.1
Jul	1	Mid	1.26	5.69	56.9	0.1	56.8
Jul	2	Mid	1.26	6.21	62.1	0.0	62.1
Jul	3	Mid	1.26	5.75	63.2	0.1	63.2
Aug	1	Mid	1.26	5.20	52.0	7.6	44.5
Aug	2	Mid	1.26	4.83	48.3	11.4	36.9
Aug	3	Late	1.25	4.27	46.9	7.6	39.4
Sep	1	Late	1.00	3.04	30.4	0.1	30.3
Sep	2	Late	0.70	1.84	18.4	0.0	18.4
Sep	3	Late	0.44	0.97	6.8	0.0	6.7
					679.1	68.9	610.2

ETo station: Osijek
Rain station: Osijek 2009
Crop: Maize FAO600
Planting date: 21/04

Figure 10. Crop water requirements (CWR)

Now the CWR is expressed as ETc, meaning that during the tested growing season 679.1 mm of water is required to fulfill crop water demands. Yet, as previously calculated there was 68.9 mm of effective rain during the growing season (April-September) which means that the Net irrigation (irrigation requirements) for maize crop is 610 mm.

2.4.   Irrigation scheduling

A CropWat model is a useful tool that can be used for irrigation scheduling, water savings, and for achieving high crop yields. In general, irrigation scheduling is based upon the monitoring of SWC and the CWR. Of course, it is also soil type, climate, and crop dependent.

In this example, the planting date was set on April 21st, while the harvest date is September 27th (Figure 11), and the yield reduction is set to be 0.0%. This means that it is planned to achieve the maximum yield potential. Here is the Net irrigation (mm) expressed as Irrigation rate (mm) so that there is no lack of water (deficit) and also there are no water losses. The difference between Net irrigation water (469.2 mm) and **Gross Irrigation Requirement (GIR)** is clearly visible (Figure 11).

Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
2 May	12	Init	0.0	1.00	100	56	69.1	0.0	0.0	98.7	0.95
30 May	40	Dev	0.0	1.00	100	57	87.2	0.0	0.0	124.5	0.51
4 Jul	75	Mid	0.0	1.00	100	55	103.4	0.0	0.0	147.7	0.49
22 Jul	93	Mid	0.0	1.00	100	56	104.1	0.0	0.0	148.7	0.96
20 Aug	122	Mid	0.0	1.00	100	56	105.4	0.0	0.0	150.6	0.60
27 Sep	End	End	0.0	1.00	0	40					

Crop irrigation schedule

ETo station: Osijek — Rain station: Osijek 2009
Crop: Maize FAO600 — Soil: Medium (loam)
Planting date: 21/04 — Harvest date: 27/09
Yield red.: 0.0 %

Table format: • Irrigation schedule ○ Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff.: 70 %

Totals:

Total gross irrigation	670.2 mm		Total rainfall	194.9 mm
Total net irrigation	469.1 mm		Effective rainfall	191.1 mm
Total irrigation losses	0.0 mm		Total rain loss	3.8 mm
Actual water use by crop	678.1 mm		Moist deficit at harvest	74.0 mm
Potential water use by crop	678.1 mm		Actual irrigation requirement	487.1 mm
Efficiency irrigation schedule	100.0 %		Efficiency rain	98.1 %
Deficiency irrigation schedule	0.0 %			

Figure 11. Irrigation scheduling

GIR (670.2 mm) is net irrigation water to be applied in reality, considering water losses (deep percolation, leaching, runoff, water application). Here, NIR is 70% (Field efficiency, Figure 11) from GIR. The efficiency of the irrigation system can range from 0.55 (light soil) to 0.8 (drip and trickle irrigation system). Since the model is set to calculate the irrigation scheduling without the yield reduction, the Efficiency of irrigation scheduling is 100%.

Actual water use by crop (678.1 mm) is the ETc for maize crop (April-September). Furthermore, the model calculates the moist deficit at harvest time, which in this example is 74 mm. Irrigation efficiency is set as 70 % which is a default value for a well-managed sprinkler irrigation system.

In this example, the Irrigation time is set on irrigation at critical depletion. This means that the irrigation event will occur when the SWC is at a MAD level and that the irrigation water will refill soil water content to FWC. It should be stated that the model offers different criteria for irrigation timing (Figure 12) that are used for non-rice crops:

- Irrigate at user-defined intervals,
- Irrigate below or above critical depletion,
- the irrigation event will occur when the SWC is below or above MAD,
- Irrigate at fixed interval per stage,
- Irrigate at fixed depletion,
- Irrigate at given ETc reduction per stage,
- Irrigate at given yield reduction.
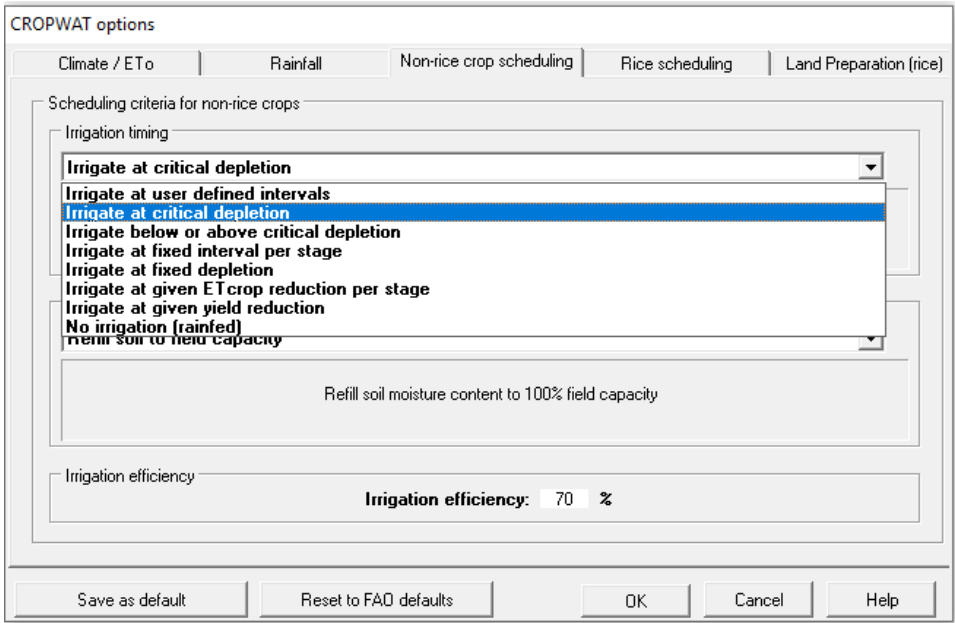
Figure 12. Scheduling criteria for non-rice crops

In the irrigation scheduling graph (Figure 13), the readily available water, total available water, and soil water depletion for the entire growing season are presented, and basically, it shows the crop irrigation schedule from Figure 11.
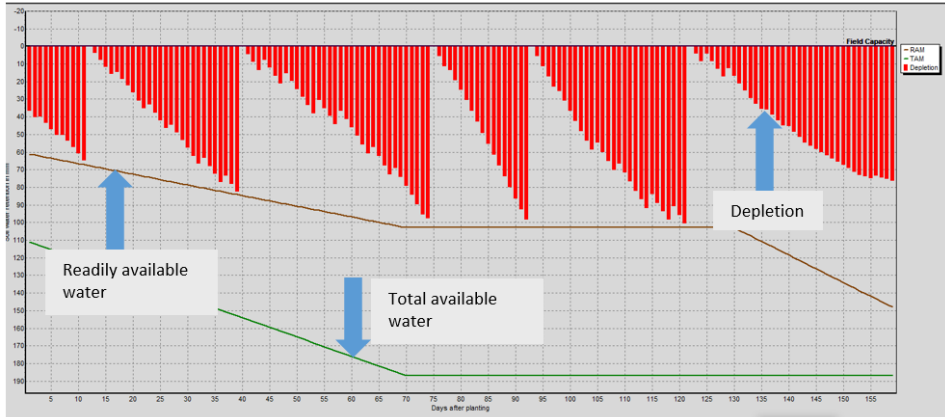
Figure 13. Irrigation scheduling graph

3.

ETo Calculator

ETo calculator is software designed by the experts of FAO (Land and Water Division), and its main task is to calculate reference evapotranspiration. Reference evapotranspiration (ETo) is the evapotranspiration rate from the reference surface (grass) that represents the evaporative demand of the atmosphere regardless of crop or agricultural practices. This means that ETo does not represent the shortage of water for a specific crop (maize, vegetables, or other crops) but for well-watered grass (Figure 14).

Figure 14. Reference grass ETo

Also, the soil is not considered to have an impact on ETo since water is abundantly available at the reference evapotranspiration surface. The only factor that has an impact on ETo is climate, i.e., air temperature, solar radiation, wind speed, and humidity. ETo is calculated from meteorological data with the use of the Penman-Monteith model which is selected as a reference method (Raes, 2009). According to Allen et al. (1998), ETo expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors. The ETo calculator is available at: http://www.fao.org/land-water/databases-and-software/eto-calculator/en/.

3.1   ETo calculator example

After the software is started an interface shows database management with the option to select an existing data file or to create a new one (Figure 15). For this example, a new file will be created.
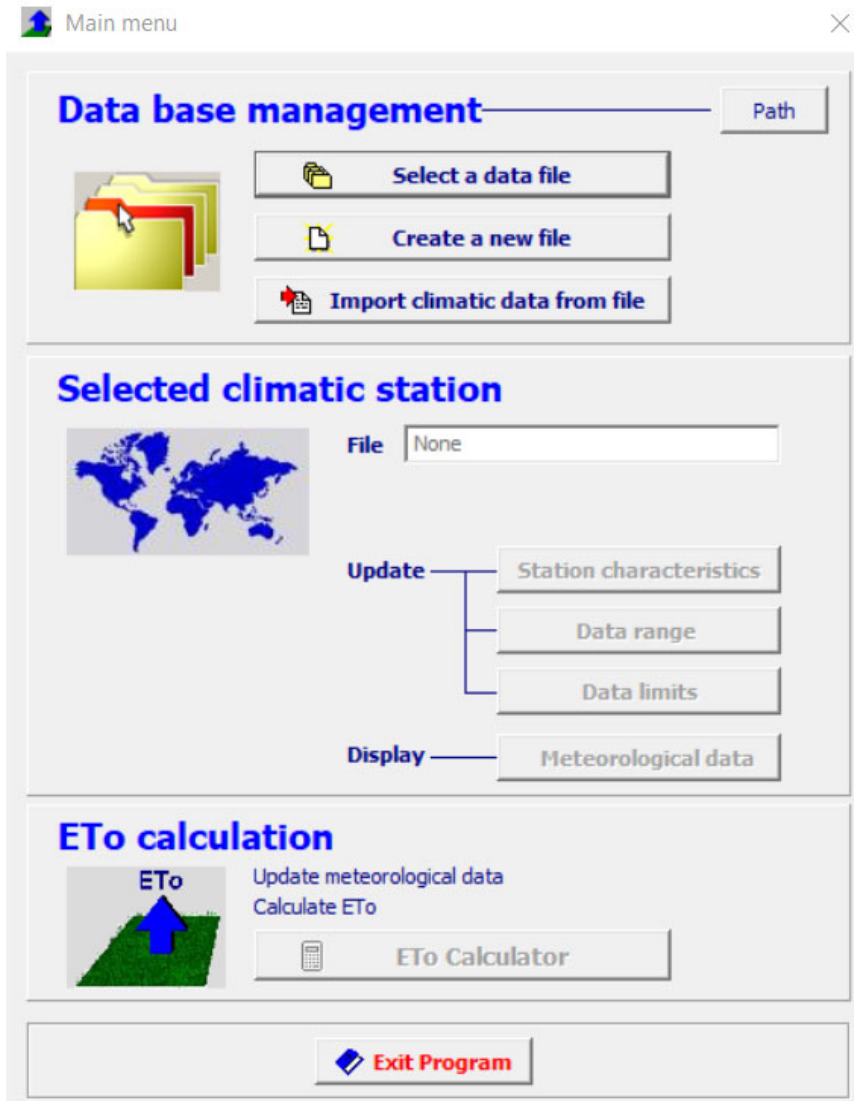
Figure 15. The interface of the ETo calculator

The given filename is Osijek 2018 since the ETo is assessed for the Osijek area, the year 2018. Following, the Station name is Osijek, and the Country name is Croatia. Location data are described with longitude and latitude data expressed in degrees and minutes, and altitude (meter above sea level).

Further, the interior coastal location is chosen since Osijek is in a continental area of Croatia, also a semi-humid or humid area with light to moderate winds is marked. Monthly meteorological data for the period from January to December 2018 are used for ETo assessment (Figure 16).

Figure 16. Station description and location description and meteorological data

The next step is to set the climate parameters (Figure 17). Of course, the oC is chosen as temperature unit. Air temperature could be expressed as minimum and maximum or the mean air temperature.

Figure 17. Input data description

For this example, the mean air temperature is chosen. Air humidity could be expressed as the mean of relative air humidity (%), minimum and maximum air humidity (%), the mean of dew point temperature (°C), or the mean of actual vapor pressure (kPa). For this example, the mean relative air humidity is chosen. As for wind speed, the mean wind speed (m/s) is measured at 2 m height. Sunshine is expressed as hours of bright sunshine (n). Besides that the sunshine and radiation could be expressed as relative sunshine hours (n/N), solar radiation (MJ/m^2 day), or net radiation (Rn). It should be noted that if some of the climate parameters are missing, the software offers calculations for wind speed, solar radiation, and air humidity.

Figure 18 presents input climate data limits. For air temperature, the lower limit is -15 °C, and the upper limit is 45 °C which corresponds to the Osijek region. The relative humidity ranges from 15 to 100 %, and wind speed from 0 to 8 m/s or 691.2 km/day.

Figure 18. Input climate data limits

Once given period can be corrected by adding or deleting a month or entire year (Figure 19). If the climate data are expressed as daily, then in this step it is possible to add or delete days and to adjust the study period.

Figure 19. Time range determination

The next step is to enter climate data (Figure 20), meaning the mean air temperatures (oC), the mean of air humidity (%), wind speed (m/s), and sunshine hours (n) for each month. If the climate data are expressed as daily data, then in this step daily data should be inserted for all previously mention climate parameters.
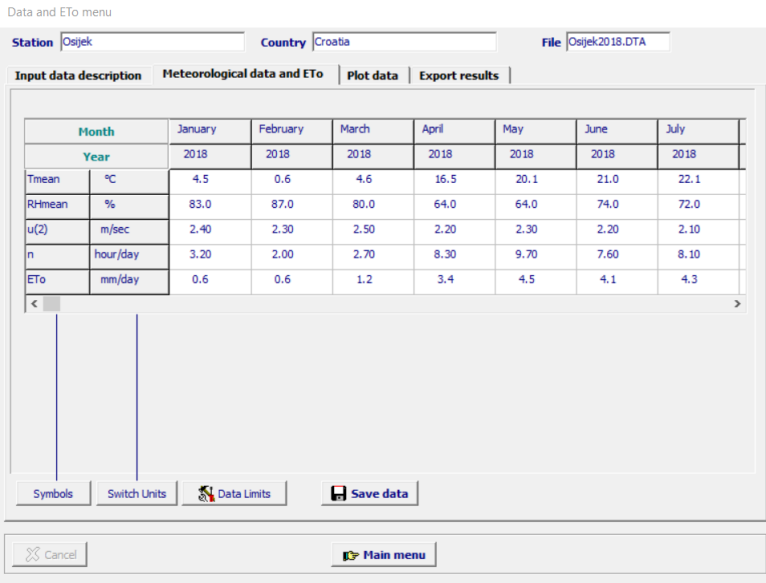
Figure 20. The input of meteorological data

After climate data have been entered the software calculates ETo for each month. If daily climate data are used, then the software calculates daily ETo. For better visual presentation, the ETo data can be presented as a plot (Figure 21).
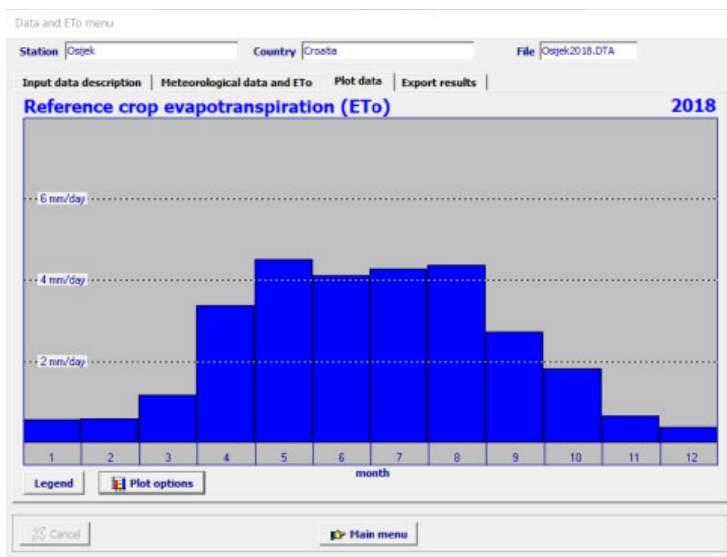
Figure 21. Reference evapotranspiration presented as a plot

Once the ETo is calculated, the software offers to save results on PC as a report or to export a climate file which could be used with AquaCrop (Figure 22).
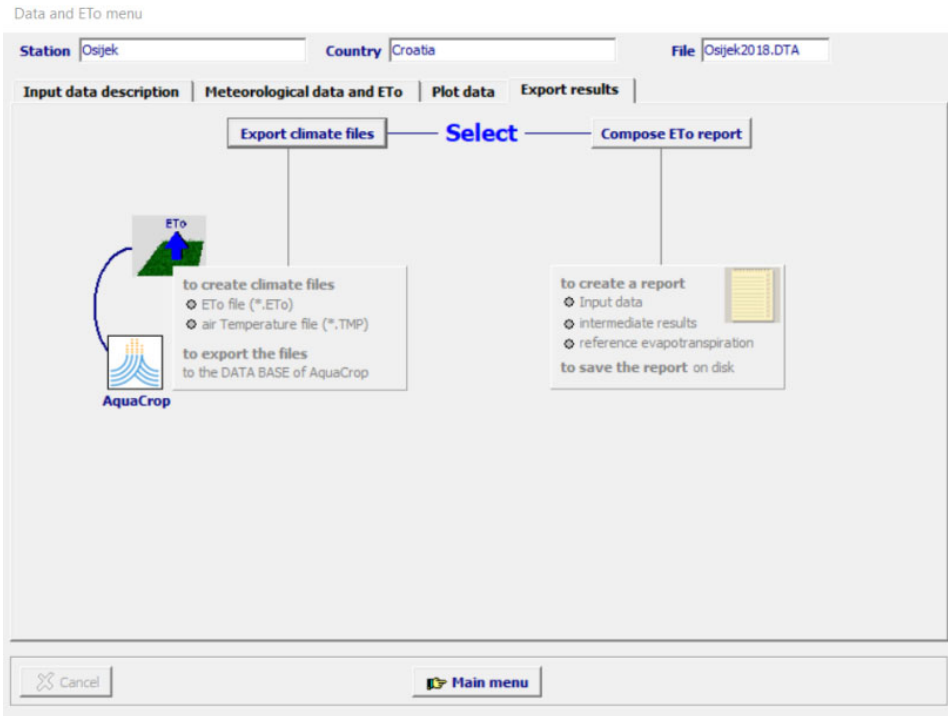
Figure 22. Data saving

4.

AquaCrop

4.1. AquaCrop model

AquaCrop is a crop growth and productivity model created by the FAO's Land and Water Division experts. Crop productivity refers to the yield response to water describing the relationship between crop yield and water stress because of insufficient supply of water by rainfall or irrigation during the growing period (Raes et al., 2018). The model's main goal is to simulate the yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production (FAO, 2016). The flowchart of the AquaCrop model is presented in Figure 23, indicating the main components of the soil-plant-atmosphere continuum (FAO, 2016).
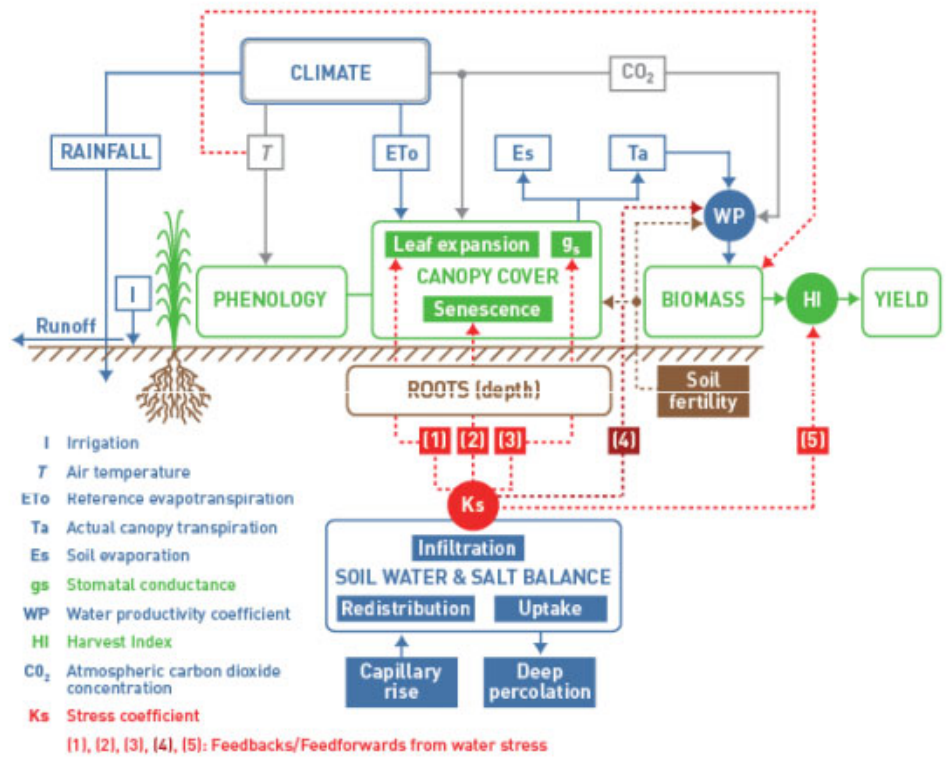
Figure 23. AquaCrop flowchart

The model is a useful tool for planning and making management decisions in irrigated and rainfed crop production. It helps to develop an irrigation schedule for maximum water productivity in different climate scenarios and to maximize water productivity in deficit irrigation. According to Raes et al. (2009), the AquaCrop evolves from the Ky approach by separating (i) the actual evapotranspiration (ET) into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). Furthermore, the separation of ET into soil evaporation and crop transpiration avoids the confounding effect of the non-productive consumptive use of water (soil evaporation). This is important especially when ground cover is incomplete early in the season or as the result of sparse planting. The separation of yield into biomass and harvest index allows the partitioning of the corresponding functional relations as a response to environmental conditions.

Raes et al. (2018) give features that distinguish AquaCrop from other crop models:

- its focus on water;
- the use of canopy cover instead of leaf area index;
- the use of water productivity (WP) values normalized for atmospheric evaporative demand and CO_2 concentration that confer the model an extended extrapolation capacity to diverse locations, seasons, and climate, including future climate scenarios;
- the relatively low number of parameters;
- input data which requires only explicit and mostly intuitive parameters and variables;
- a well-developed user interface;
- its considerable balance between accuracy, simplicity, and robustness;
- its applicability to be used in diverse agricultural systems that exist worldwide.

FAO (2017) gives the following limitations of the AquaCrop model:
- AquaCrop can simulate daily biomass production and final crop yields for herbaceous crops with single growth cycles only.
- AquaCrop is designed to predict crop yields at the single field scale (point simulations).

The field is assumed to be uniform without spatial differences in crop development, transpiration, soil characteristics, or management.

- Only vertical incoming (rainfall, irrigation, and capillary rise) and outgoing (evaporation, transpiration, and deep percolation) water fluxes are considered.

4.2.   AquaCrop application

Figure 24 presents the Aqua-Crop model interface with all the necessary data entered into the model: climate, crop, management (irrigation, field), and soil (soil profile, groundwater). At the bottom part of the interface is the simulation menu.
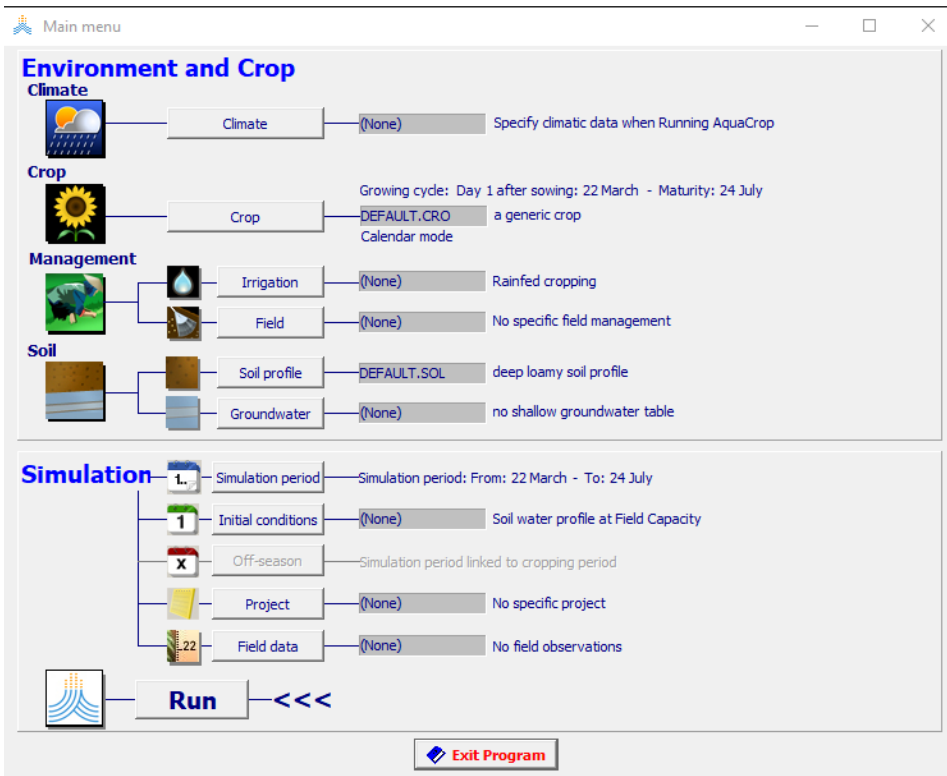
Figure 24. AquaCrop interface

4.2.1 Climate file

The AquaCrop model gives the option to import data from an existing file or to create a climate file if the climate data are available for a specific location (Figure 25). The model gives the option to analyze daily, decade, or monthly climate data. In the AquaCrop model following climate data are used: solar radiation (MJ/day), rainfall (mm), minimum and maximum air temperatures (°C), and reference evapotranspiration (ETo, mm/day) and wind speed (km/day). For this example, the monthly climate data are used. Some of the locations (weather stations) are previously integrated into the model and can

be used for the simulation of crop productivity. Climate data (sunshine hour, rainfall, minimum and maximum air temperatures, air humidity, wind speed) were obtained courtesy of Croatian meteorological and hydrological service, while the ETo was calculated by use of ETo calculator (see chapter 3). In the present analysis, a new climate file is created for the Osijek location, and the year 2018 (January to December). Plot rainfall data for the year 2018 are presented in Figure 26. Furthermore, ETo (Figure 27) and maximum and minimum air temperature (Figure 28) is allowed to be modified or exported as the mean of monthly or yearly values.
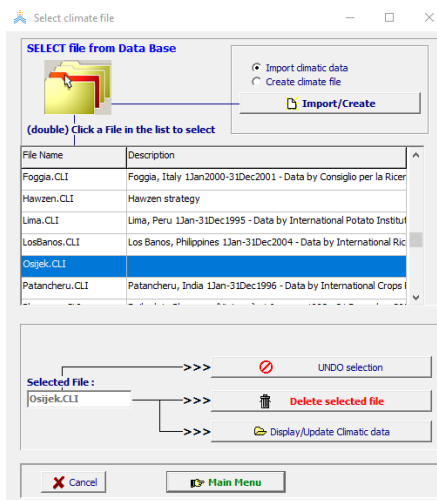
Figure 25. Climate data interface
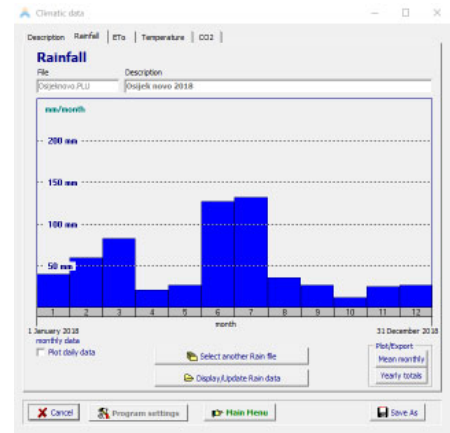
Figure 26. Rainfall data
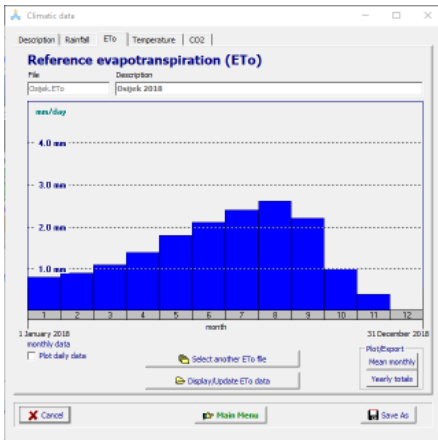
Figure 27. ETo data
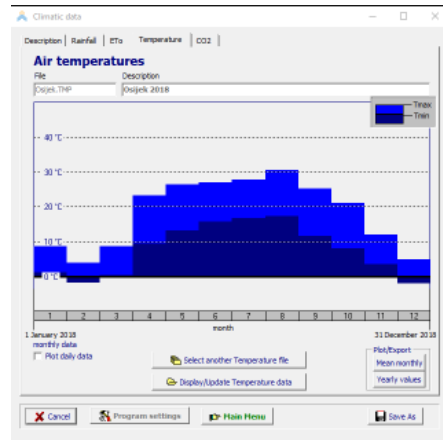
Figure 28. Air temperature data

4.2.2 Crop file

The same as with the climate file, one can choose to create a new crop file or to use one of the existing files that are integrated into the model. For the present analysis crop file is selected for maize with the beginning of the growing cycle on 23 March 2018 (Figure 29). In the crop file, the limited (development, production, fertility stress, calendar) and a full set of data with all crop parameters (development, ETo, production, water, temperature, salinity, fertility stress, calendar) can be chosen. This time, limited crop parameters are used. Crop canopy development is analyzed according to calendar days. The threshold temperatures for crop development are 8 °C as base temperature and 30 °C as upper temperature. Here, the calendar days file is connected with the temperature file (in this example from 1 January to 31 December 2018). Direct sowing is chosen for maize crop, good initial canopy cover, and 75000 plants/ha. Furthermore, very fast canopy expansion almost entirely covers the canopy (96%). Green canopy cover (CC) is used to express the foliage development, and it represents the fraction of the soil surface covered by the canopy (Figure 30).

Figure 29. Crop file

Figure 30. Crop development

After the sowing, the CC is low since 0% of the soil surface is covered by the crop. During the mid-season, the canopy cover reaches a maximum value (1) when 100% of the soil surface is covered by the canopy, and it will depend on crop type and planting density (Figure 31). Canopy Growth coefficient (CGC) describes the expansion of CC from germination to extensive growth; low (germination), maximum (mid-season), and declining (late-season).

In this example, crop development is studied in no water, fertility of salinity stress. Of course, water stress can affect the expansion of the 'leaves and eventually result in canopy senescence at an early stage. Water stress coefficients (Ks) are used to describe the effect of water stress on CC, (i)

Ks for leaf expansion (Ksexp) with CGC as target crop parameter, (ii) and Ks for early canopy decline (Kssen). Here the CDC is the target crop parameter and represents Canopy Decline Coefficient (CDC), previously described as the CC declination. Ksexp is <1 and canopy expansion declines when the water content in the root zone drops below the threshold for leaf expansion. As for early canopy decline, Kssen is <1, and canopy decline is triggered in conditions where the soil water content in the root zone drops below the threshold. Lack of water during or after the flowering stage can reduce the yield and induce the reduction of HI whereby the duration and the magnitude of the drought stress will determine the reduction.

31. Canopy development

32. Flowering and yield formation

If water stress occurs after flowering or root enlargement it could result in Harvest index (HI) reduction (Figure 33). HI represents the relationship between the grain yield and aboveground biomass. FAO (2017) claims that depending on (i) when the water stress occurs during yield formation, (ii) the magnitude of the stress, and (iii) the sensitivity of the crop the adjustment can be upwards or downwards:

• As long as vegetative growth is still possible, the daily rate with which HI increases might be adjusted upwards if water stress affects leaf expansion. The enhancement of HI is the result of a decrease of the competition of leaf growth with reproductive growth;

• The daily rate with which HI increases during yield forma-

tion might be adjusted downwards if water stress induces stomatal closure. It is the corresponding reduction in assimilate supply that will slow down the increase in HI. At a permanent wilting point the reduction becomes 100%.

At sowing the effective rooting depth is at a minimum. The maximum effective root depth is 2.30 m (for deep-rooted crops), while the maximum rooting depth is on the 108th day after sowing (Figure 34). The conditions affecting rooting depth are previously described by (FAO, 2017):

• When the root zone depletion exceeds the threshold for stomatal closure the incremental daily

• root deepening under optimal conditions is adjusted by multiplying the expansion rate

- with the water stress coefficient for stomatal closure (Ks_{sto}). The water stress alters the shoot/root ratio since water stress affecting canopy expansion occurs earlier than water stress affecting stomatal closure (which affects the expansion of the root zone);
- If the sub-soil at the front of root zone expansion is too dry, the root deepening will slow down and can even stop if the soil water content at the front is at a permanent wilting point;
- Root deepening is slow in soil layers with low penetrability (expressed as a percentage between 100 and 0%). Below the restrictive layer, the root zone expansion is normal again.

33. Harvest index

34. Root deepening
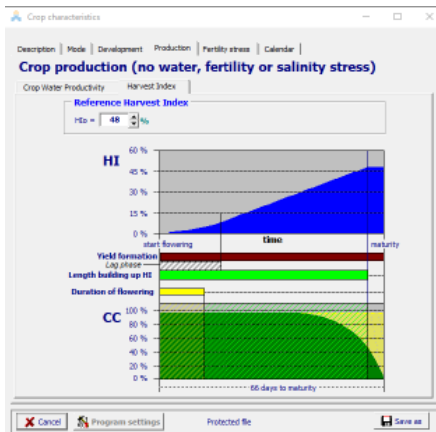
Biomass water productivity is shown in Figure 34, and basically, it represents the amount of water that is transpired in relation to a certain amount of biomass (kg/m^3). Since soil evaporation should be considered then ET water productivity is introduced and it shows the kg of crop yield per unit of evapotranspired water (m3). As it can be seen from Figure 35, different indicative ranges are presented for C3 and C4 crops. This is because the C3 plants are able to moderately increase crop water productivity by restricting the transpiration process. C4 plants (maize, sorghum, sugarcane) tend to be more productive in high light and temperature environments which is an important fact dry in improving of water productivity (WP) in regions with arid climate or drought conditions. WP is normalized for the climate by divid-

ing the transpiration and ETo, so that it could be applicable to different locations and seasons. While the normalization for CO_2 refers to considering the WP for a reference atmospheric CO_2 concentration (369.41 ppm, the atmospheric CO_2 concentration for the year 2000, FAO 2018). If the year with different CO_2 con-

centrations is analyzed, then WP is multiplied with the correction factor (fco2). The f_{CO_2} is >1 for CO_2 concentration higher than the reference year, and <1 for lower CO_2 concentration. Finally, the crop characteristics file ends with the crop calendar with the given date and length of specific growth stages (Figure 36).
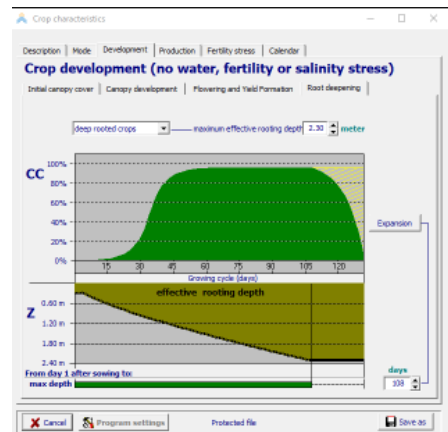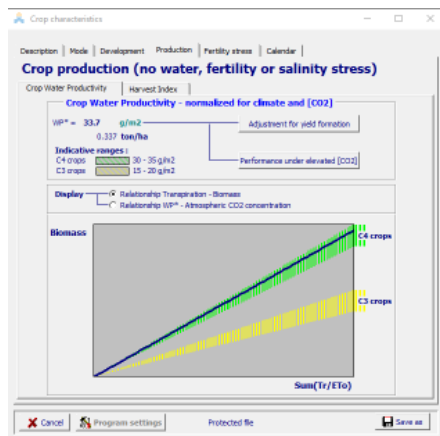
35. Water productivity
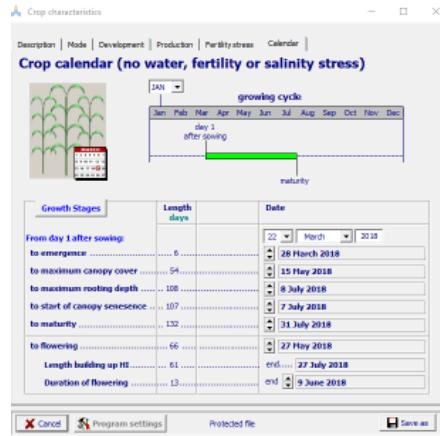
36. Crop calendar

4.2.3 Management file

The management file is divided into categories, irrigation, and field (Figure 24). In the AquaCrop model are choices of rainfed (irrigation is not considered) or irrigated crop. As for irrigation methods, the user chooses sprinkler irrigation, surface, and drip irrigation. Furthermore, the fraction of wetted surface, and specification of irrigation water quality, timing, and

amount of water for each irrigation event. In this example, the maize crop is irrigated, so the irrigation schedule is used from data base. Sprinkler irrigation is chosen method with 80% of wetted soil surface.

Irrigation time can be determined by:
• fixed interval, that is the number of days between two irrigations events. The interval will depend on the ETc, effective

rainfall, soil water holding capacity, and allowable depletion.
• allowable depletion (mm)
• allowable depletion as % of readily available water (RAW).

It is assumed that the crop is irrigated so that the soil water content is back to field water capacity, while the irrigation water quality is excellent (Figure 37). The irrigation file is completed by specifying irrigation events, i.e. day, water depletion as % of RAW, and date. Under Field management practices users chose soil fertility level, weed management, mulches, soil bunds, and field surfaces. Basically, parameters that have an impact on soil water status, run-off, or evaporation. The difference between the CROPWAT and AQUACROP models is visible here since in the first model only climate, soil, and crop data are considered, while in the second model also the crop management is taken into consideration. The soil fertility classes are non-limiting, near-optimal, moderate, about half, poor, and very poor.

Figure 37. Irrigation schedule

Soil fertility stress corresponds to CC, CGC reduction, canopy cover declination, and WP reduction. Classes of soil cover by mulches are: none, spars, about half, significant and complete. If the mulch is taken into consideration, then the user can choose the organic or plastic mulch or user-specified mulch. The type of mulch determines the reduction of evaporation losses, e.g. 50% for organic mulches, 100% for synthetic mulches, and 75% for user-specified mulch. For the present analysis, it is as-sumed that the soil surface is not covered with mulch (Figure 38). As for field surface practices, the user can choose situations field surface practices do not affect the run-off where the estimation of surface runoff is based on soil profile character-istics. Thant the situation where the field surface practice affects surface runoff, prevent surface run-offs such as tied ridges and closed-end furrows. Also, the situation with soil bund that prevents surface run-off, and store excess water.
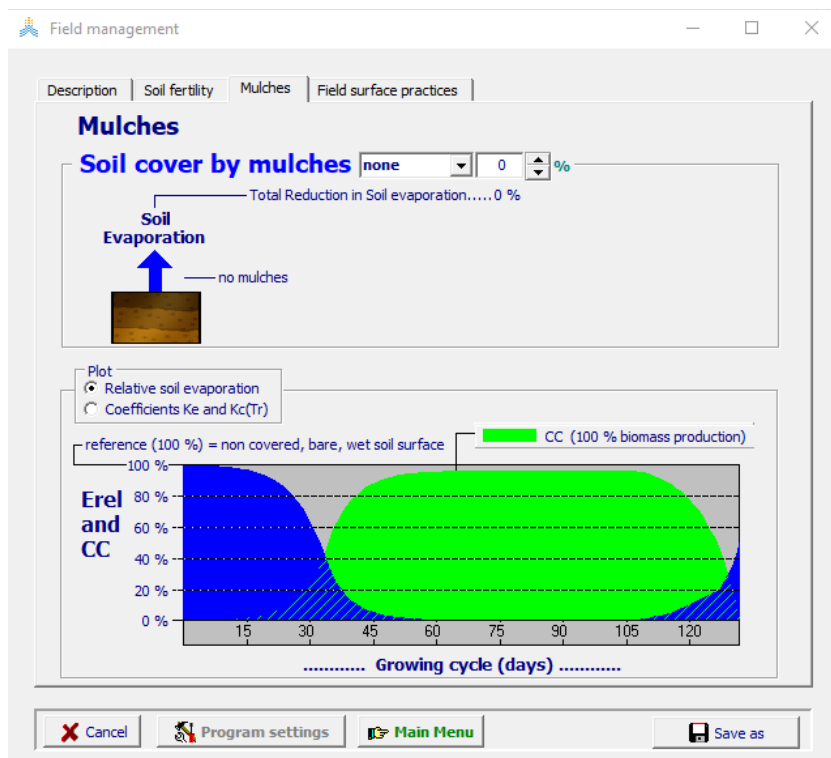
Figure 38. Mulches file

4.2.4 Soil file

Similar to previous datasets, a new soil file can be created or one of the indicative values for soil datasets (sand, sandy clay, sandy clay loam, sandy loam, silt, silt clay loam, silt loam, silty clay) can be used. The user can choose up to five soil horizons where each soil horizon has its own specified characteristic. The characteristics are (Figure 39) soil thickness, soil water content, that is permanent wilting point (PWP), field capacity (FC), saturation (SAT), and total available water (TAW). User can choose between the soil without the restrictive soil layer and specify the soil depth on which the restrictive soil layer is located. Restrictive layer means horizon or layer that restricts one or more physical, chemical, or thermal properties that significantly reduce movement of water and air through the soil, restrict roots or provide an unfavorable root environment. USDA (2016) states that a "restrictive layer" is a nearly continuous layer that has one or more physical, chemical, or thermal properties that significantly impede the movement of water and air through the soil or that restrict

roots, or otherwise provide an unfavorable root environment. Examples are bedrock, cemented layers, dense layers, and frozen layers. ,The next step is to adjust soil capillary rise. According to Lu and Likos (2004), the capillary rise is a well-known unsaturated soil phenomenon that describes the movement of pore water from lower elevation to higher elevation driven by the hydraulic head gradient acting across the curved pore air/pore water interface. The author states three fundamental physical characteristics related to capillary rise that are of primary practical concern: the maximum height of capillary rise, the fluid storage capacity of capillary rise, and the rate of capillary rise (Figure 40). The soil file is completed by specifying groundwater. As in previous datasets, a new groundwater file can be created or one of the indicative values for groundwater can be used. User can choose the condition without or with the present groundwater table. In late one, groundwater table can vary with the soil depth, or it can have constant depth and salinity.
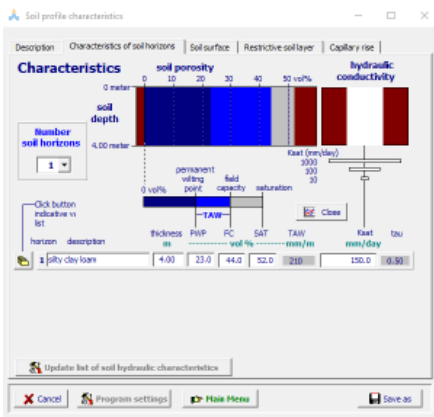
Figure 39. Soil water content characteristics
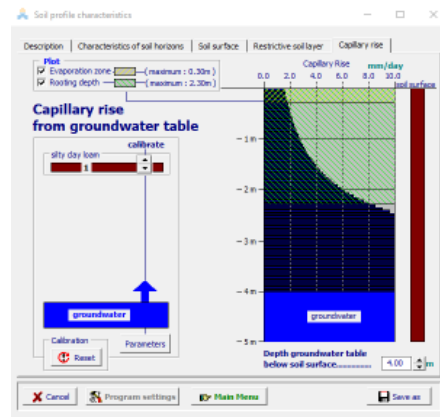
Figure 40. Soil capillary rise

4.2.5 Simulation

At the beginning of a simulation, the initial conditions for soil water content (Figure 41) and salt balance (Figure 412) in the root zone needs to be specified. The model calculates the amount of water in soil and salt accumulation at the end of the growing cycle based upon the initial situation. The best way to establish the initial situation is to measure the soil water content and salt accumulation, ideally one day after sowing. In case the samples cannot be taken on the day of sowing then the values from the previ-ously taken samples are taken, and in that case, the simulation starts on the day when the samples were taken. If data on soil water content are not available, they are estimated so that it is assumed that the initial water content in the soil was close to the field water capacity during wintertime. That way the simulation will start for example during January although the sowing was in springtime. For the Mediterranean region, the middle months of August are taken as the initial period when the water content in the soil is close to the value of the wilting point.
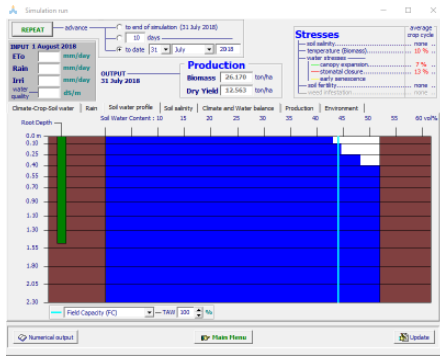
Figure 41. Initial soil water content

Figure 42. Initial salt balance

The rainfall data before sowing can be evaluated according to cumulative rainfall, 10-days or as a few successive days (Figure 43). The salt content of the soil is an important factor in crop production, especially in an irrigated field. Irrigation with water with increased salt content or raising the level of groundwater with increased salt content results in the accumulation of salt in the surface layer of the soil. Increased salt concentration has a negative effect on crop growth and yield.
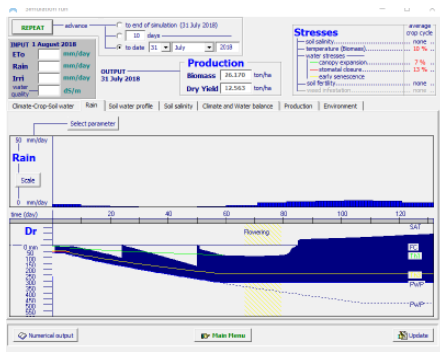
Figure 43. Rainfall data

Figure 44. Canopy cover (CC)

In the AquaCrop model, the soil salinity is simulated using soil salinity stress coefficient (Kssalt) and average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone. The drop in yield due to the stress caused by the increased salt content comes because of canopy cover (CC) reduction as well as stomata closure (Figure 44).

In such conditions, the CC is reduced because the growing capacity of the crop is decreased. Furthermore, when there is a higher salt concentration in soil, soil water potential is lower due to the osmotic potential and the water is less available to the crop as well as stomatal closure which clearly affects transpiration.

Different criteria for evaluation of air temperature before sowing can be specified. That is, daily minimum air temperature for each day of a given number of consecutive days. Then, cumulative and sum of growing degrees days (GGD). Specification of the first and last day could be used for the estimation of planting dates in future conditions. Furthermore, simulation for future conditions, i.e. climate change gives the opportunity to analyze the impact of higher air temperature, rainfall pattern, and CO_2 concentration (Figure 46) on crop productivity. For example, the increase in CO_2 concentration will reduce crop transpiration, yet significantly less than it will increase the biomass water productivity (Figure 47).
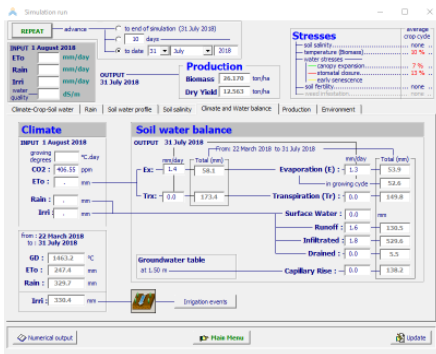
Figure 46. CO2 concentration
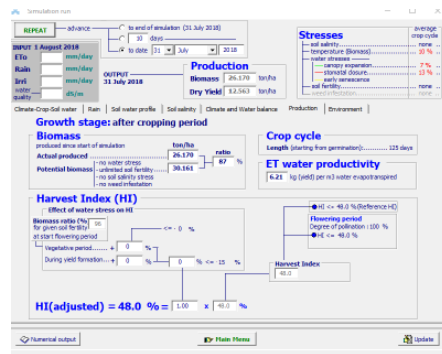
Figure 47. Biomass

5.

Databases in water management

Available information is of great importance for improving water management as well as agricultural productivity in general. The ability to access and share data has improved the use of ICT (Information and communication technology) in irrigation management by improved water use. This refers not only to farm levels but to governments in planning and implementation of irrigation strategies. Several agricultural-irrigation databases are now available, which provide information and services that facilitate the planning and management in agriculture generally. Databases are free, easy to access, and up to date so that the farmers, scientists, and professionals can easily get the information they are looking for. Some of the databases that are used in irrigation planning and water management are Aquastat, Aquamap, Climwat, and FAOSTAT.

5.1. AQUASTAT

Aquastat is a useful tool in water management and global water information system provided by FAO (Land and Water). It provides data, information, and fact sheets related to water resources, water uses, and agricultural water management. The following information are available in Aquastat: country database and profiles, datasets and fact sheets, maps, tables, regional water resources, and water uses. Furthermore, it provides information about irrigation water use, a global map of irrigation areas by source of water, water, and gender, water-related country-level institutional framework, wastewater, etc.

The Aquastat is available on: http://www.fao.org/aquastat/en/.

5.2. AQUAMAPS

Aquamaps is developed by FAO experts and it is complimentary to Aquastat's statistical data. It provides regional and global spatial database on water and agriculture that are commonly used for GIS so that the water actions, decision-making, and

investments are more efficient. Spatial datasets in Aquamaps are regional, global, and organized in the following themes (Figure 48):

• Irrigation and infrastructures - Dataset shows area equipped for irrigation, geo-referenced database on dams (Africa, Central Asia, Middle East, Southern eastern Asia), irrigation areas, percentages of the irrigated area serviced by groundwater.
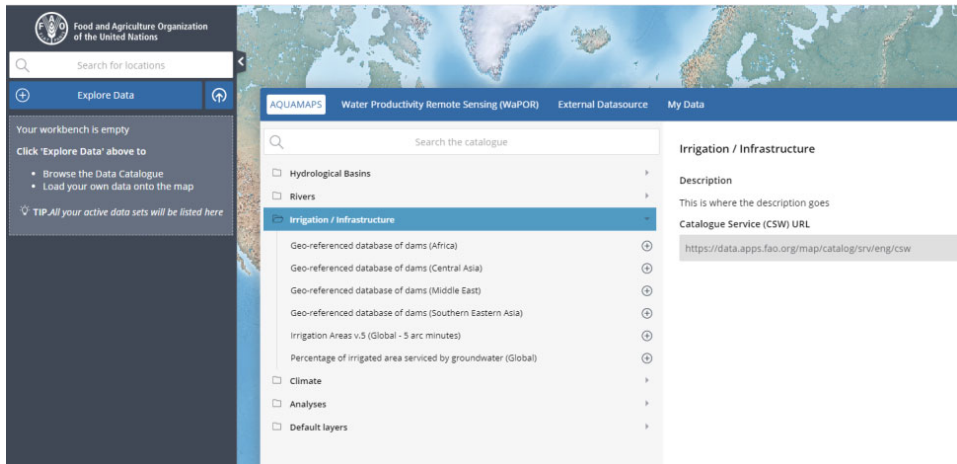
Figure 48. Irrigation infrastructure dataset

• Climate dataset – Dataset shows a map of aridity, monthly and yearly grids of precipitation and ETo, and rain days/month.
• Hydrological basins by continent
• Inland water bodies and major rivers of the world

• Analyses human pressure on land and water, major agricultural system, land salinization due to irrigation (Figure 49), percentages of area equipped for irrigation, etc.

Aquamaps is available on: https://data.apps.fao.org/aquamaps/.
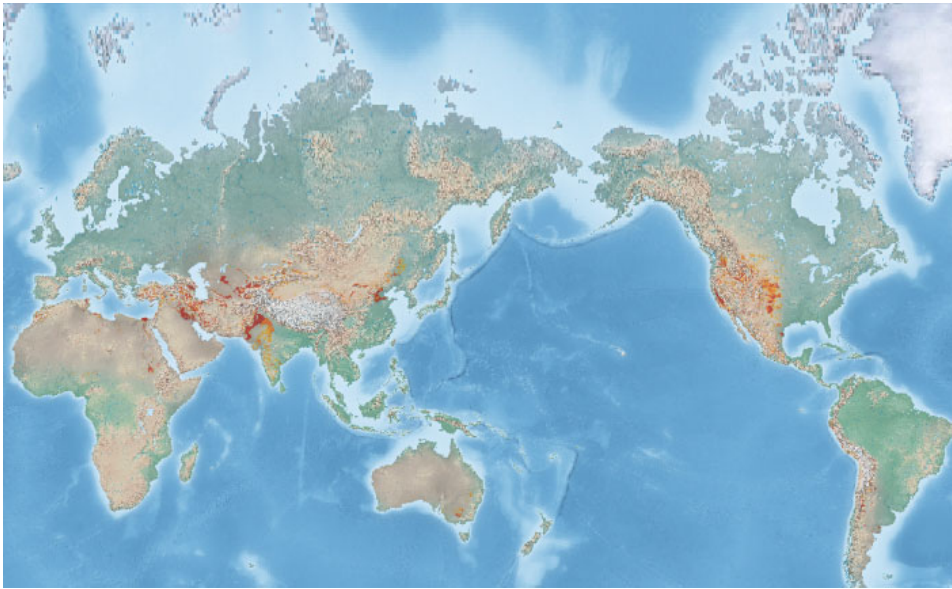
**Figure 49. Proportional of land salinized due to irrigation
(https://data.apps.fao.org/aquamaps/)**

5.3. CLIMWAT

CLIMWAT is database formulated by the Water Development and Management Unit and the Climate Change and Bioenergy Unit of FAO that provides the monthly mean values of the following climatic parameters:the mean of daily maximum temperature (°C), the mean of daily minimum temperature (°C), the mean of relative humidity (%), the mean of wind speed (km/day), the mean of sunshine (h/day), the mean of solar radiation (MJ/m2/day), monthly rainfall (mm/month) and monthly effective rainfall (mm). The Reference evapotranspiration (ETo) is calculated with the Penman-Monteith method and expressed as mm/day.

CLIMWAT can be combined with the CROPWAT model which is previously presented in chapter 2. The CLIMWAT data can be extracted for single or multiple stations in the format suitable for their use with the CROPWAT model. For this example, the Osijek station is chosen (Figure

50). When the specific climate station is chosen, the interface presents the location's longitude and latitude. After the country is selected, one can choose to display all weather stations within a selected country or within and around the selected country. Afterward, data are exported as a file that can be used as a climate file in the CROPWAT model.

Figure 50. CLIMWAT interface

6.

Partial equilibrium models

6.1. Partial equilibrium models and their applications

Economic models provide a simplified view and analyze complex phenomena of economic reality and are also considered useful tools for linking mathematical theory with statistical data. For the analysis of economic phenomena in agricultural markets and policy, various methods of economic modeling have been developed, and one of the most commonly used is modelling using partial equilibrium models.

Partial equilibrium models usually simulate international markets for a particular group of market goods, e.g., agricultural goods. Usually, partial equilibrium models see the agricultural sector as a closed system with no links to the rest of the economy. Nevertheless, the influences of the rest of the domestic and world economy on the agricultural sector can be included in a top-down manner by changing parameters and exogenous variables.

Partial equilibrium models can be the single or multi-product, multi-product models can capture the supply and demand interactions of different agricultural products. They also incorporate exogenous variables such as technological change, world population, and household income into their supply-demand relationships.

International trade in agriculture in these types of models generally focuses on trade in primary goods. That is, they cover agricultural supply, demand, and trade for unprocessed agricultural products or first-degree agricultural products processing without taking into account trade in processed food products.

The standard agri-food market partial equilibrium model must have the following characteristics:
• global coverage
• parametric differences between countries represented in the model
• dynamic feature
• policy representation
• theoretical consistency
• exogenous market factors that are non-agricultural

Quantitative models are important sophisticated tools for analyzing the impact of agricultural

policies and other exogenous changes on key agricultural markets. One of the modelling approaches used to analyze such impacts is AGMEMOD (AGricultural MEmber states MODelling), an econometric, dynamic, partial equilibrium, multi-country, multi-market model. AGMEMOD model provides extensive details of the agricultural sector in the individual EU Member States over common country model templates and the EU as a whole through the combined EU 27 model. Typical AGMEMOD applications refer to the:

• Medium-term market projections
• Set-aside/ ecological focus areas and payments
• Modelling of Production quotas whenever applied for the countries
• Resource demand for biofuels
• Fertilizer policies for some countries
• Rainfall data for some countries
• Landing Obligation

Simulations of the impact of irrigation on the growth of crops production volume due to the increase in productivity can effectively be projected by Partial Equilibrium (PE) models. PE models incorporate more details on production and policy instruments and describe one sector or a group of closely related products (Salvatici et al., 2001). Generally, PE models are used for quantitative impact assessments of agricultural policy reforms, but they can be used in various simulations of the commodity markets within the agricultural sector such as grains and oilseeds markets. Such simulations of various agricultural commodity markets are called "outlooks" and they present detailed medium-term (10 years) projections of key agrarian-policy indicators (production, yield, imports, exports, etc.) within individual agri-food markets.

Various PE models are developed so far, but today there are three core partial equilibrium models in the Integrated Modelling Platform for Agro-economic Commodity and Policy Analysis (iMAP) hosted by the EU Joint Research Center (JRC) (M'barek et al., 2012; M'barek and Delincé, 2015). One of the core models in the iMAP platform is PE model AGMEMOD - (Agriculture Member State Modelling) which application in simulation of the impact of irrigation on agricultural production will be presented (Figure 51).
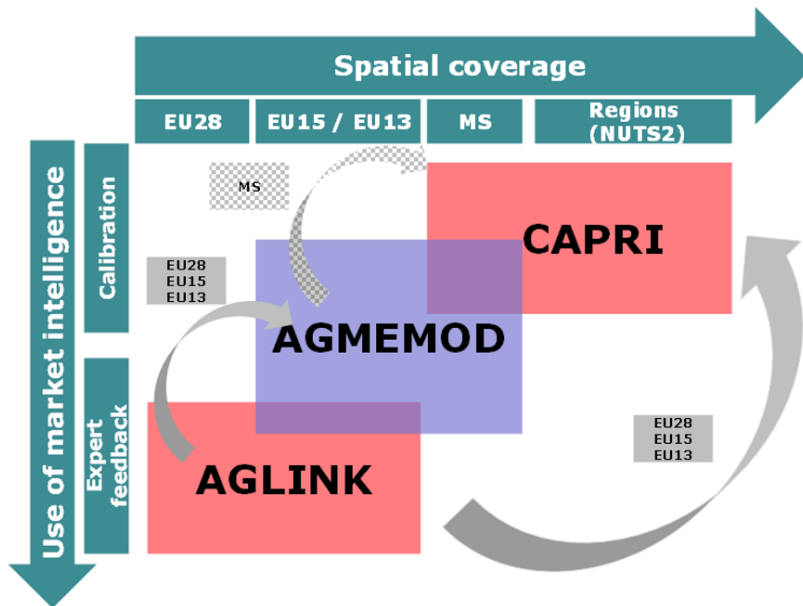
Figure 51. Role of AGMEMOD in the framework of the iMAP modelling platform at the JRC (Salamon et al., 2017)

6.1.1 AGMEMOD (PE) model

The AGMEMOD model is an econometric, dynamic, multi-product, multi-country partial equilibrium (PE) model. The main purpose of the model is to produce medium-term projections or market outlooks for key agricultural products by 2030. The modelling strategy uses the bottom-up approach, based on country-level models, using a common country model template, which is combined into a composite EU model (Chantreuil et al., 2012). The Member State model is composed of commodity market sub-models (for grains: soft and durum wheat, barley, and corn; for oilseeds: rapeseed, soybean, and sunflower; for livestock and meat: cattle, beef, pigs, pork, poultry, sheep and mutton; and for milk and dairy products: cheese, butter, whole milk powder and skimmed milk powder), where each commodity market is based on annual time-series data. In the case of Croatia, the data range from 1995 to 2018 and are compiled mainly from national sources (Croatian Bureau of Statistics and Ministry of Agriculture). The database covers data on production, food and feed consumption, imports, and exports in the

form of market balance sheets. As mentioned, data is collected from national statistical institutes, EUROSTAT, research institutes, or from industry sources, but the database in the model itself has to be organized in a specific manner (Figure 52).
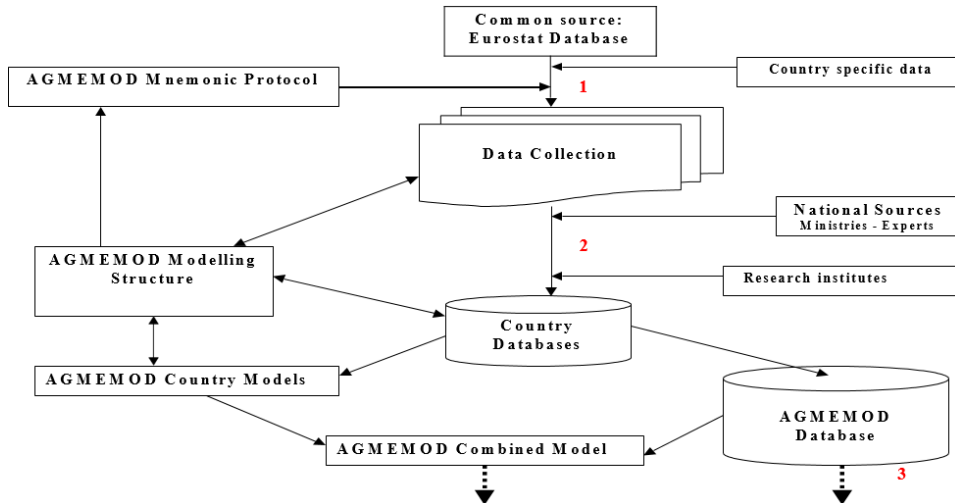
Figure 52. AGMEMOD data sources

A plausible and consistent database is necessary in order to modelling process to perform well. The criteria for assessing the admissibility of data include:
• reliability and accessibility of the data series and their up-dating;
• additivity of variables: the country level numbers for many variables have to add-up to acceptable totals for the EU as a whole (e.g., the national commodity balance sheets must add-up to that for the EU);
• data consistency across all models for the variables that drive the individual models, (e.g., the currency exchange rates);
• availability of the projections for the macroeconomic variables that drive the models (e.g., GDP, inflation, population growth);
• relevance of the data to the users of the results.

The model uses two specific types of variables which can generally be divided into endogenous and exogenous and each variable has a unique mnemonic and can only be allocated to one parameter type. The general logic behind variable type and how mnemonic will look inside the model is presented in Table 2.

Table 2. Parameter types used in AGMEMOD

Parameter type	Meaning	Variable type
V2(P_A,C,T1)	Product P and Activity A in Country C in year T1; endogenously calculated	endogenous in model
V(P_A,C,T1)	Product P and Activity A in Country C in year T1; fixed on the last observed year	exogenous in model
VWP(P_A,T1)	World market price for Product P and Activity A in year T1	exogenous in model
VPOL(P_A,T1)	EU dependent Policy variable for Product P and Activity A in year T1	exogenous in model
VPOLC(P_A,C,T1)	Policy variable for Product P and Activity A in Country C in year T1	exogenous in model
Vph(P,A,C,T1)	Policy Harmonization variable for Product P and Activity A in Country C in year T1	exogenous in model
VPOL_SFP(P_A,T1)	Single Farm Payment policy variable for Product P and Activity A in year T1; exogenous in model	exogenous in model
VMAC(A,C,T1)	Macroeconomic variable for Activity A in Country C in year T1	exogenous in model
DUM(D,T1)	Dummy D in year T1	exogenous in model
TREND (T1)	Trend T in year T1	exogenous in model

Commodity markets are modelled as interrelated in such a way that they reflect the competition between different products for resources, various interactions between crop and livestock markets, etc. Supply and demand, international trade, and prices are endogenously determined in the commodity market sub-models (Chantreuil et al., 2012). Country-specific models demonstrate changes in the behavior of economic stakeholders (producers and users), changes in exogenous data (macroeconomic variables, technical progress, policy instruments), and prices. Using sets of econometrically estimated equations, the model generates projections of endogenous variables from exogenous and endogenous data. In order for the model to satisfy

the partial equilibrium condition, it is necessary to establish for each individual key agricultur- al market a market equilibrium, which implies the following equal- ity at a certain product price:

$$Production_t + Beginning\ stocks_t + Imports_t = Domestic\ use_t + Ending\ stocks_t + Exports_t$$

In the commodity market sub-models (Figure 53), in this case for soft wheat, supply and demand, international trade, and prices are endogenously determined inside the model (Chantreuil et al., 2012).
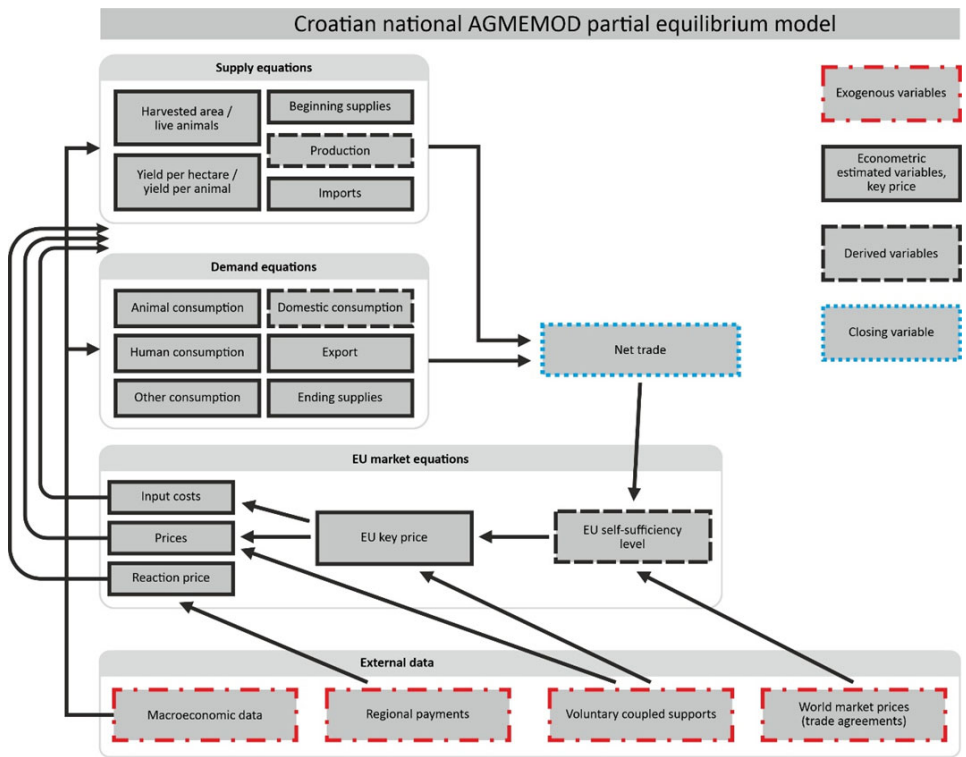
Figure 53. Croatian AGMEMOD partial equilibrium model scheme

Country-level models demon- strate changes in the behavior of producers and consumers, changes in exogenous data (macroeconomic variables, technical progress, policy in- struments), and prices. From exogenous and endogenous data using sets of econometri- cally estimated equations, the

model generates simulations of endogenous variables.

The general form of the econometric equation according to which the model derives the output variables is the regression equation. Therefore, the general equation of the model can be written as:

$$Y=\alpha+\varepsilon\beta_1 X_1+\varepsilon\beta_2 X_2+\varepsilon\beta_3 X_3...+\epsilon \qquad (1)$$

Equation 1. presents standard regression equation, where Y is the dependent indicator α is the intercept, ε the elasticity coefficient, β the regression coefficients, X_{123} are independent factors affecting on change of the dependent indicator and ϵ is presenting an error term.

AGMEMOD model software application was realized through the General Algebraic Modeling System (GAMS) computer program (McCarl, 2010). Before the realization of the AGMEMOD model in GAMS (Figure 54), all estimated and calibrated equations, as well as the data entering the model, must be specified in the MS-Excel program in separate sheets.

Figure 54. AGMEMOD-GAMS software

The model has its own interface that contains several MS Excel documents that are interconnected or loaded via the GAMS program. These excel sheets are located above in the drop-down menus under "InputData" and "ModelSources" (Figure 55).
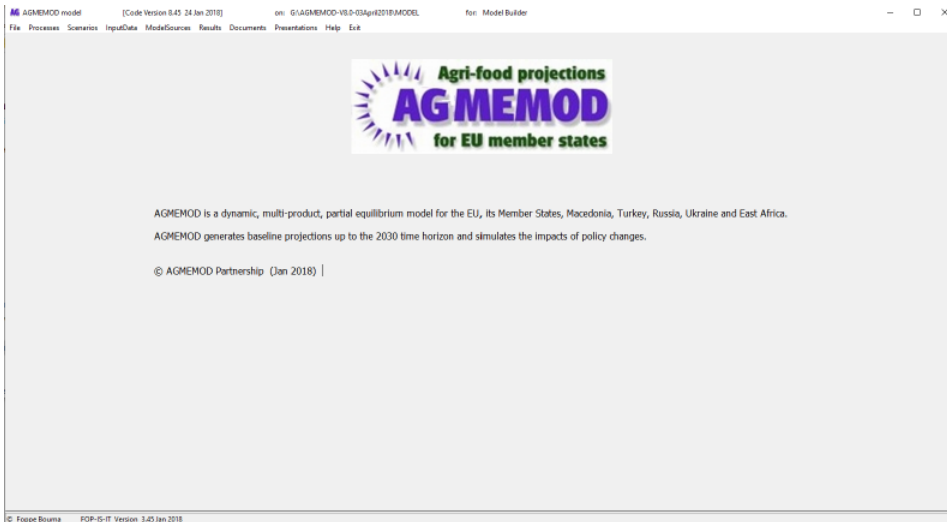
Figure 55. AGMEMOD interface

"InputData" drop-down menu contains MS Excel documents that cover commodity markets historical data, assumptions input data, and policy harmonization data. While, "Model-Sources" drop-down menu contain an MS Excel document with model equations for each country, commodity, and variable within the model itself. One more key feature of the model is under the "ModelSources" drop-down menu which relates to the R program in which econometric behavioral equations are estimated.

Currently AGMEMOD model has data and the corresponding equations for all EU 27 Member States. There are also partners from other European countries (Serbia, Bosnia and Herzegovina, Russia, Ukraine, and Kazakhstan) and some other countries outside Europe: Brazil, Ghana, Ethiopia, Kenya, and Rwanda. The Croatian country-level model is a result of the authors' standalone model according to the AGME-MOD Partnership rules. The national commodity market models of the key Croatian crop and livestock markets, are estimated,

calibrated, and then validated based on experts' knowledge and literature afterward.

Each country model is based on a database template of annual time series, which depending on the country ranges from as early as 1973 to the latest available. Usually for the oldest EU Member states data ranges from 1973 and for New Member States from the 1990s in the case of Western Balkan

Countries data ranges from the year 2000.

Historical data MS-Excel sheet is found in "InputData" drop-down menu within AGMEMOD interface and holds annual data on initial stocks, production, imports, human consumption and animal feed, industrial consumption, exports, ending stocks, and domestic prices for all key agricultural markets in each country model template (Figure 56).
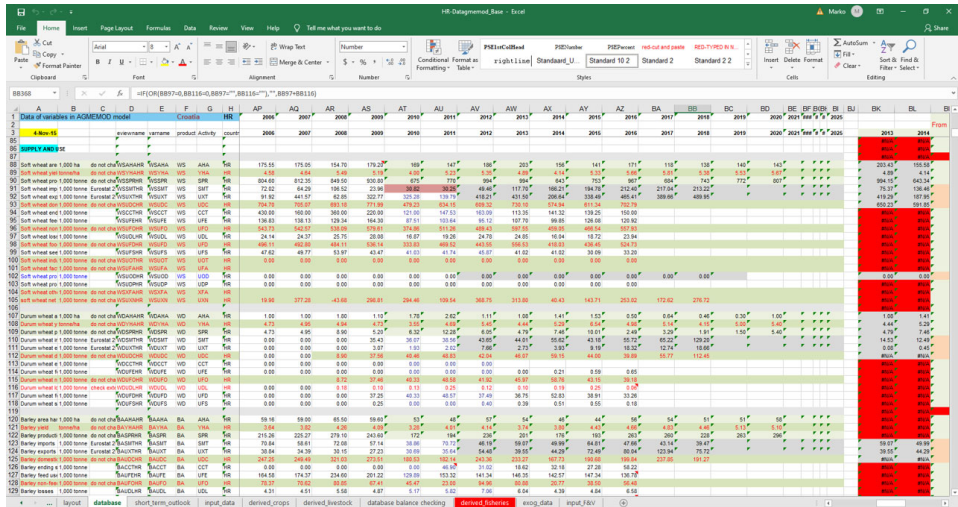
Figure 56. AGMEMOD historical data input sheet

Where possible, the AGMEMOD Partnership uses Eurostat sources such as the Agricultural Information System and New-Cronos to populate the AGMEMOD database (Levert and Chantreuil, 2006).

As Eurostat no longer provides supply and use balances, data

compilation has become more complicated, time-consuming. National teams responsible for country models and data compilation are required to turn to diverse national data sources.

The second MS-Excel sheet under the "InputData" drop-down menu holds a set of data

related to the exogenous assumptions that lie beyond the combined model (Figure 57). This set of data contains annual data about world market prices, population estimates mid-year, real Gross Domestic Product, GDP deflator, real GDP per capita, average annual exchange rate HRK / EUR, EU policy instruments, dummies, and trends.

Figure 57. AGMEMOD assumptions input datasheet

For assumptions on the development of macroeconomic conditions, the AGMEMOD uses the same sources as the EU Agricultural Outlook, which itself relies on a combination of the European Commission's short-term outlook, forecasts from IHS Markit, and other sources including the International Monetary Fund, the World Bank and the OECD. Their respective major assumptions include data on economic growth, inflation, and exchange rates (EC, 2016). The EU Agricultural Outlook covers the EU in its current composition (EU-27), following Brexit, which took place in 2020. It presents the medium-term outlook for the EU agricultural markets, income, and environment up to 2030, based on a set of coherent macroeconomic assumptions deemed most plausible at the time of the analysis.

Country-specific policy instruments are contained in the policy harmonization sheet also to be found under the "InputData" drop-down menu in the AGMEMOD interface (Figure 58).
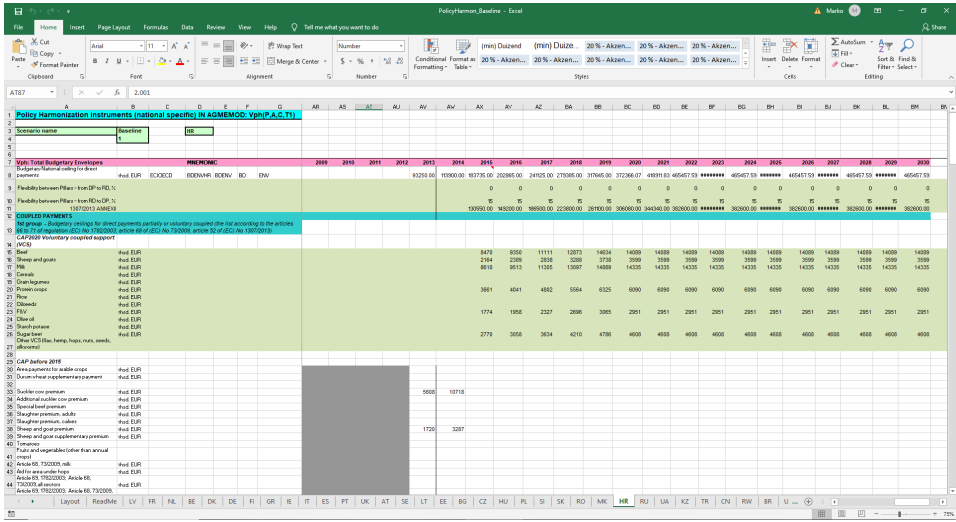
Figure 58. Policy harmonization datasheet

Policy harmonized approach assumes the inclusion of current 2015-2020 CAP measures and instruments, which relate to regional and voluntary coupled supports (Salputra et al., 2011). Regional, coupled payments as well as state aids are recalculated and included as a policy price addon to producer prices for each observed agricultural products market, in order to form a reaction price that affects the level of production, sown area, average slaughter weight, and numerous other variables in the Croatian national AGMEMOD model (Figure 59).
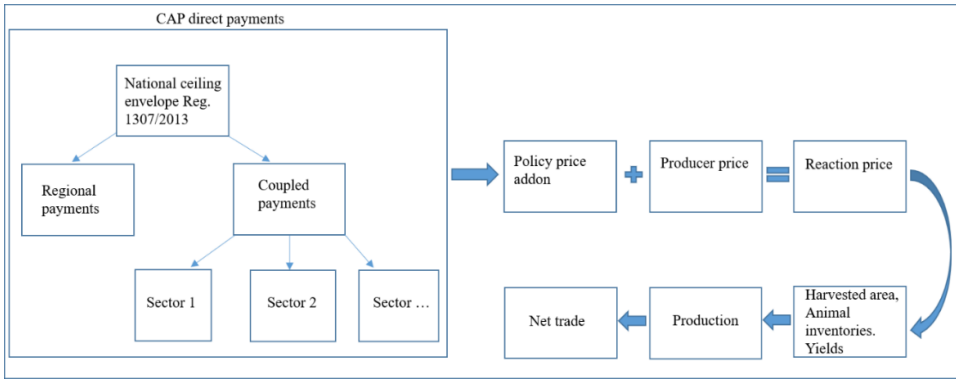
Figure 59. Policy harmonized approach in the AGMEMOD model

Finally, the last sheet found in the "ModelSources" drop-down menu is containing sets of econometrically estimated equations. Some variables in the model are estimated and some are derived from a historical datasheet. Estimated variables come from the R application program which is also an integral part of the AGMEMOD model and also it is found under the "ModelSources" drop-down menu.

Figure 60. AGMEMOD equation sheet

Equation type (EQ) means that the variable has been estimated or calibrated, identity type (IDEN) indicates that the variable is defined as a derived variable of other variables. Fixed variable type (FX) - indicates that the variable was determined by its last observation in the historical data and is therefore treated as an exogenous variable in the model. The variables included in the regression model are usually numerical variables. In some cases, in addition to numerical variables, qualitative variables are included in the model as regressors in order to describe the impact of qualitative information, and thus expand the scope of regression analysis. Qualitative variables are included in the model using dummy variables. A regression model in which the dependent variable is numerical, and which contains one or more dummy variables

as independent variables in addition to the numerical ones, is analyzed in the same way as the standard regression model. Model is generating results in MS-Excel tables, and to generate results in such manner

user has to go to "ModelSources" drop-down menu of model interface and find "AGMEMOD Gams Model and Analyzing Tool for" then click on "TI GDX2Excel Tool" then the model will generate tables shown in Figure 61.

Figure 61. AGMEMOD Excel results table

Results are generated in separate documents which relate to crop markets results (soft and durum wheat, corn, barley, rapeseed, sunflower, and soybeans), livestock market results (cattle, pigs, poultry, sheep, and goats with associated markets for meat, dairy cows, milk and dairy products).
The results are presented in the form of production-consumption balance sheets and contain simulated data results on harvested areas, animal slaughters, slaughter weights, yields, production, domestic use (food, feed, and processing use), imports, exports, stock change, market prices, and self-sufficiency rates by 2030.
In addition to the tabular display, the model is capable of generating graphical results for the same listed simulated results (Figure 62).
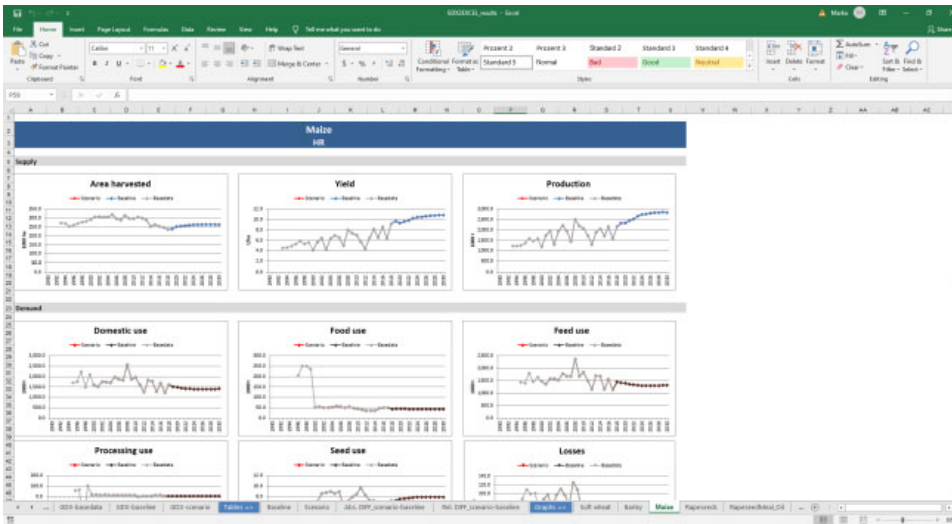
Figure 62. AGMEMOD Excel results graphs

Also, it is possible to generate results in GAMS for each individual variable for each country in the AGMEMOD model (Figure 63). To produce results in GAMS user has to go to the "Results" drop-down menu and find "OutPut Tables for all Scenarios (GDX/Gamside)".
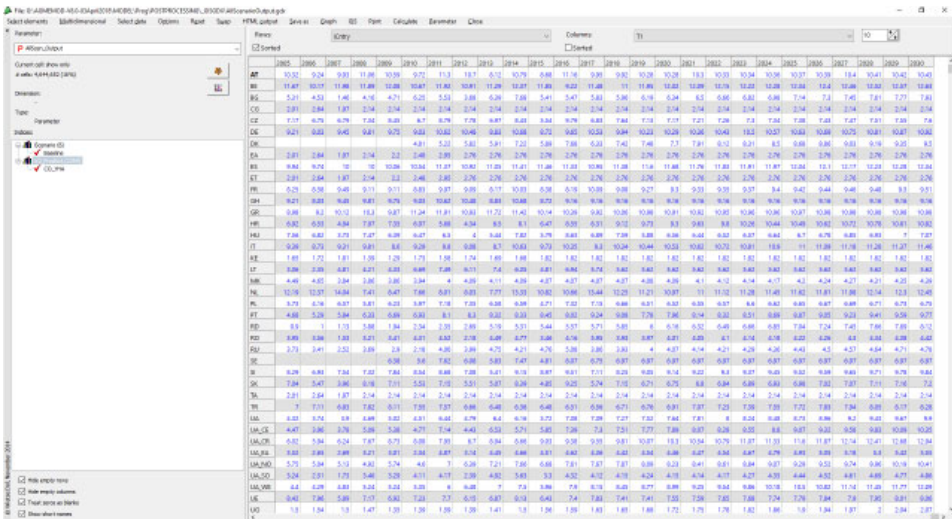
Figure 63. AGMEMOD GAMS results

6.1.2 AGMEMOD (PE) model in the practical use of simulating future soft wheat yield and production volumes under the irrigation

This section will show the actual modelling results of the Croatian soft wheat market (harvested area, yield, and production) via the AGMEMOD model by 2030. Two simulations will be made, one without the effect of irrigation and the other with the effect of irrigation on all observed soft wheat is sown. Namely, no country or region irrigates all sown areas, but the intention is to test the application of the model and its capability to simulate the impact of irrigation on soft wheat yields and production. When creating a real simulation, it is possible to place part of the areas that are truly irrigated or planned to be irrigated in the future in the model itself.

Croatian soft wheat market historical balance sheet data ranges from 1995 up to 2018, and they are compiled from the national statistical office and cover data on production, consumption, imports, exports, beginning stocks, and ending stocks in the form of balance sheets (CBS, 2021). The Croatian soft wheat market modelled using an appropriate econometric methodology as described by the general rules of the AGMEMOD modelling approach (Hanrahan, 2001; Erjavec and Donnellan, 2005). The simulation assumes stable market conditions without market distortions with stable climatic and weather conditions (ceteris paribus) and with the continuation of existing agricultural policy measures up to 2030 (baseline) (Jansik et al., 2006).

Next, the general forms of econometric equations in the model used for the simulation of the soft wheat market (harvested area, yield, and production) in Croatia will be presented. Future simulated total wheat production is determined by simulation of future soft wheat sown areas and yields. Therefore, the equation for the total harvested area of cereals, oilseeds, and root crops can be written as:

$$ah_{i,t} = f(p^j_{i,t-1}, ah_{l,t-1}, V) \qquad j = 1,...,n; \quad i,l = 1,...,3; \quad i \neq l \qquad (3)$$

Where:

$ah_{i,t}$ = harvested area in year t of crop group i

$p^j_{i,t-1}$ = the actual price of culture j belonging to the group of crops i in year t-1

V = vector of exogenous variables that may affect the harvested area of culture (e.g. certain policy instruments such as coupled payments)

The share of culture k that belongs to the group of cultures and is determined by the following equation:

$$sh^k_{i,t} = f(p^j_{i,t-1}, sh^k_{i,t-1}) \quad j,k = 1,...,n \quad (4)$$

The share of the harvested area of an individual crop is calculated according to principle 1 - part of the area of all other (n-1) crops, which means that the harvested area of the observed crop = Total harvested area × share of nth crop.

The yield of culture k which is in the group of cultures i can be expressed as:

$$r^k_{i,t} = f(p^j_{i,t-1}, r^k_{i,t-1}, V) \quad j,k = 1,...,n \quad (5)$$

Where:

$r^k_{i,t}$ = yield per hectare of crop k which is in the group of crops i

$p^j_{i,t-1}$ = the actual price of culture j belonging to the group of crops i in year t-1

$r^k_{i,t-1}$ = yield per hectare of crop k which is in the group of crops i in the year t-1

V = a vector of exogenous variables that may affect the yield per hectare of crop k located in the crop group i.

Based on the previous equations, the production of observed crop culture is determined: crop production = harvested crop area × crop yield. When the general form of econometric behavioral equations is transferred to the AG-MEMOD program via mnemonics to the R program through which equations are econometrically estimated using national annual time series (Figure 64). Using sets of econometrically estimated equations, the model creates projections of endogenous variables from exogenous and endogenous model data. The corresponding econometric equations are estimated using standard econometric techniques and simulation will be the results of the mathematical solutions to this set of equations (Figures 64 and 65).
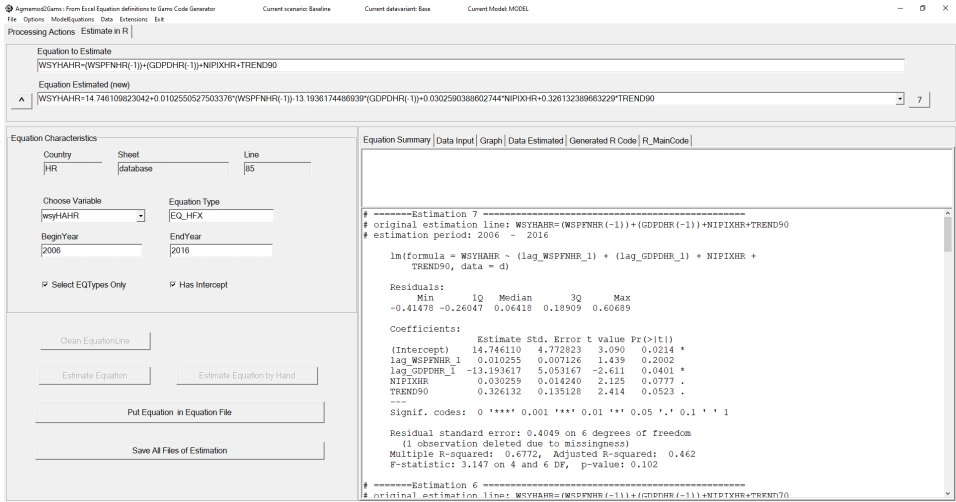
Figure 64. Estimation process in R program

The evaluation of the model in terms of testing the significance of regression parameters is performed by T-test, and then performs the significance test of the entire regression by F-test with the coefficient of determination R^2. Then, the estimated results are evaluated by standard statistical tests for heteroskedasticity (white heteroskedasticity) and autocorrelation.
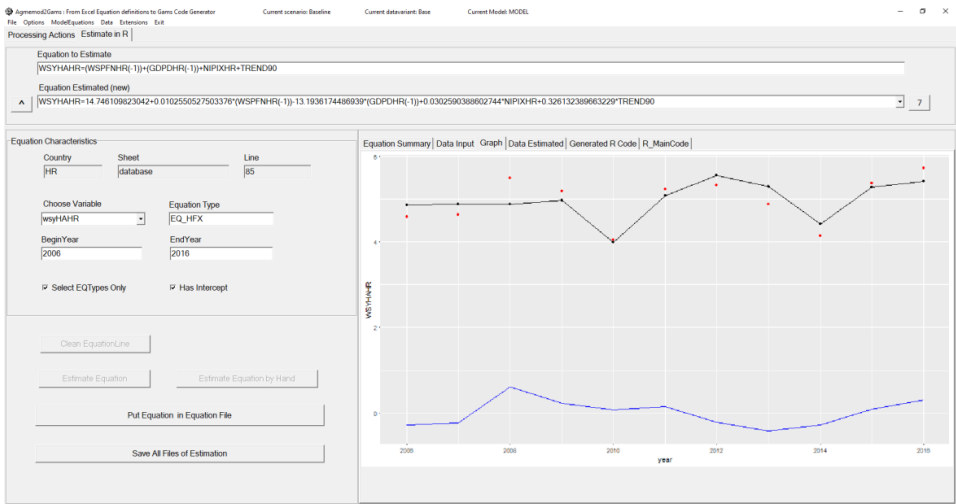
Figure 65. Estimation process in R program – estimation graph

After the process of estimation, estimated equations are calibrated so that they correspond to standard tests that assess the statistical coherency and quality, as well as their compliance with necessary biological constraints. In order to produce plausible simulation validation of the produced simulation results has to be conducted. This means that commodity market experts and agricultural economists will examine the provisional model baseline simulation results and will provide feedback on the model's projections. Regarding their comments, further calibration steps might be undertaken. By following previously described steps which relate to:

- Data collection
- Assumption's determination
- Setting up econometric behavioral equations
- Estimation of econometric behavioral equations
- Calibration of econometric behavioral equations
- Validation of econometric behavioral equations
- Re-calibration regarding validation if needed

We get a good medium-term simulation that can serve as a decision-making basis, this approach also relates to evidence-based policy making (EBPM) (Cairney, 2016).

Simulation results of the Croatian soft wheat market under baseline assumption are modelled producing medium-term projections of soft wheat harvested area, yield and production by 2030. In order to simulate the effects of irrigation on observed variables calibration technique was used. In the first step simulation with the equation shown in Figure xy was used to produce regular baseline results. Irrigation effects are simulated simply by adjusting the regression coefficient of the trend variable in the estimated equation in order to produce results with irrigation effect simulation. Namely, the importance of irrigation in economic terms is most evident in the increase in yields of cultivated crops where it is estimated that irrigation of the area with average annual rainfall can have up to 20% higher yields, while in years with low annual rainfall up to 40% higher yields (Marković et al., 2018; Marković et al., 2017; Marković et al., 2016; Čagalj et al., 2015; Šoštarić et al. 2014). Therefore, we took an arithmetic mean of 30%, and by this percentage, we increased the regression coefficient of the trend in the estimated equation for soft wheat yield in Croatia.

Baseline simulation without irrigation effect indicates that soft wheat yields in Croatia will continue to grow by the end of the simulated period (Figure 66). The introduction and development of new technologies in arable farming production, EU funding sources, Common Agricultural Policy (CAP) direct pay-

ments and mechanisms, changes in the landowner structure in favor of larger and more efficient farms should significantly contribute to further convergence of productivity per unit area, where Croatia should be near the old Member States in terms of productivity levels.
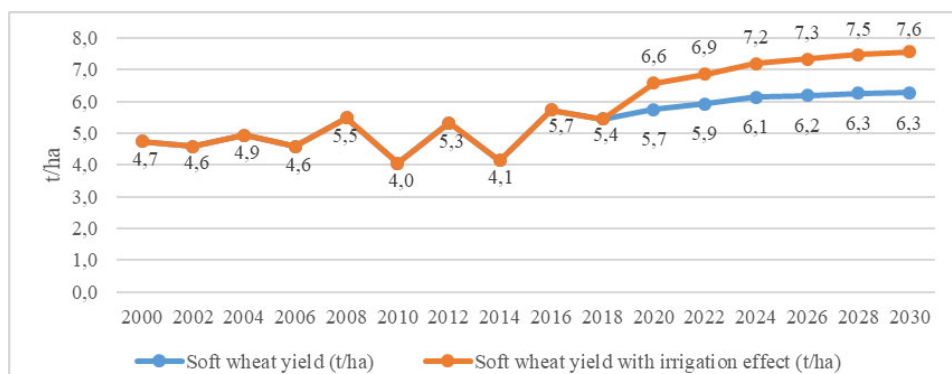
Figure 66. AGMEMOD modelling results – soft wheat yield

However, when we increase the trend regression coefficient by 30% in order to simulate irrigation effect on soft wheat yields increase up to 7.6 t/ha compared to 6.3 t/ha by 2030. This means 20.5% increase in soft wheat yields compared to baseline simulation results by the end of the simulated period.

The soft wheat sown areas in Croatia have a declining trend particularly after Croatia's accession to the EU (Figure 67). Relatively low soft wheat average producer prices in Croatia, which

are below the levels of average producer prices in the EU are the cause of soft wheat sown area declining trend (Iljkić et al., 2019). Therefore, a part of domestic soft wheat producers has reoriented their production to other crops production whose average producer prices are closer to the EU levels (Kranjac et al., 2020).

According to the AGMEMOD model baseline simulation results, it is expected stable amounts of soft wheat sown areas in the future with a slight growth trend until 2030 compared to 2018.
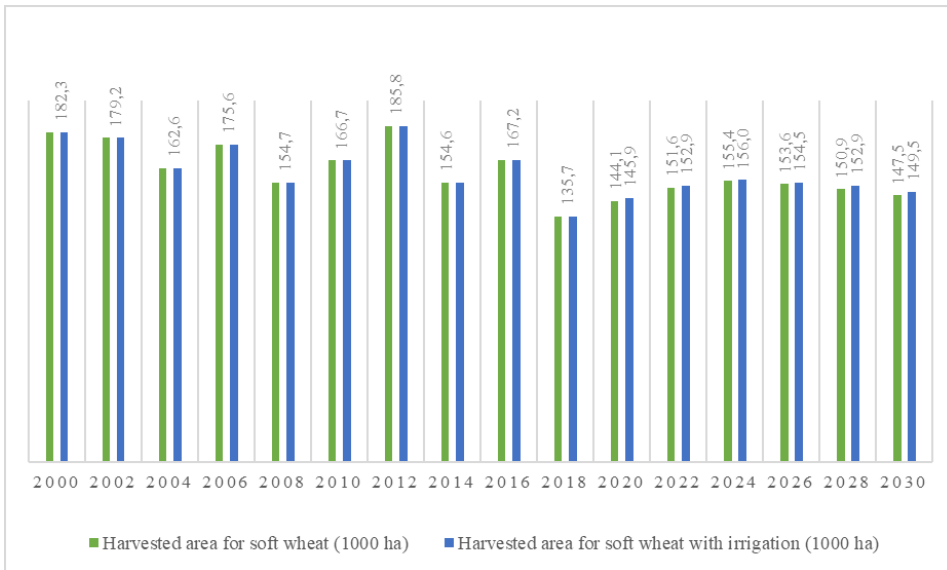
Figure 67. AGMEMOD modelling results – soft wheat harvested area

When we simulate the irrigation effect in the trend variable, we can observe that soft wheat harvested areas slightly increase compared to baseline simulation results. Simulated results show an increase of 1.4% in a harvested area compared to baseline by 2030. This can be explained by fact that higher soft wheat yields provide more incentive to producers so they become more willing to sow soft wheat. Given the expected growth in yields and stable levels of sown areas, soft wheat production is also expected to approximately grow by 25% under the baseline scenario by 2030 compared to 2018 (Figure 68).
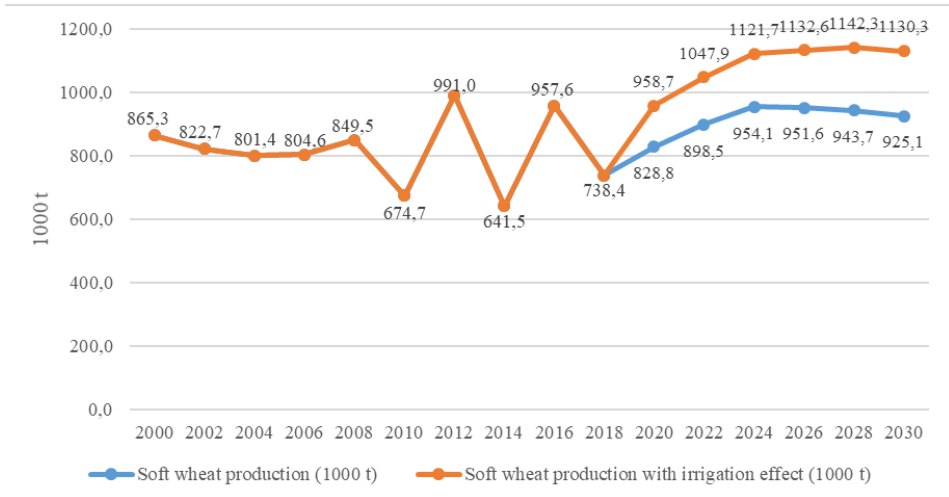
Figure 68. AGMEMOD modelling results – soft wheat production

Under the simulated effect of irrigation soft wheat production volumes in Croatia is expected to grow by 22.2% compared to baseline modelling results by 2030, and by respectively 53.1% compared to 2018 production quantity.

In a similar way, this kind of simulation of irrigation impact on other key crop markets can be applied. Simulations of this type can help decision-makers in their decisions to support investment in irrigation infrastructure projects. As such investments are extremely expensive, good impact analysis on production indicators is needed and partial equilibrium models as sophisticated tools can deliver impact assessment analyzes that will simulate such effects.

7.
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