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Crop Water Requirements

Crop Scheduling.

Yield – Water Relationship

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Strengthening of master curricula in water resources management for the Western Balkans HEIs and stakeholders

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1. General Information

- The Irrigation System (IS) is designed and operated with one aim - to deliver water to farmers
  - ➢ Farmers use water for irrigation of crops
  - ➢ Farmers request water delivery according to ***crop needs***
  - ➢ Thus, the design and operation of IS depends on crop needs or on so called *Crop Water Requirements*
- **Crop Water Requirements** – the total quantity of water and the way in which it is required by the crop during its vegetation period (also called *crop period*)
  - ➢ Base period – period between the first and the last applications
  - ➢ *Crop period* is a bit longer than Base period
    - ✓ Considering irrigation, these terms are used as synonyms.

1. General Information

- Crop Water Requirements are essential for:
  - ➢ Design of the Irrigation System
    - ✓ design flow rates of canals, total water abstraction, etc.
  - ➢ Operation of the Irrigation System
    - ✓ irrigation frequency, flow rates, duration, water use, efficiency, etc.
- Crop Water requirements are presented by 3 parameters:
  - ➢ Irrigation requirement – $\boldsymbol{M}$ (net M_{net} or gross M_{gr});
  - ➢ Irrigation dose (also called *application*) – $\boldsymbol{m}$ (net or gross)
    - ✓ number of doses
    - ✓ frequency of delivery (period between two applications);
  - ➢ Water Duty (hydraulic module, or hydromodule) – $\boldsymbol{q}$ (net or gross).

1. General Information

- **Irrigation requirement** ***M*** is used to determine the annual demand *U* of the IS:

$$U = \frac{F_{IS} M_{net}}{\eta_{IS}}, \text{ m}^3.$$

- **Irrigation Requirement** (*M*) is defined as the sum of irrigation doses *m* for the crop period [m^3/ha]

$$M = \Sigma m, \text{ m}^3/\text{ha}$$

- **Irrigation dose** ***m*** (also called *application*) is the amount of water delivered to plants during one watering (for one water application)

1. General Information

- **Irrigation dose *m*** is used to determine:
  - the design and operational parameters of the irrigation equipment;
  - the specific water flow rate (so called *water duty* or *hydromodule*).
- **Water duty (hydromodule) *q*** is the flow rate in ℓ/s needed for irrigation of 1 ha.
  - It is used to determine the design flow rate Q_0 of irrigation canals:

$$Q_0 = \frac{q_{net} F_{IS}}{\eta_{IS}}, \quad \frac{l}{s}$$

where F_{IS} is the irrigation system net command (or suitable) area, ha;
η_{IS} – the efficiency of the irrigation system.

1. General Information

- ***Irrigation Schedule*** contains and provides data for ***M*** and ***m***
  - ➢ It contains data for:
    - ✓ the number and size of irrigation doses ***m*** and
    - ✓ the moments for their delivery.
    - ✓ the irrigation requirement M ($M = \Sigma m$)
  - ➢ Irrigation Schedule is done for one (a single) crop
- ***Irrigation Regime*** contains and provides data for ***q***
  - ➢ Irrigation regime is presented by *water duty diagram*
  - ➢ Irrigation regime can be done for:
    - ✓ One crop;
    - ✓ Multiple crops (more than one crop);
    - ✓ Crop rotation(s).

2. Crop Water Requirements

- **Crop Water Requirements** depend on climatic factors (air temperature, vapor pressure deficit, precipitations, etc.)
  - the climatic factors are stochastic variables.
  - thus, the Crop Water Requirements have probability of occurrence
- Crop Water Requirements for **design purposes**
  - They are determined only once – when the IS is designed
  - They are determined on the basis of ***past period*** of time
  - A representative year is chosen to obtain data for climatic factors
  - **In Bulgaria**, this representative year is a ***moderately dry year***
    - ✓ ***A moderately dry year*** is a year in which the value of the irrigation requirement M has a cumulative probability of $p = 75\%$.
      - In other words, the Irrigation requirement will be equal or less than this value of M in 75 out of 100 years.

2. Crop Water Requirements

- Crop Water Requirements **for operational purposes**
  - They are determined each year
  - They are determined on the basis of **a forecast** for climatic factors for the upcoming irrigation season
  - They are done in the beginning of the irrigation season year (end of March or beginning of April)
- For both design and operational purposes **3 basic irrigation factors** should be determined :
  - **Frequency** (or **Rotation Period**);
    - ✓ in Bulgaria *Irrigation Interval T* – minimum period between two applications is used instead of frequency
  - **Flow Rate *Q*** of delivered water
  - **Duration *t*** of the flow rate *Q*

3. Determining Crop Water Requirements

- Crop Water Requirements are established by means of a water balance of a given soil volume
  - This water balance is known as water budget
  - The water balance is done by means of a balance equation
- The water balance equation (WBE) of a soil volume can be solved for:
  - design purposes – using data for representative year
  - operational purposes – using data from forecasts
- Determining of the Crop Water Requirements for the design purpose, i.e. for representative (moderately dry) year is further described

3. Determining Crop Water Requirements

3.1. Kostyakov's Method (USSR) for Irrigation Schedule

- The general view of the water balance equation is as follows:

$$W_{end,i} = W_{beg,i} + Inflow_i - Outflow_i + m_i - G\text{, m}^3\text{/ha,}$$

while $W_{end,i} \leq W_{max,i}$, m^3/ha (shows presence of G_i)

and $W_{end,i} \geq W_{min,i}$, m^3/ha (show presence of m_i)

Notation:

$W_{end,i}$ is the water content of the soil in the end of calculation interval i;

$W_{beg,i}$ is the water content of the soil at the beginning of the interval i;

$Inflow_i$ is the amount of water infiltrated in the soil during the interval i;

$Outflow_i$ is the amount of water left the soil during the interval i;

m_i is the irrigation dose for the calculation interval i,

G_i is the deep percolation from soil volume for the interval i;

3. Determining Crop Water Requirements

3.1. Kostyakov's Method (USSR) for Irrigation Schedule

- Notation:

  $W_{max,i}$ is the maximum water content in the soil (at its field capacity);

  $W_{min,i}$ is the amount of water at minimum allowable capacity of the soil

- Continuity of the equation

$$W_{beg,i} = W_{end,i\text{-}1}$$

  - The water content at the beginning of the interval *i* is equal to water content at the end previous interval (*i*-1).

- Calculation interval and period
  - Calculation interval (step) = Irrigation interval $T = 10$ days
  - Calculation period – vegetation period of the crop

3. Determining Crop Water Requirements

3.1. Kostyakov’s Method (USSR) for Irrigation Schedule

- **Constituents of the water balance**

$$Inflow_i = P_e + \Delta W + K$$

$$Outflow_i = E$$

where P_e is the income from effective precipitation

$$P_e = P - S,$$

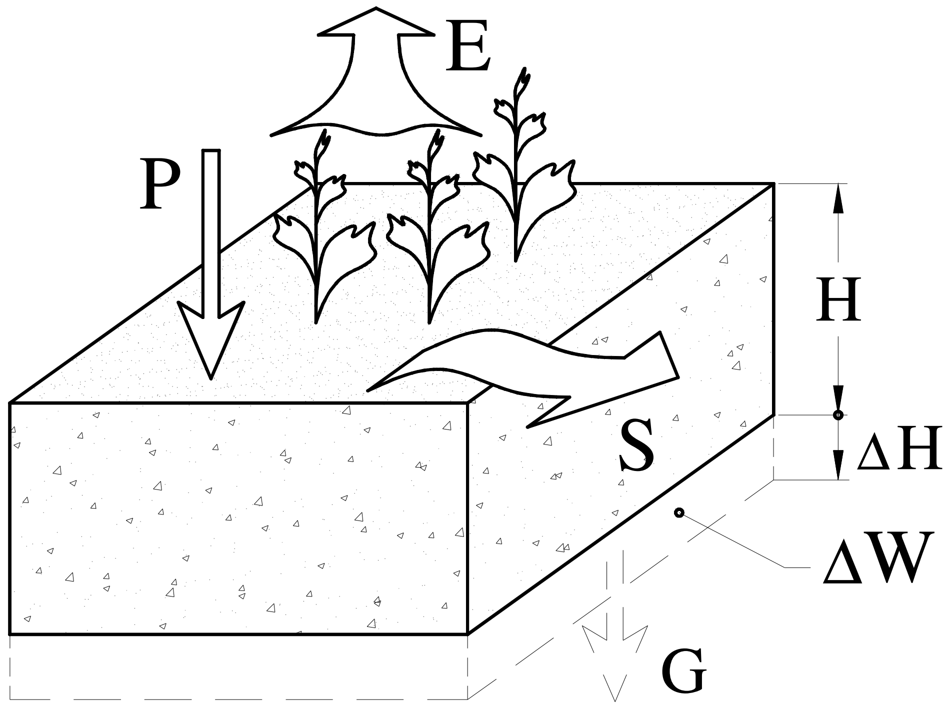
P – precipitations

S – surface runoff;

ΔW – income from available water into increased soil volume;

K – income from capillary rise

E – Evapotranspiration.



3. Determining Crop Water Requirements

3.1. Kostyakov's Method (USSR) for Irrigation Schedule

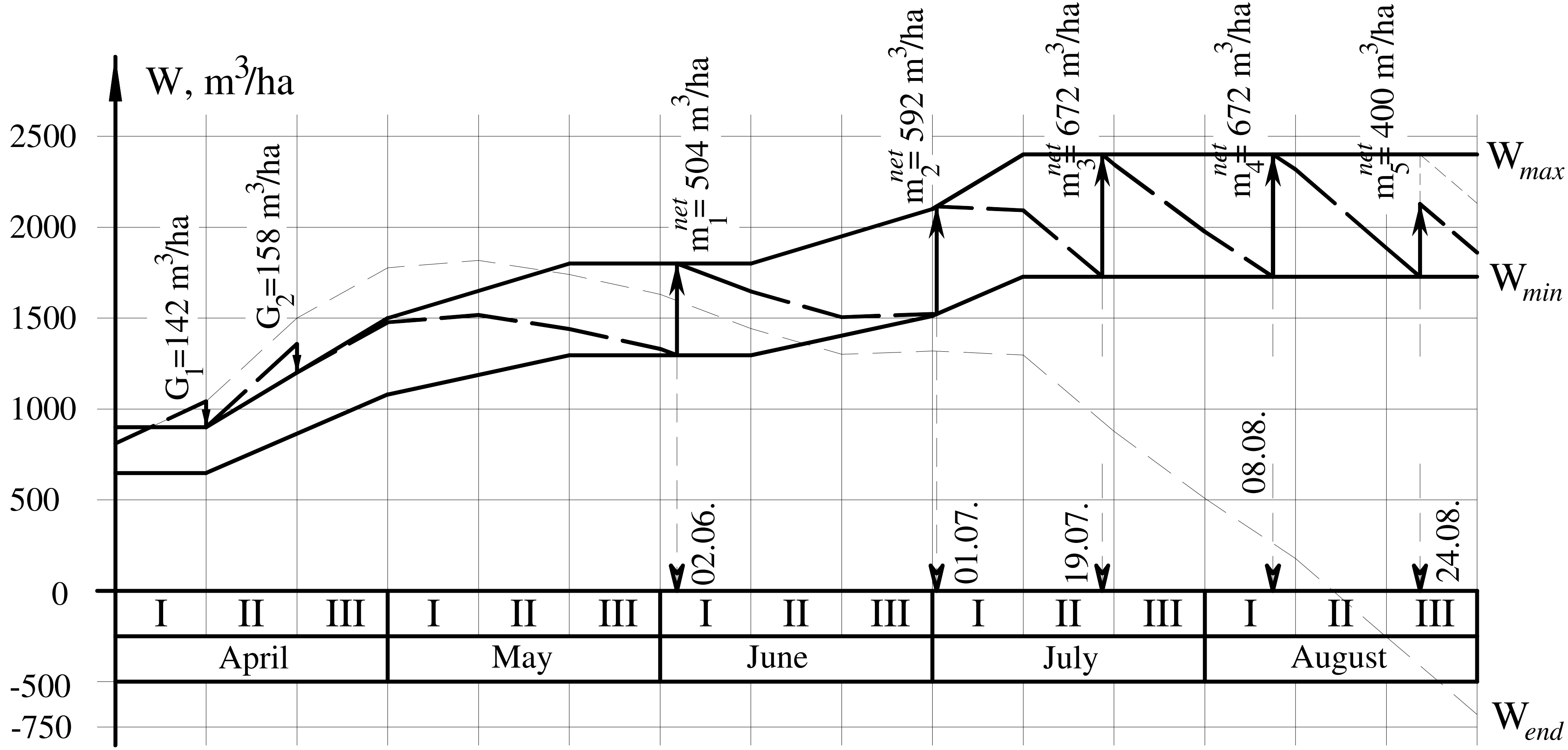
Solving the Water Balance Equation

- Kostyakov Method (USSR)
  - The value of each constituent is estimated for all calculation intervals of the crop base period
  - The difference between *Inflow* and *Outflow* is estimated for each calculation intervals.
  - A Balance is made, without taking into account the constraints.
  - Then, plotted on the graph, balance polyline, and constraints polylines help to determine when to irrigate.

3. Determining Crop Water Requirements

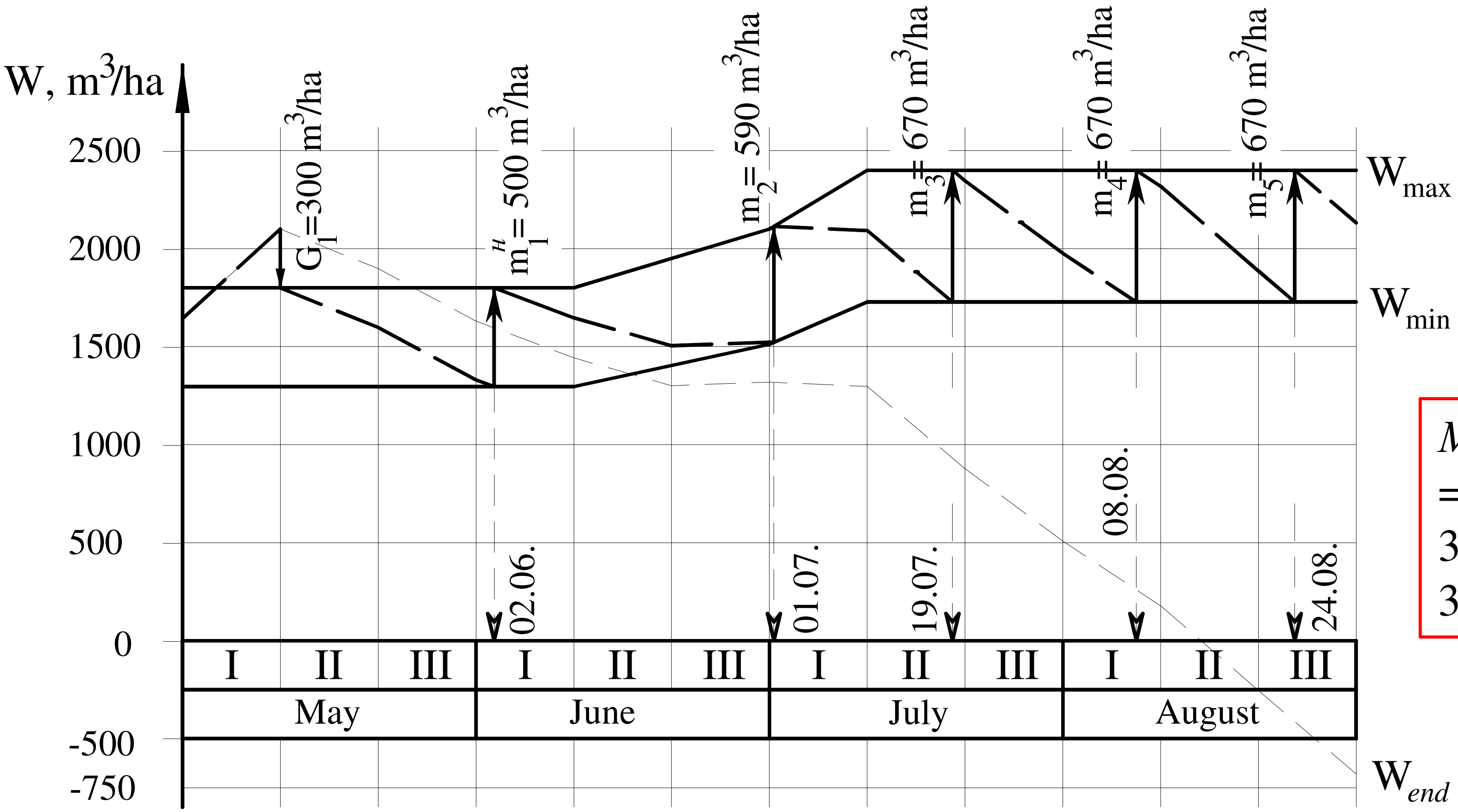
3.1. Kostyakov's Method (USSR) for Irrigation Schedule

Graphical solution



3. Determining Crop Water Requirements

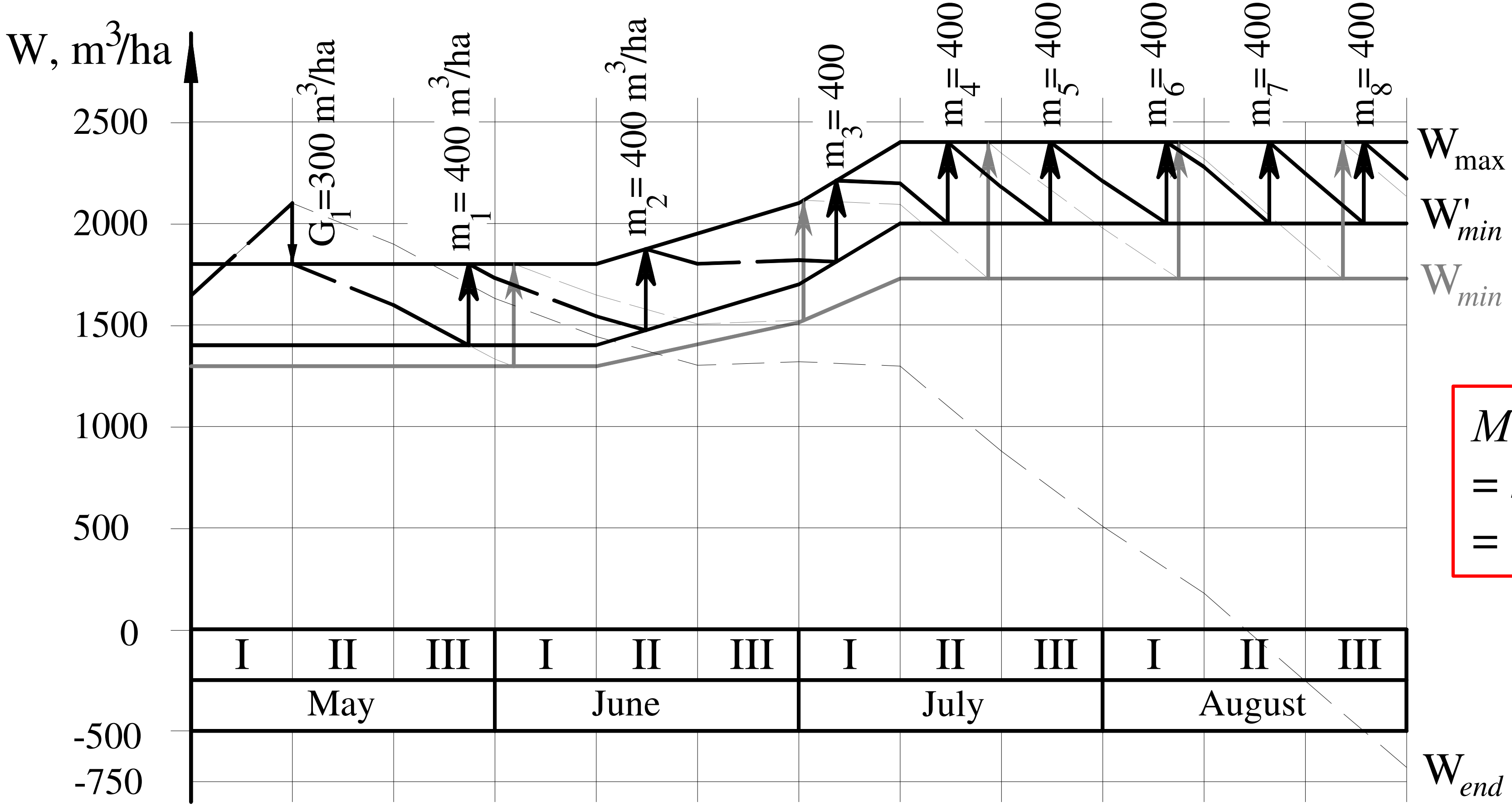
- Constraints influence on *m* and *T*.
  - ➢ Classic lower constraint: $W_{end,\, i} \geq \boldsymbol{W}_{\mathbf{min}}$
  - ➢ ***Result:*** Irrigation interval (July - August) T = 18-20 days.



$M = \Sigma m =$
$=500+590+$
$3.670 =$
3100 m^3/ha

3. Determining Crop Water Requirements

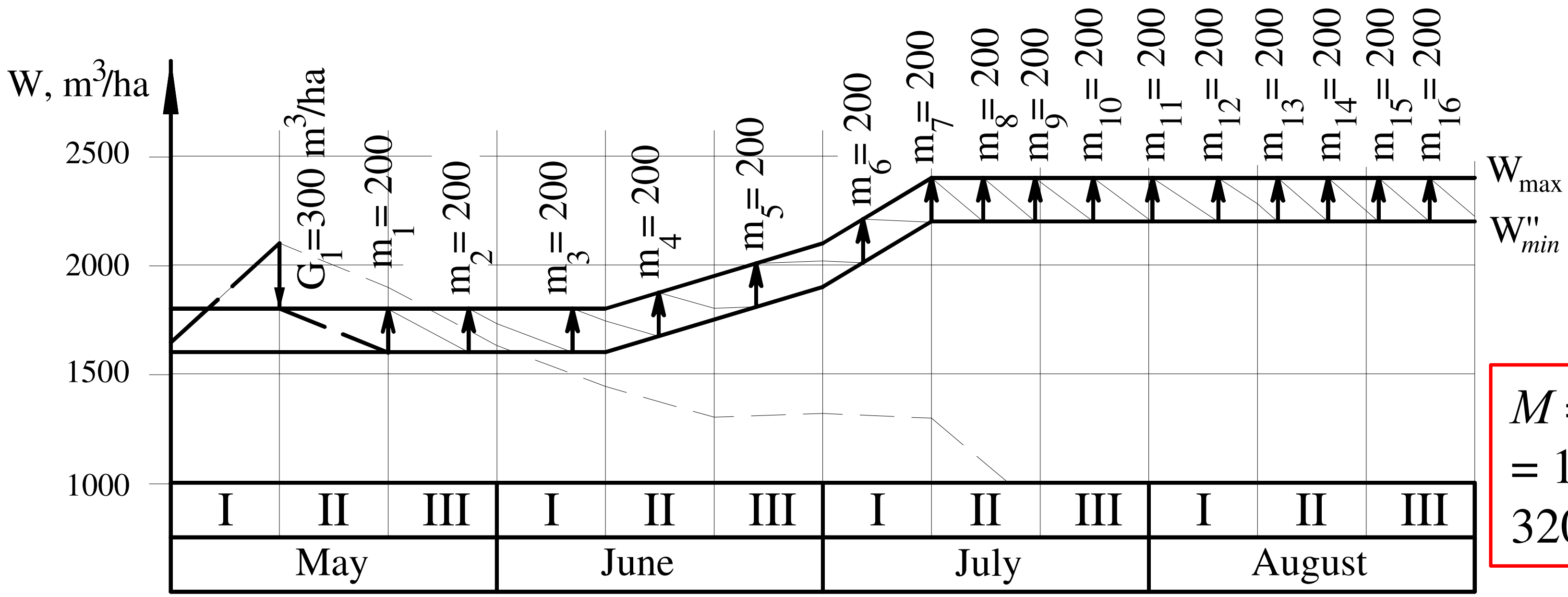
- Constraints influence on *m* and *T*.
  - ➢ Modified lowed constraint: $W_{end,\,i} \geq \mathbf{W'_{min}} > \mathbf{W_{min,\,i}}$
  - ➢ ***Result:*** Irrigation interval (July - August) T = 10-12 days.



$M = \Sigma m =$
$= n.m = 8.400$
$= 3200$ m³/ha

3. Determining Crop Water Requirements

- Constraints influence on *m* and *T*.
  - ➢ Modified lowed constraint: $W_{end,\,i} \geq \boldsymbol{W''_{min}} > \boldsymbol{W'_{min,\,i}} > \boldsymbol{W_{min,\,i}}$
  - ➢ ***Result:*** Irrigation interval (July - August) $T = 4 - 6$ days.

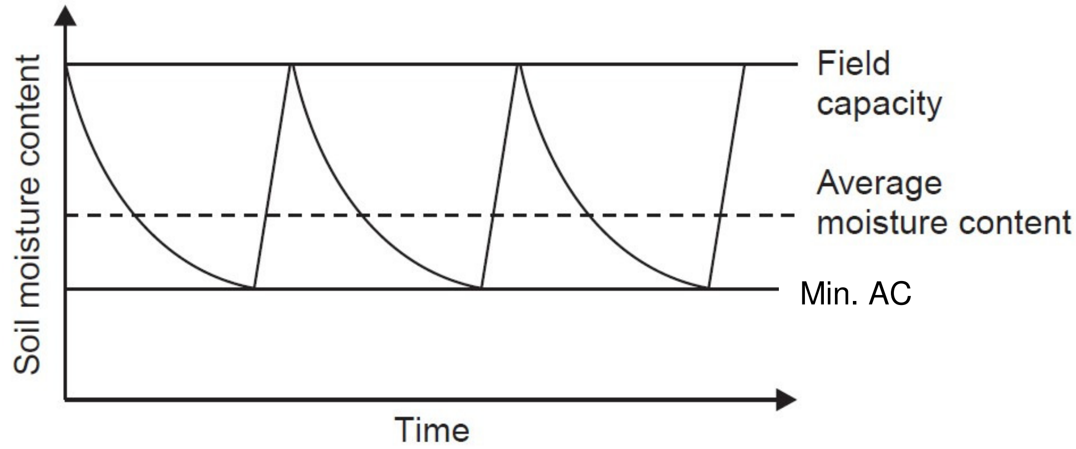


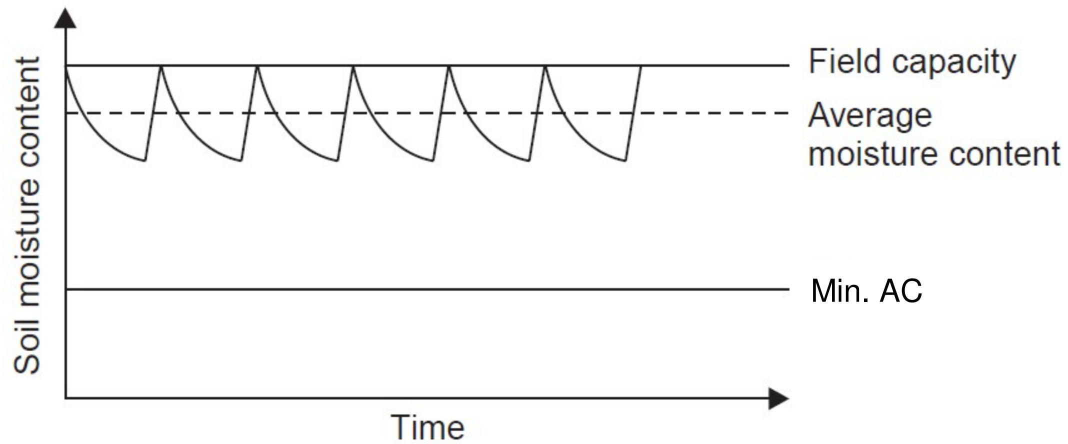
$M = \Sigma m = n.m$
$= 16.200 =$
$3200\ m^3/ha$

➢ The same approach can be applied for the upper constraint – W_{max} to be decreased

3. Determining Crop Water Requirements

- Constraints influence on *m* and *T*.
  - ➢ If the application is made before the water content drops to Min. Allowable Capacity, then:
    - ✓ the applications will be more frequent, i.e. the ***frequency will increase***
    - ✓ ***Irrigation doses m will be smaller***
    - ✓ ***Irrigation requirement M will stay the same***
    - ✓ Average moisture content will increase



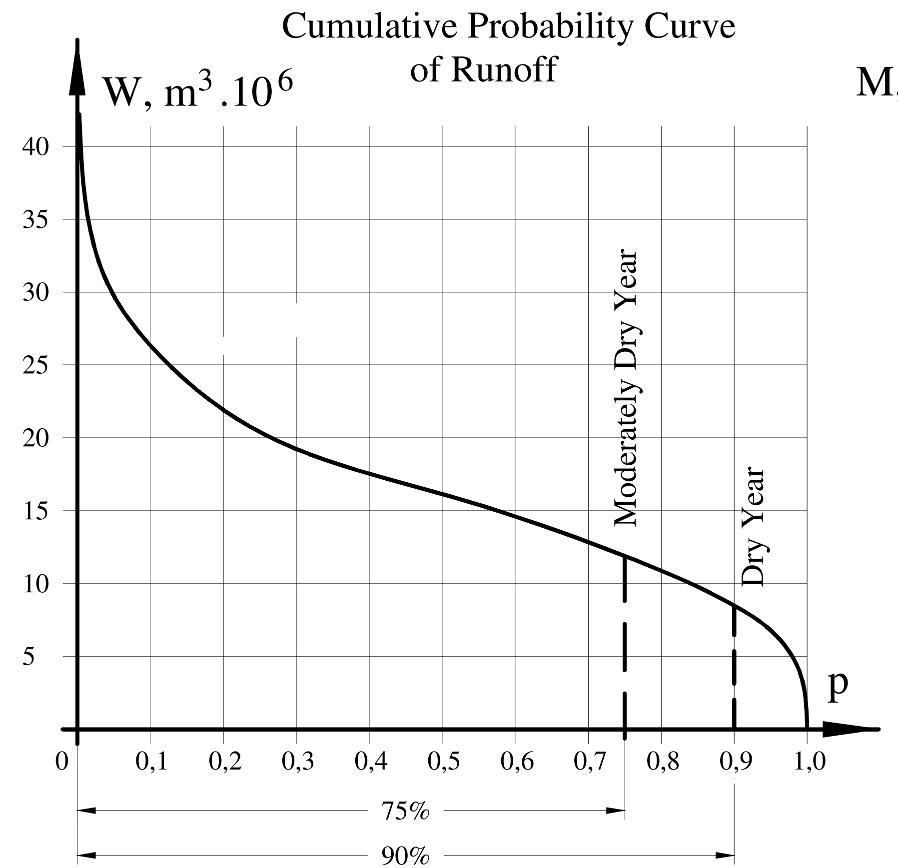


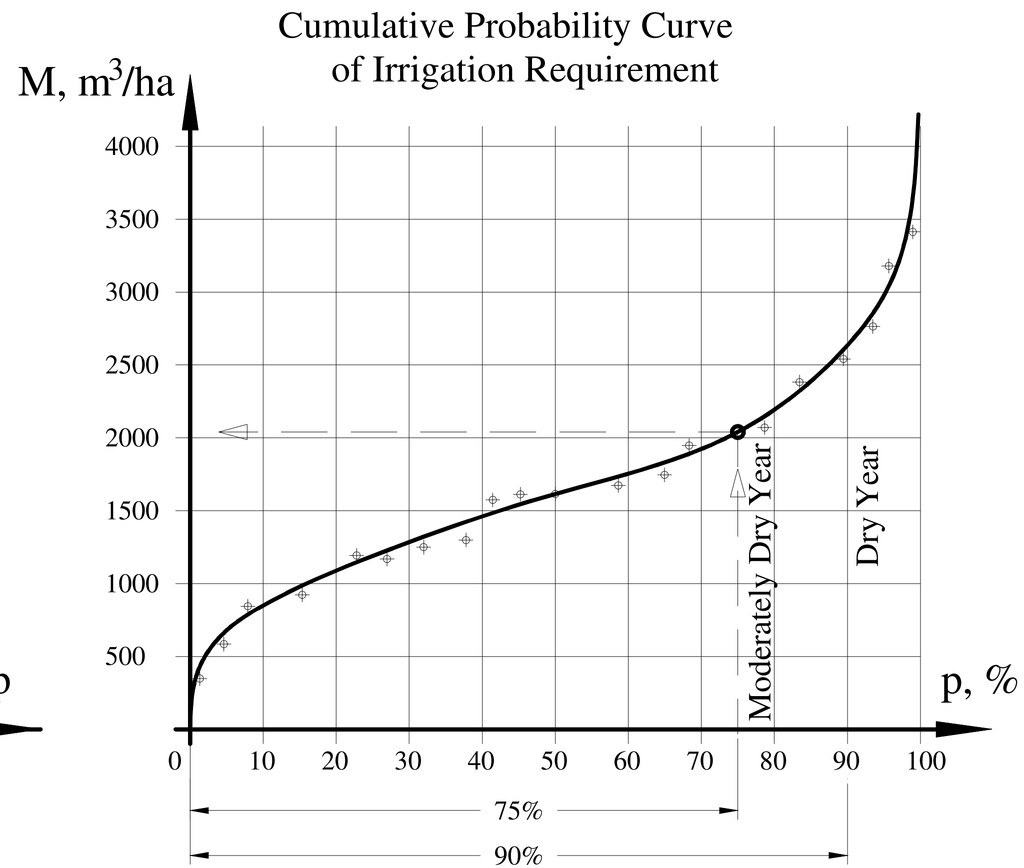
➢ This is what is happening in drip irrigation.

3. Determining Crop Water Requirements

3.2. Variation of Crop Water Requirements in Time

- The data for the Irrigation Requirement for series of years is processed and drawn as Cumulative Probability Curve.

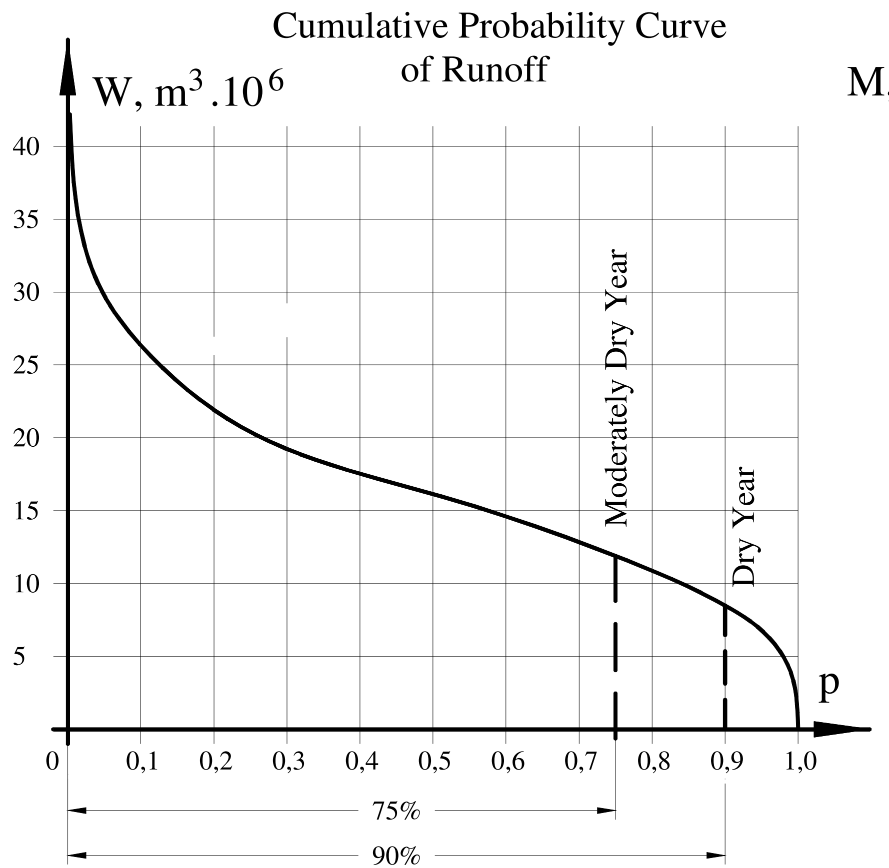


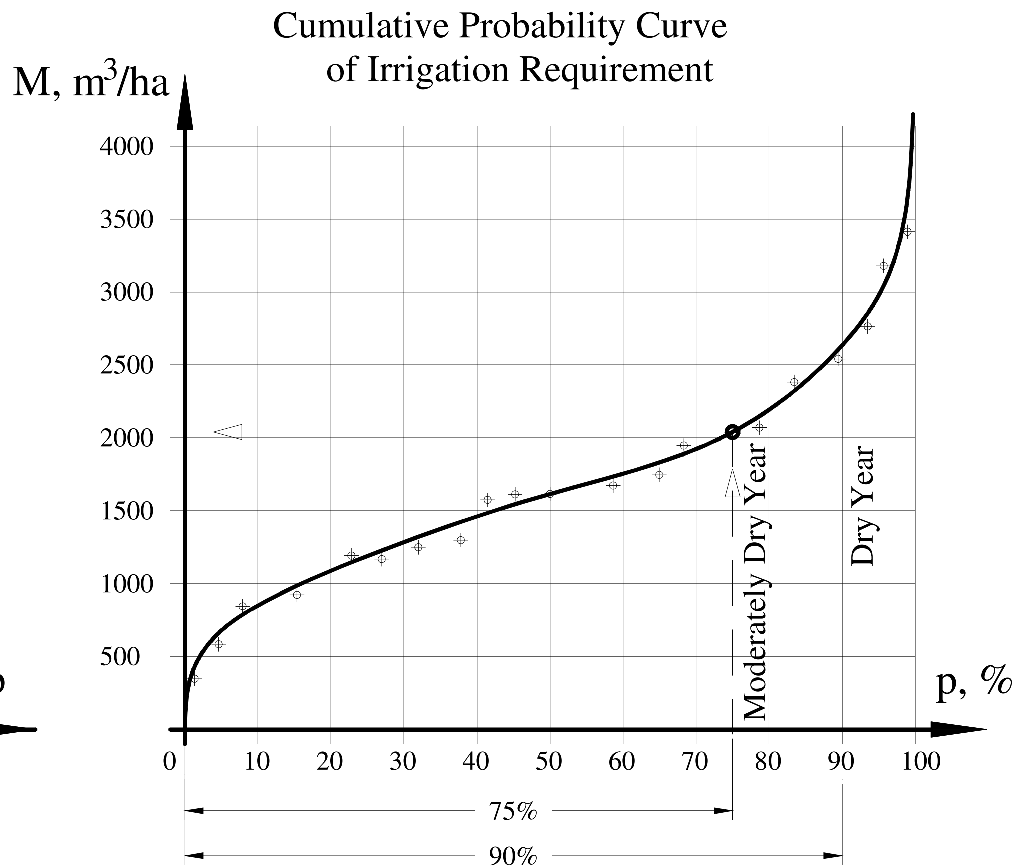


3. Determining Crop Water Requirements

3.2. Variation of Crop Water Requirements in Time

- Cumulative probability for Irrigation Requirement – probability not to surpass a given value.





4. Deficit Irrigation Scheduling

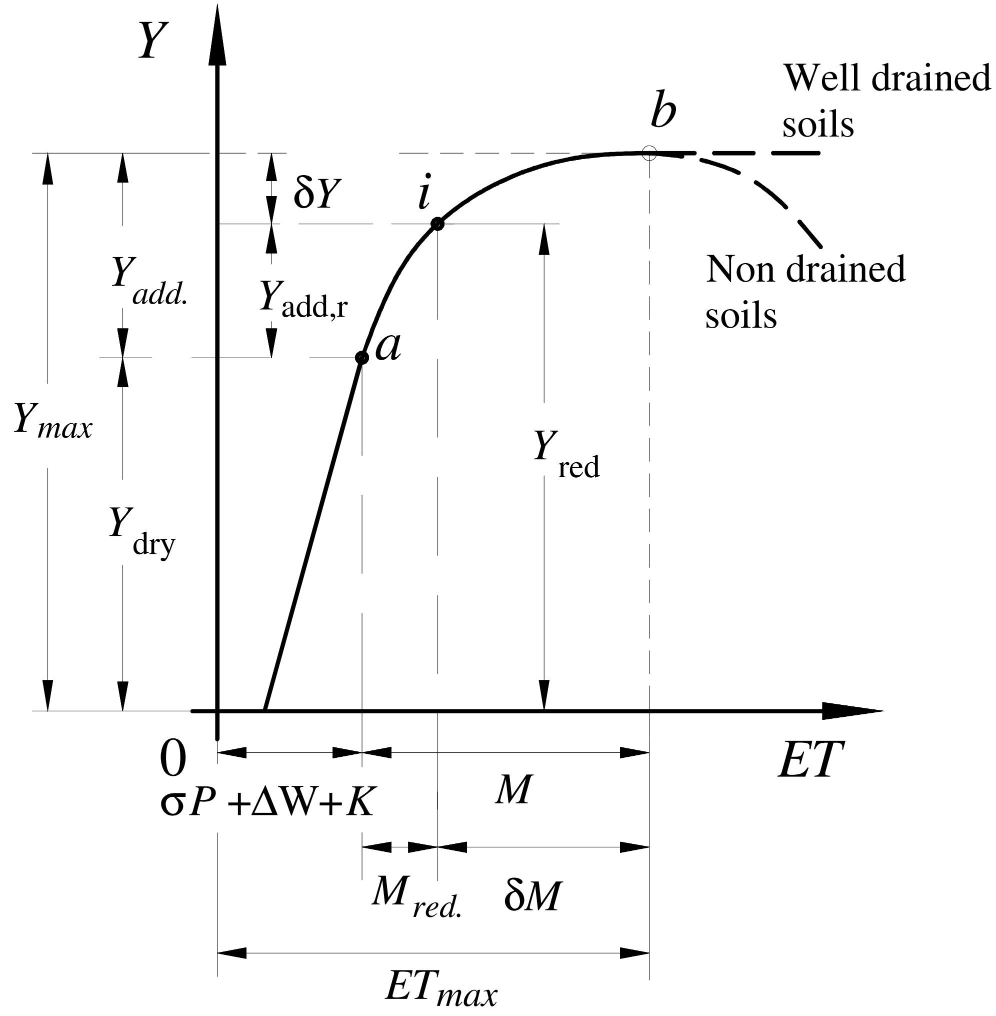
- **Deficit Irrigation Scheduling** – when there is not enough water to meet the crop requirements during the crop period
  - ➢ recently called ***water stress***
- Reasons:
  - ➢ Not well secured water source
    - ✓ insufficient volume (runoff) W - in Regulated Runoff IS;
    - ✓ insufficient flow rate Q - in Run-of-the-River IS.
  - ➢ Extremely hot year – low capacity of delivery network of IS or distribution network of IF.
  - ➢ Bad flow regulation in IS delivery network
  - ➢ Breakdowns or malfunctions of IS delivery network

4. Deficit Irrigation Scheduling

- The IS operates in water shortage conditions during some years of its exploitation
  - ➢ Acc. to Bulgarian Standards IS is designed for moderately dry year, i.e. security of irrigation requirement $p = 75\%$;
    - ✓ On average - in 1 out of 4 years IS will operate in water shortage conditions.
    - ✓ On average - in 3 out of 4 years IS will be capable to deliver requested irrigation requirements.
- For the farmers it is essential to know how the crops respond to water and what is the effect on yield in case of water deficit
    - ✓ The "Yield – Water" relationship provides needed information

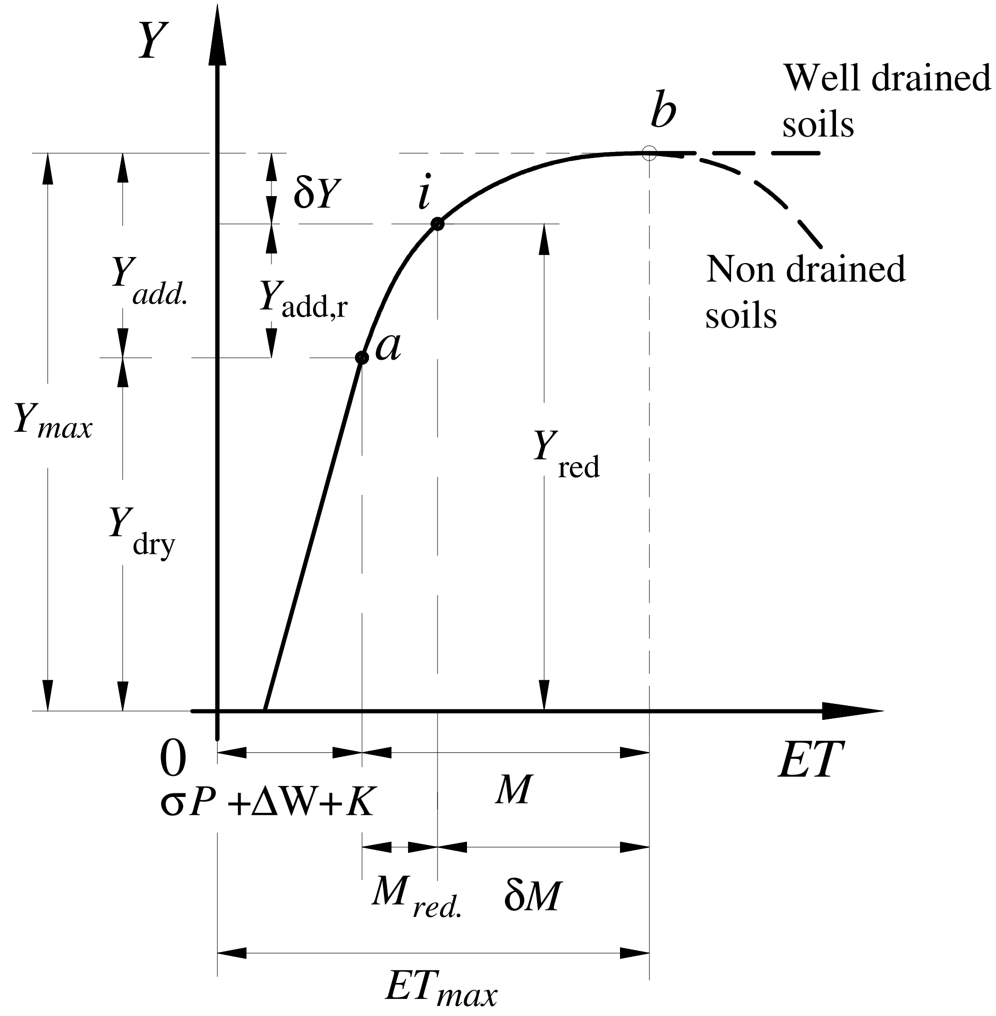
5. Yield – Water Relationship

- **Yield – Evapotranspiration in absolute terms**
  - ➢ Usefull for a good understanding of the idea,
  - ➢ Not exact and commonly used.
  - ➢ On *x* axis - ET includes the natural water sources $\sigma P + \Delta W + K$ and irrigation requirement M.
  - ➢ On *y* axis - the maximum value of the yield Y_{max} corresponds to $ET_{\max} = \sigma P + \Delta W + K + M$. (***point b***)
  - ➢ ***Point a*** – represents the max. yield in dry (rainfed) conditions.



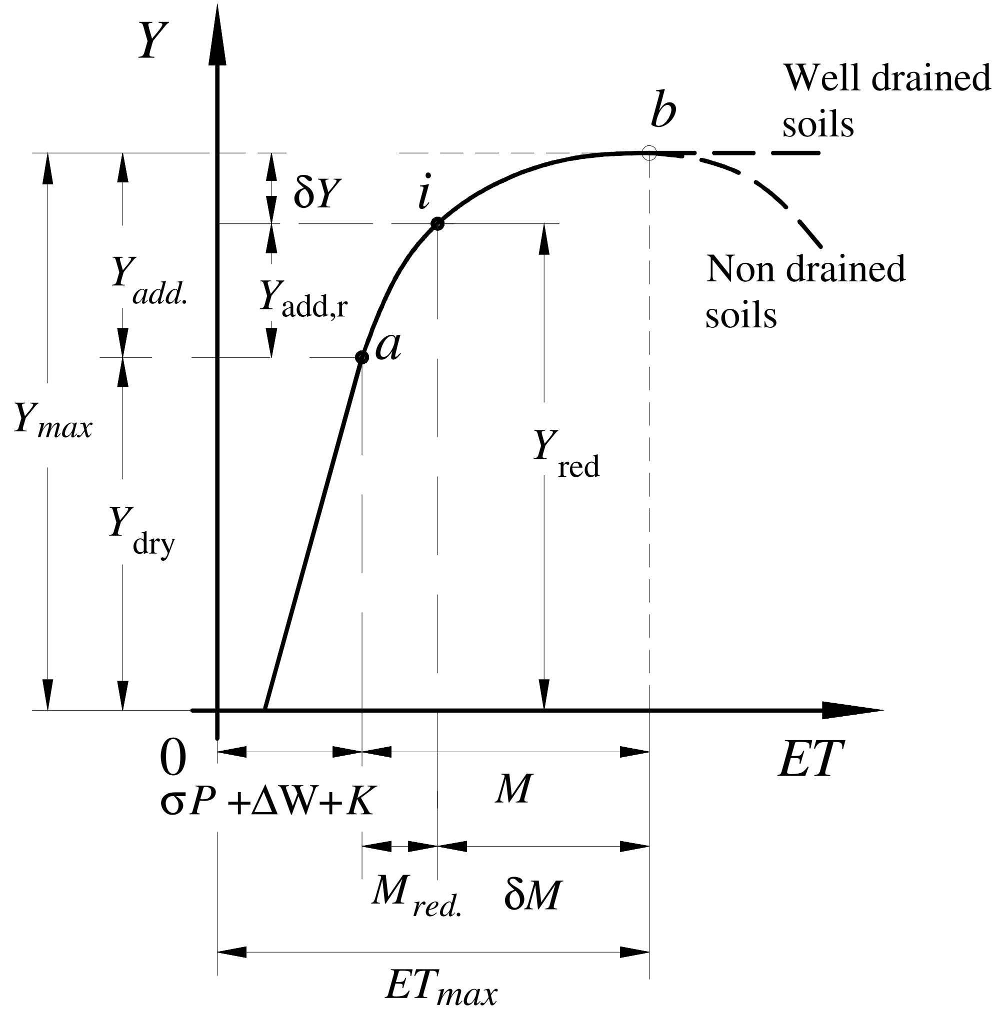
5. Yield – Water Relationship

- **Yield – Evapotranspiration in absolute terms**
  - Below ***point a*** the line is straight one (linear function).
  - Above the ***point a*** is the additional yield Y_{add} due to irrigation (due to M).
  - Some scientist claim that after ***point b*** the *Yield –ET* relationship declines, if the soils are not well drained and remains horizontal line if they are well drained.
  - Other scientist claim that in any case the excess (surplus) water leads to yield decrease.



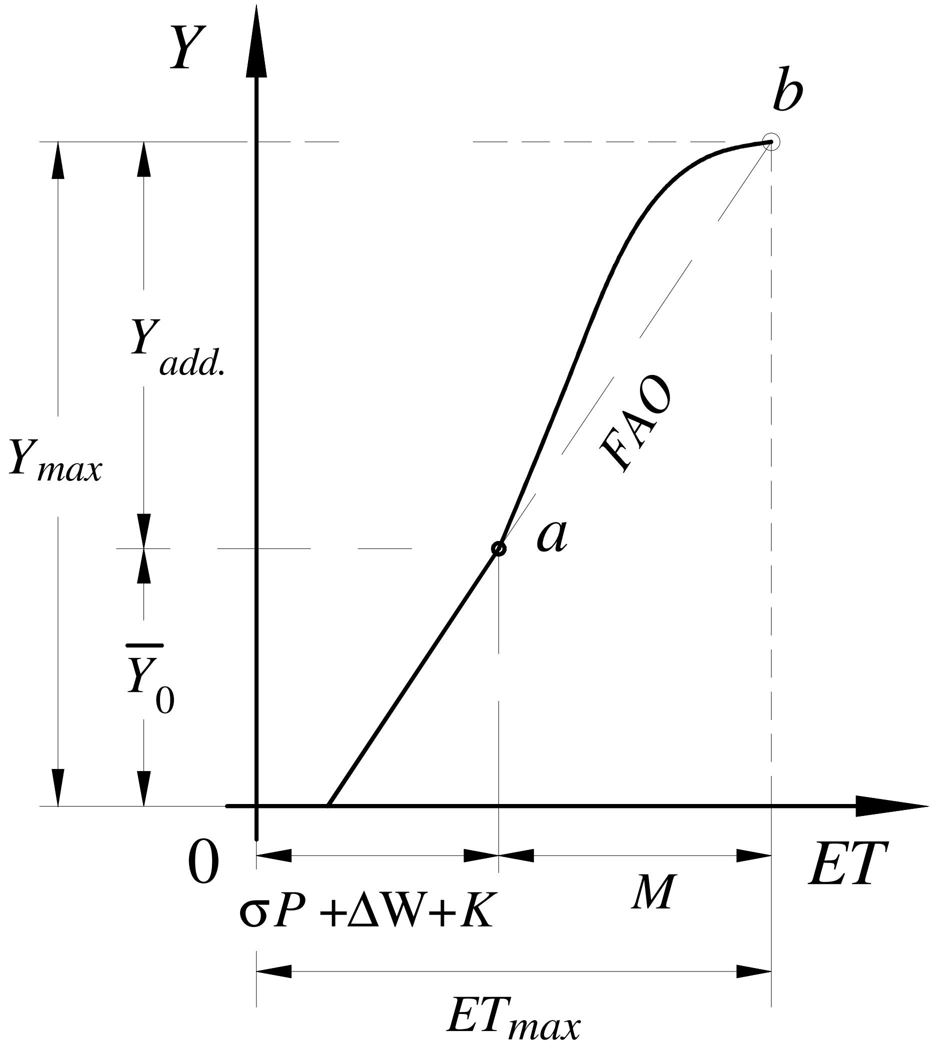
5. Yield – Water Relationship

- **Yield – Evapotranspiration in absolute terms**
  - ***Point i*** represents an example case of water shortage. If the decrease of irrig. requirement is δM, then it is read from the curve the yield decrease δM.
  - $Y_{add,r}$ is will be reduced additional yield in that case.
  - Y_{red} is the reduced absolute yield in the same case.
  - The effect of irrigation decreases near ***point b*** – the yield increment is almost zero!
  - Vice-versa – near ***point b*** water reduction is almost without effect.



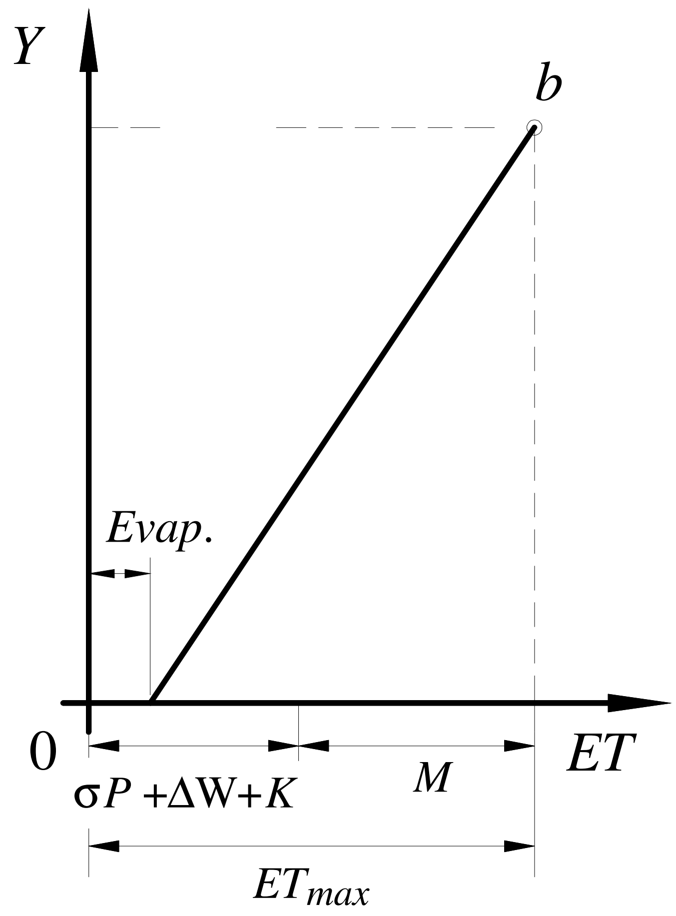
5. Yield – Water Relationship

- **Yield – Evapotranspiration in absolute terms**
  - Some scientist claim that at ***Point a*** there is a bend
  - This is effect from irrigation – the yield increases more rapidly when irrigation appear.
  - Others (like FAO) claim that *Y- ET* relationship is not a curved line, but a **straight line** (see the dashed line right).
  - In any case the *Y-ET* relationship does not pass through the origin of the coordinate system – ***point* 0**.



5. Yield – Water Relationship

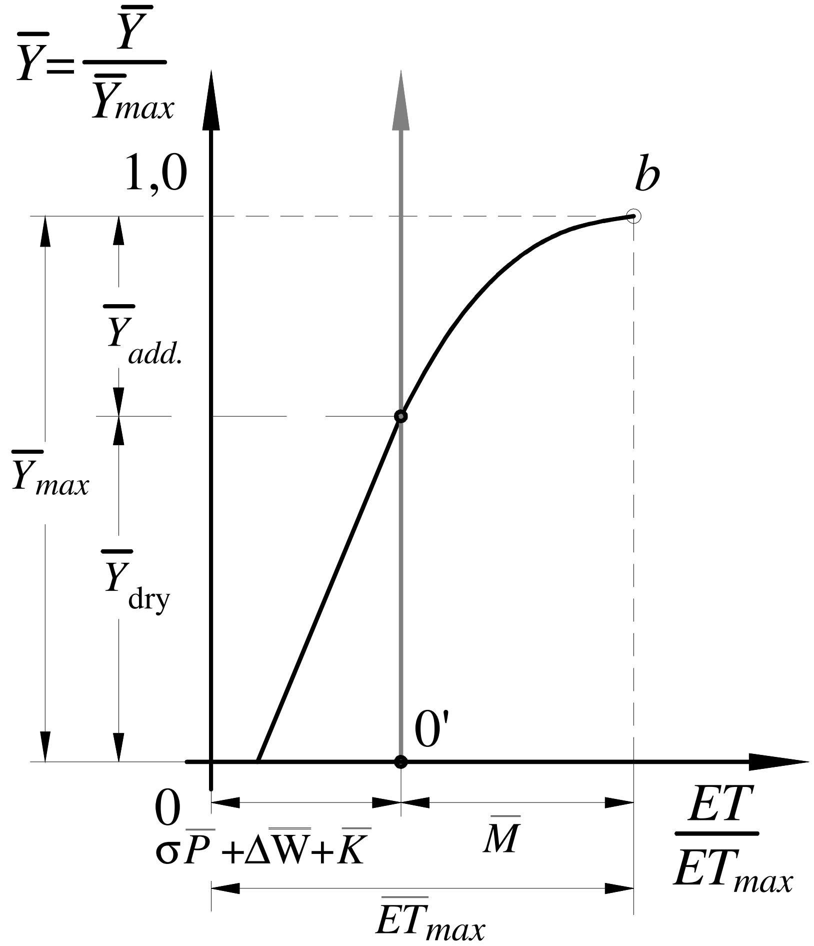
- **Yield – Evapotranspiration in absolute terms**
  - ➢ The *Y*- *ET* relationship does not pass through the origin 0, because there is evaporation from the soil surface even without a crop.
  - ➢ Thus, the section marked with *Evap*. (see right) is the evaporation.
  - ➢ The *Y* – *ET* relationship in absolute terms is not usable, because in different years, different part of natural inflow ($\sigma P + \Delta W + K$) will occur .



5. Yield – Water Relationship

- **Yield – Evapotranspiration in relative terms**
  - When plotted on *x* axis relative ET and on *y* axis relative yield, then the relationship becomes "more stable".
  - ET_{max} and Y_{max} are maximum observed (on a long term basis) ET an Yield.
  - Even in that case, FAO claims that the relationship is a straight line, but in Bulgaria it is established via experiments that after the ***point a*** there is a curve or the whole relationship is a curved line.

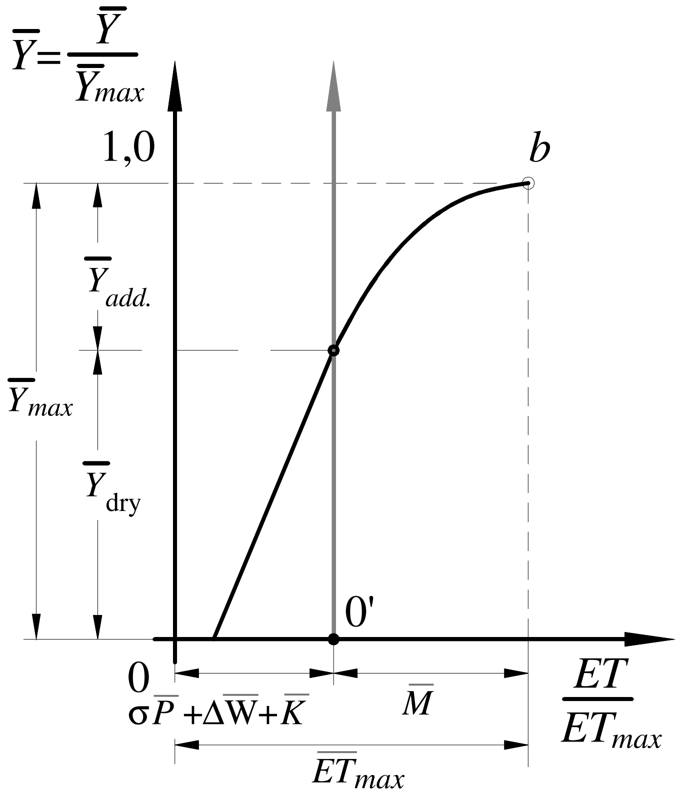
Yield - ET Relationship



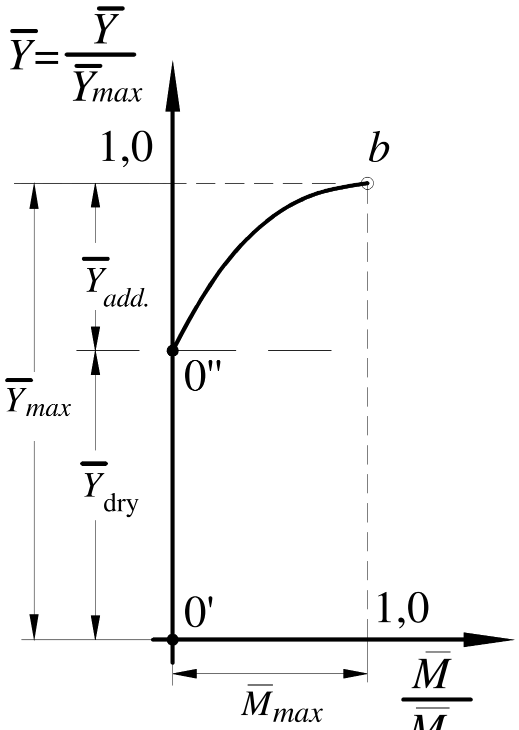
5. Yield – Water Relationship

- **Other expressions**
  - ➢ If the origin of the coordinate system is moved in such a way that *y* axis crosses ***point a***, then the relationship Yield-Irrigation Requirement is established.
  - ➢ If the origin of the coordinate system is moved to point a, then the relationship Additional Yield-Irrigation Requirement is established.

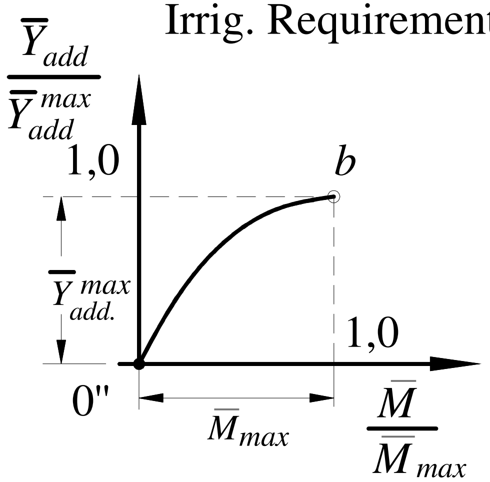
Yield - ET Relationship



Yield - Irrig. Requirement



Additional Yield vs.
Irrig. Requirement



5. Yield – Water Relationship

- **Some formulae**
  - **Yield – Evapotranspiration in relative terms**
  - FAO

$$\frac{Y}{Y_{max}} = 1 - k_Y \left(1 - \frac{ET}{ET_{max}}\right)$$

where Y is estimated yield in a year in which a value of ET is observed;

k_Y – is the yield response factor.

If $k_Y > 1$, then the crop is sensitive to water stress (deficit)

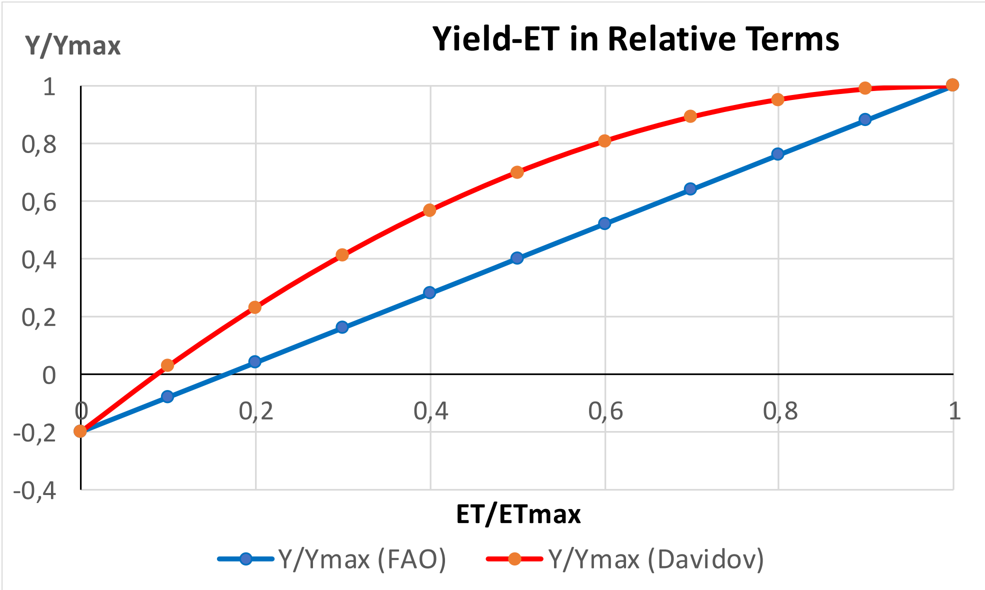
If $k_Y < 1$, then the crop is more tolerant to water shortage

- Davidov (Bulgaria)

$$\frac{Y}{Y_{\max}} = 1 - k_Y \left(1 - \frac{ET}{ET_{\max}}\right)^n$$

all notation is as in FAO formula;

the power factor n is a subject of adjustment depending on the observed data. It can very between 1 and 2, so *this is non-linear function!*



5. Yield – Water Relationship

- **Some formulae**
  - **Yield – Irrigation requirement in relative terms**
  - Vurlev (Bulgaria)

$$y = 1 - (1 - y_{dry})(1 - x)^2$$

where y = Y/Y_{max}, $y_{dry} = Y_{dry}/Y_{max}$,
$x = M/M_{max}$;

  - Davidov (Bulgaria)

$$y = 1 - (1 - y_{dry})(1 - x)^n$$

where y = Y/Y_{max}, $y_{dry} = Y_{dry}/Y_{max}$,
$x = M/M_{max}$;

n = 1.2 – 2.0 is subject to adjustment

- **Additional Yield vs. Irrigation requirement in relative terms**
- Davidov (Bulgaria)

$$\Delta y = 1 - (1 - x)^n$$

$\Delta y = Y_{add}/Y_{add}^{max}$;

$x = M/M_{max}$;

n = 1.0 – 2.0 is subject to adjustment

5. Yield – Water Relationship

- The Yield-Water relationship is not an universal tool
- The Yield-Water relationship is relative (dependable):
  - ➢ When fertilizer application is increased, the Yield increases for the same amount of water applied
  - ➢ Not always the maximum quantity (yield) matches the maximum quality
    - ✓ Examples – Grape, Sugar beet.
- The Yield-Water relationship does not take into account the crop specifics in different growth stages
  - ➢ In different growth stages the crops react to deficit differently
    - ✓ usually in the first and last stage crops are more tolerant to water stress (deficit).