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Simulation-Optimization Model of a Multi-Purpose Reservoir for Water Allocation and Irrigation Scheduling Under Diverse Hydrological Conditions

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Motivation

The main objectives:

- Determining the optimal operating rule curves to meet municipal, environmental and agricultural demands under various hydrological conditions
- Optimizing the cropping pattern
- Optimizing full irrigation scheduling
- Optimizing deficit irrigation scheduling

Model Formulation

Start

Read Database File

Meteorological Sub-Model

Create the matrices of meteorological factors time series:

- Maximum and Minimum Air Temperatures
- Maximum and Minimum Relative Humidity
- Atmospheric Pressure
- Actual Duration of Sunshine
- Wind Speed

Calculate daily reference evapotranspiration

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$ (Allen et al, 1998)

ET_0: reference evapotranspiration (mm day^{-1})
R_n: net radiation at the crop surface (MJ m^{-2} day^{-1})
G : soil heat flux density (MJ m^{-2} day^{-1})
T : mean daily air temperature at 2 m height (°C)
u_2 : wind speed at 2 m height (m s^{-1})
e_s : saturation vapor pressure (kPa)
e_a : actual vapor pressure (kPa)
$e_s - e_a$: saturation vapor pressure deficit (kPa)
Δ : slope vapor pressure curve (kPa °C^{-1})
γ : psychrometric constant (kPa °C^{-1})

Hydrological Sub-Model

Synchronize time series of reservoir inflow, rainfall and evaporation from water surface

Determine appropriate PDFs for hydrological variables

Select hydrological condition:
- Dry
- Normal
- Wet

Estimate hydrological parameters

Hydrological Condition	Probability Level of Exceedence		
	Evapotranspiration (%)	Rainfall (%)	Inflow (%)
Dry	40	80	80
Normal	50	50	50
Wet	60	20	20

(Georgiou & Papamichail, 2008)

Model Formulation

Demand Sub-Model

Agricultural demand

Calculate potential evapotranspiration

$$ET_{ci} = K_{ci} \times ET_{0i}$$

K_{ci} : crop coefficient in each day
ET_{0i} : reference evapotranspiration in each day (mm day^{-1})

Estimate the effective root depth

$$Z_r = R_{DM}[0.5 + 0.5\sin(3.03\frac{D_{AS}}{D_{TM}} - 1.47)]$$

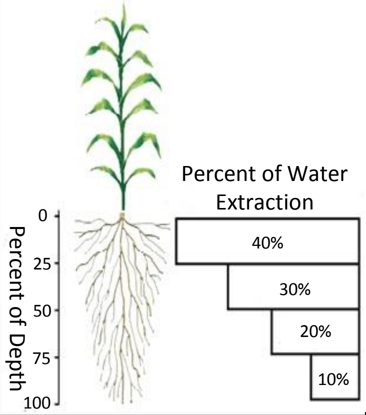
)Borg & Grimes, 1986)

Z_r : root depth (mm)
R_{DM} : maximum root depth (mm)
D_{AS} : time after planting (day)
D_{TM} : time from planting to reaching the maximum root depth (day)

Simulate root zone soil moisture

$$D_{i.l} = D_{i-1.l} - Dp_{i.l-1} + S_{i.l} \times ET_{ci} + Dp_{i.l}$$ (Shabani et al, 2014)

$D_{i.l}$: depleted soil water depth from lth layer of root zone for ith day (mm)
$D_{i-1.l}$: depleted soil water depth from lth layer of root zone at the end of previous day (mm)
$Dp_{i.l-1}$: depth of water entered each soil layer in day i from upper layer $(l-1)$ (mm)
$S_{i.l}$: relative root water uptake in no water stress conditions from lth layer of root zone for ith day (mm)
$Dp_{i.l}$: deep percolation from each soil layer in day i (mm)



Determine the date and net depth of irrigation

$$TAW = (\theta_{FC} - \theta_{PWP})Z_r$$

TAW : total soil available water (mm)
θ_{FC} : volumetric soil water content at field capacity (mm^3 mm^{-3})
θ_{PWP} : volumetric soil water content at permanent wilting point (mm^3 mm^{-3})

$$p = p_{Tab} + 0.04(5 - ET_c)$$

p : fraction of TAW which is readily available for crop use
p_{Tab} : standard value for p at ET_c of 5 mm d^{-1}, dimensionless

$$d_n = \sum_{l=1}^{n}(\theta_{FCl} - \theta_l) \times Dl$$

d_n : net irrigation water depth (mm)
Dl : thickness of each soil layer (mm)
n : number of soil layers

Simulate irrigation system

Border Irrigation

Furrow Irrigation

1- Hydrodynamic ✓
2- Zero-inertia
3- Kinematic-wave

.Continuity equation:

$$\frac{A\partial v}{\partial x} + \frac{Bv\partial y}{\partial x} + \frac{B\partial y}{\partial t} + I = 0$$

.Momentum equation:

$$\frac{1}{Ag}\frac{\partial Q}{\partial t} + \frac{2Q}{A^2 g}\frac{\partial Q}{\partial x} + (1 - \frac{Q^2 T}{A^3 g})\frac{\partial y}{\partial x} S_0 + S_f = 0$$

The end of the growing season? — No / Yes

Municipal demand

Calculate municipal demand based on:

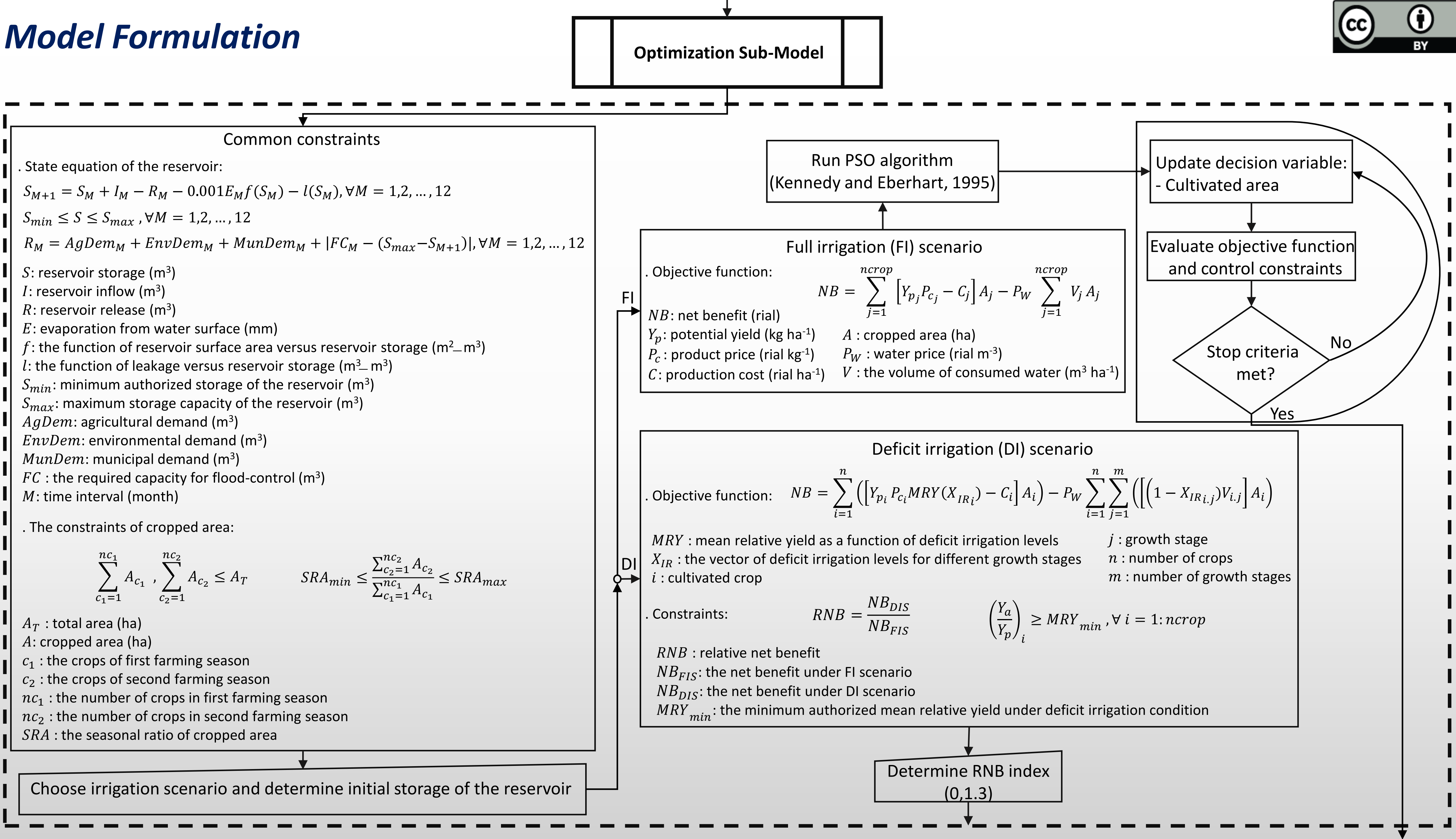
- Per capita water consumption
- Basic population
- Population growth rate

Environmental demand

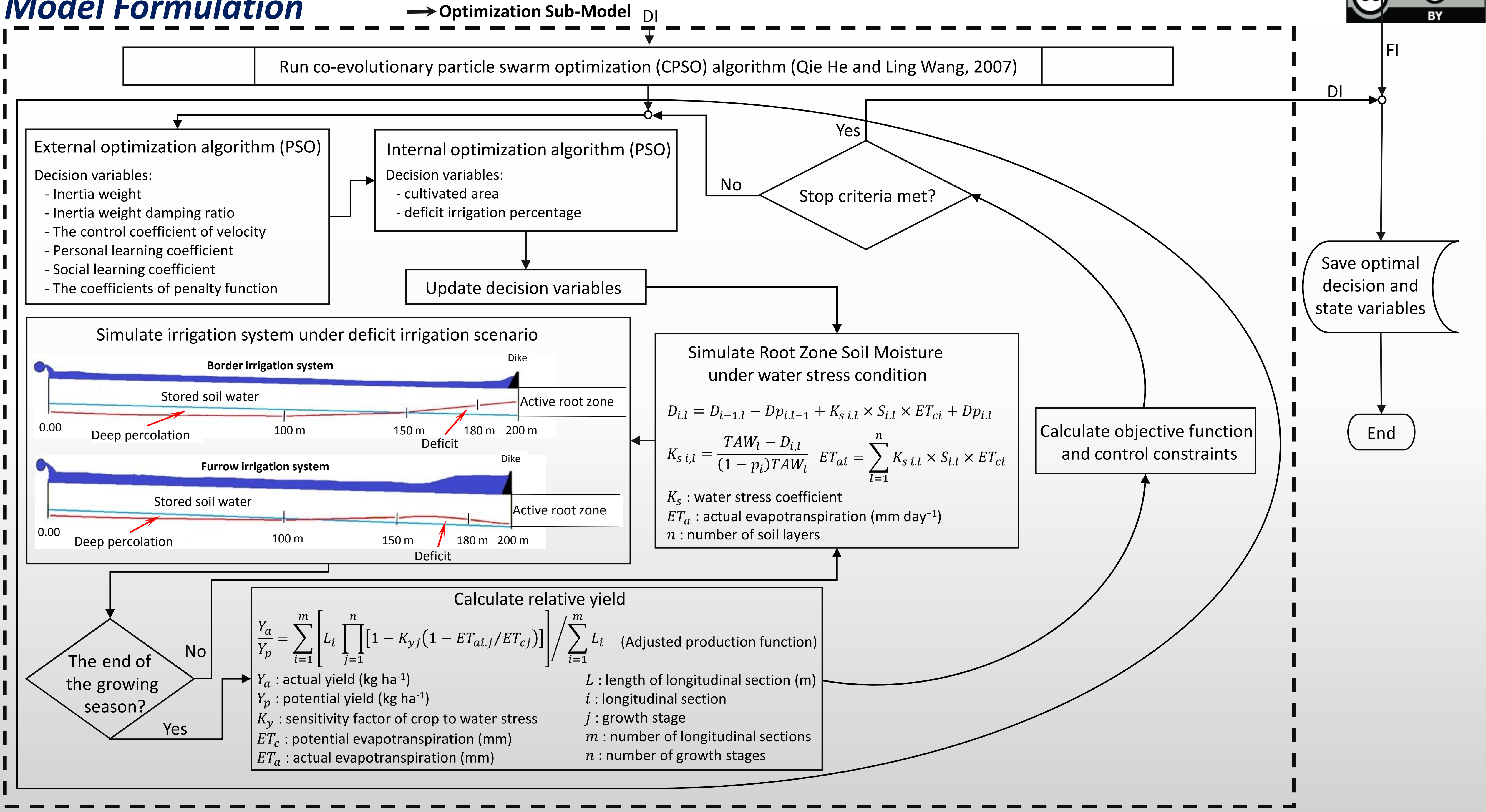
Calculate environmental demand:

Hydrological condition	Release (Percentage of monthly inflow)
Dry	30%
Normal	20%
Wet	10%

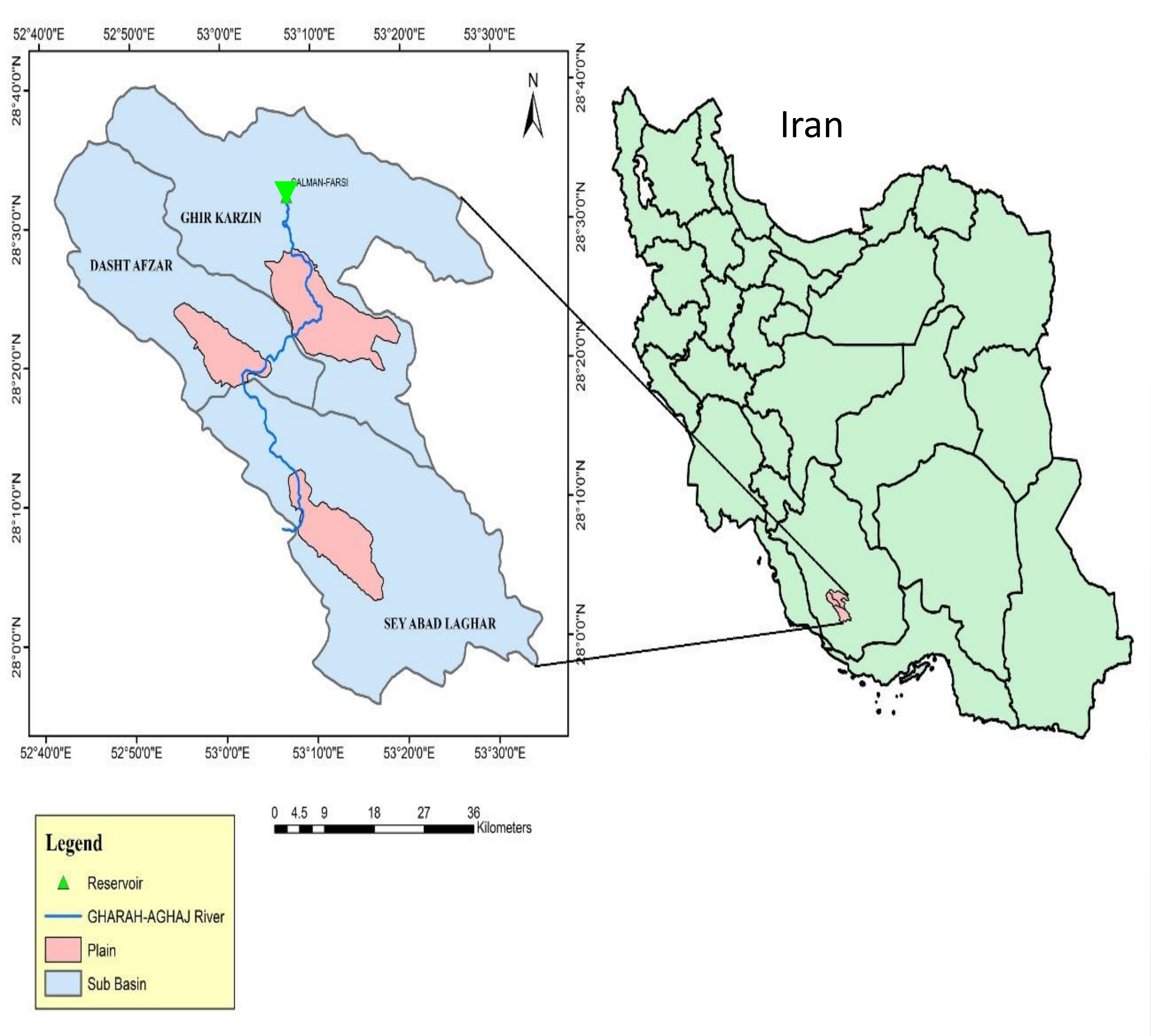
Model Formulation



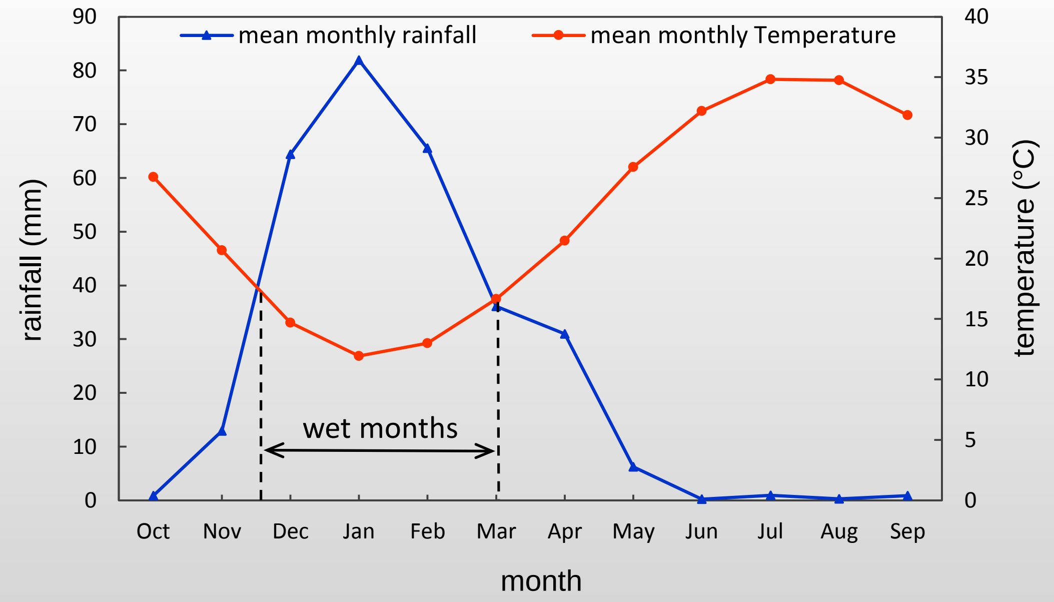
Model Formulation



Case Study



Total area: 22130 ha
Mean annual rainfall: 270 mm
Maximum temperature: 50 °C
Minimum temperature: -3 °C
Annual mean evaporation from water surface: 2089 mm
Annual average relative humidity: 53.4 %
Annual average sunshine hours: 3358 hr
Annual mean wind speed: 2.34 m s^{-1}



Case Study

Nominal capacity: 1400 MCM

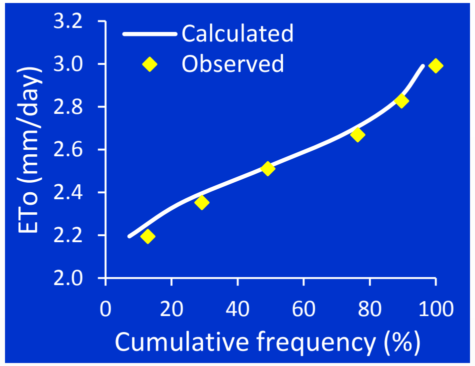
Active capacity: 1236 MCM

Flood control capacity: 100 MCM

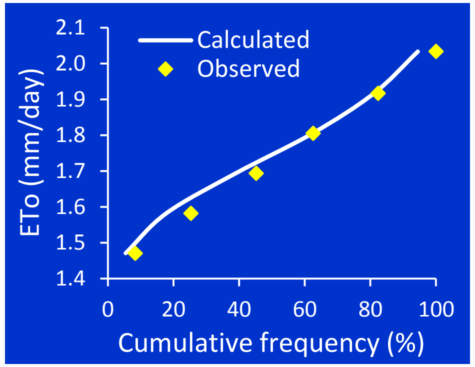
Mean annual inflow: 514 MCM

Results

The probability distribution of daily evapotranspiration:
Lognormal cumulative distribution function



5 Nov.



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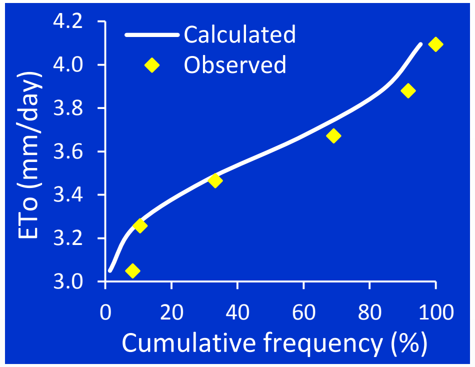
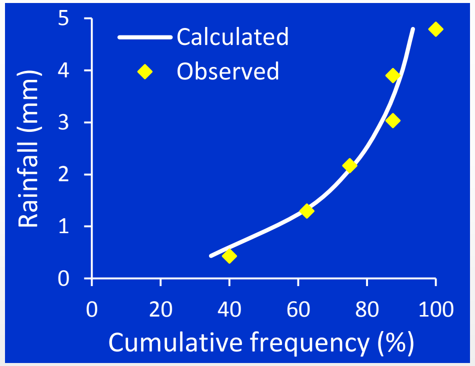
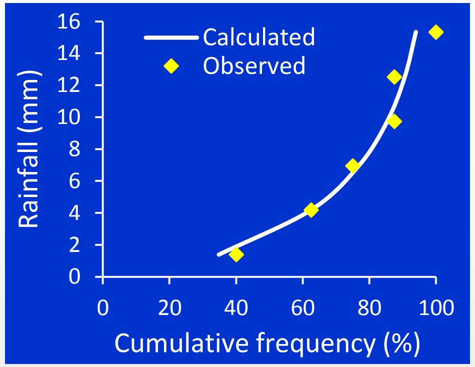


5 Mar.

The probability distribution of daily rainfall:
Gamma cumulative distribution function



15 Nov.



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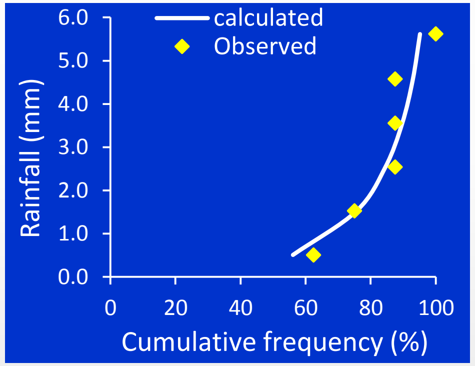
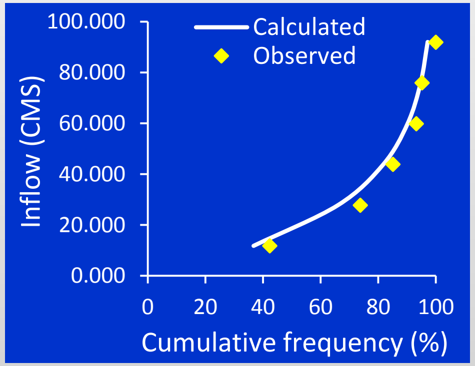
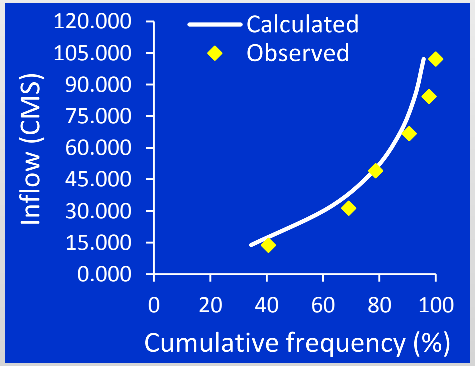


5 Apr.

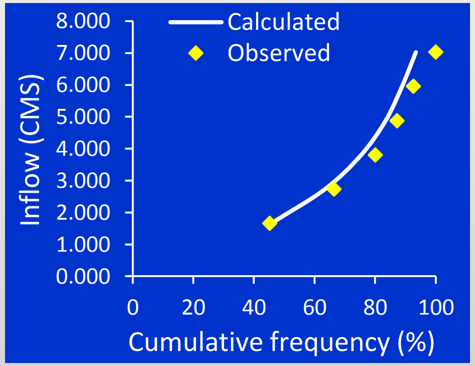
The probability distribution of monthly inflow:
Exponential cumulative distribution function



Jan.

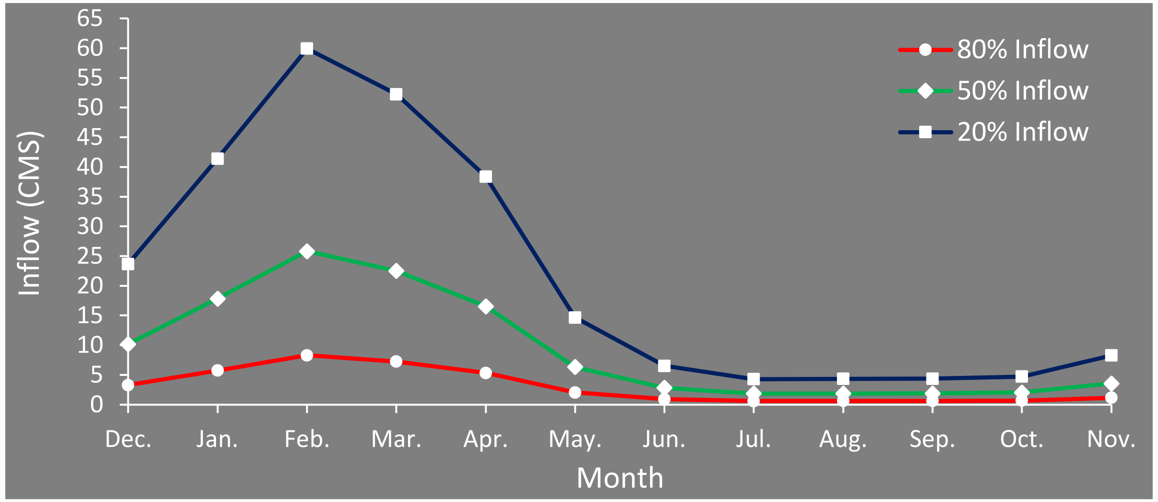


Mar.

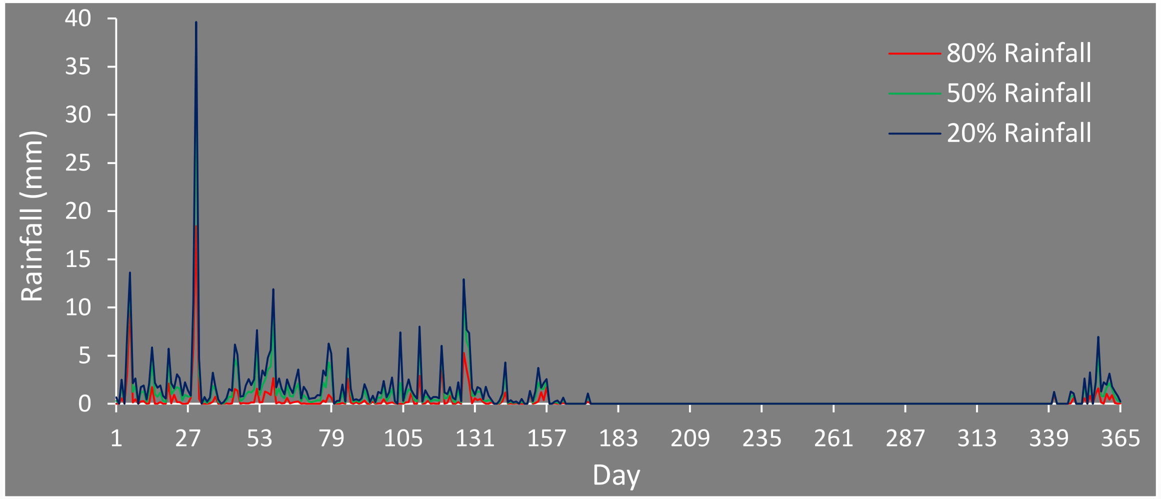


Sep.

Results

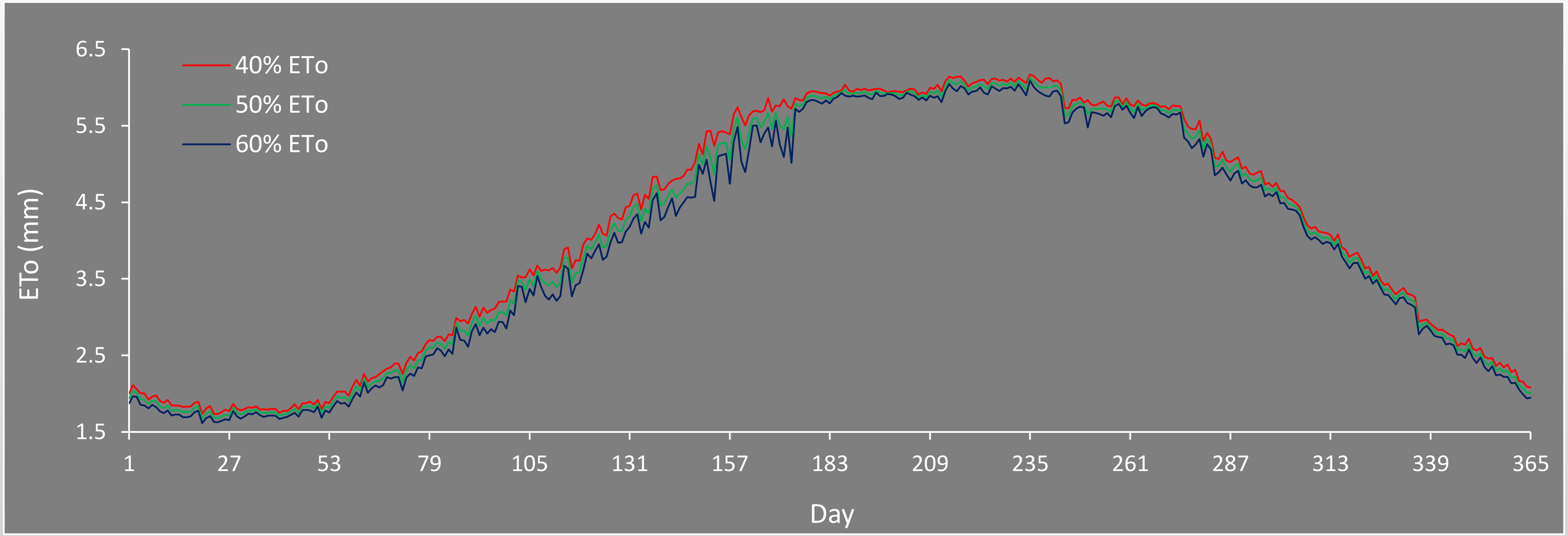


Monthly inflow levels with various probability levels (%) of exeedence



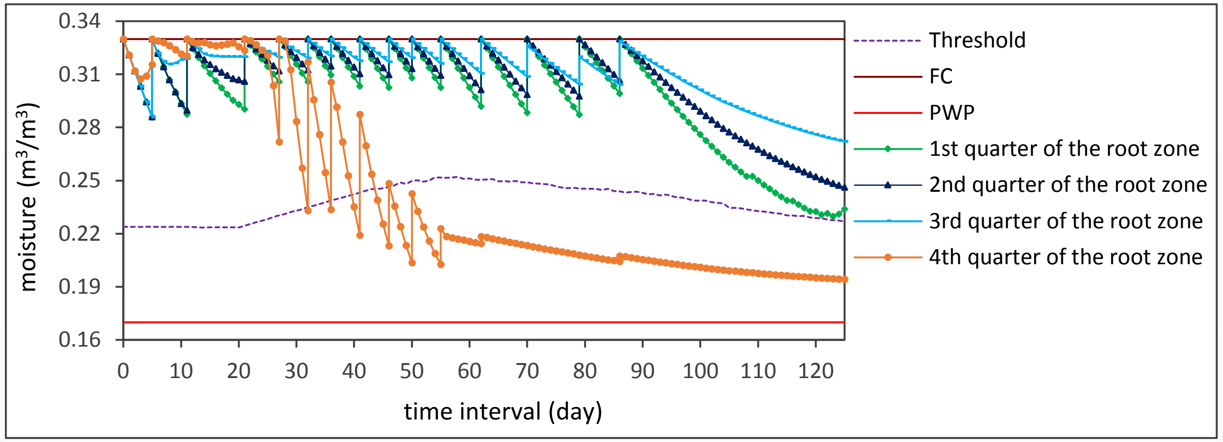
Daily rainfall levels with various probability levels (%) of exeedence

Daily reference evapotranspiration levels with various probability levels (%) of exeedence

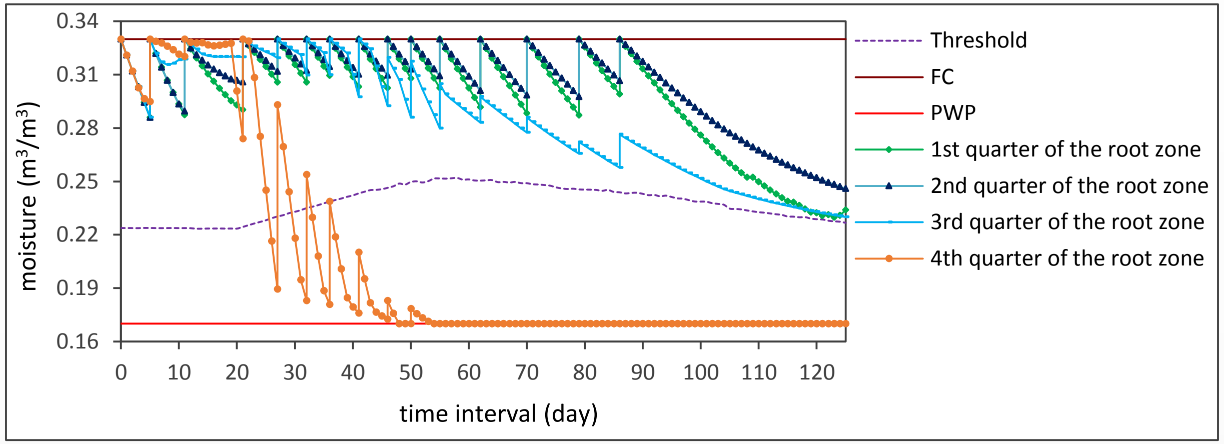


Results

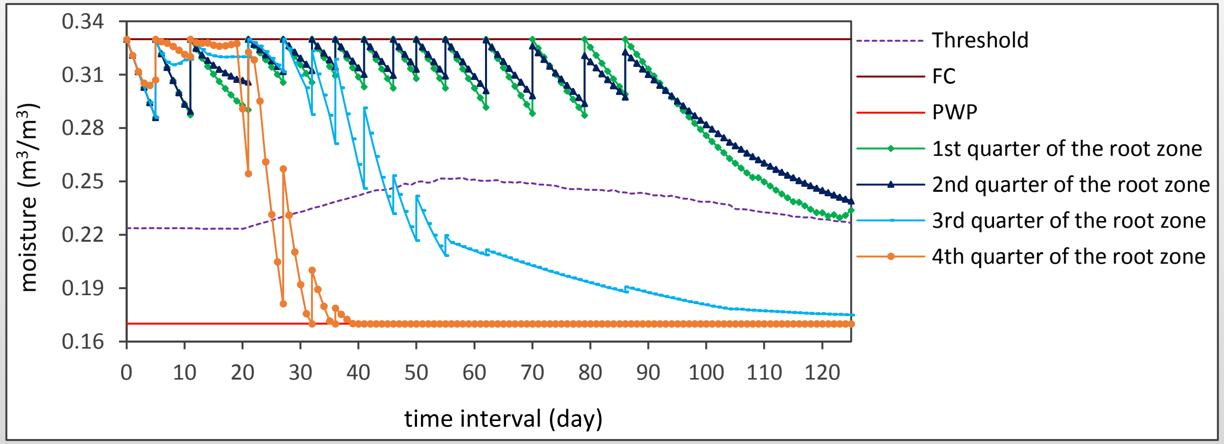
Simulated root zone soil moisture at the end of each time interval under DI scenario and dry hydrological condition for Maize



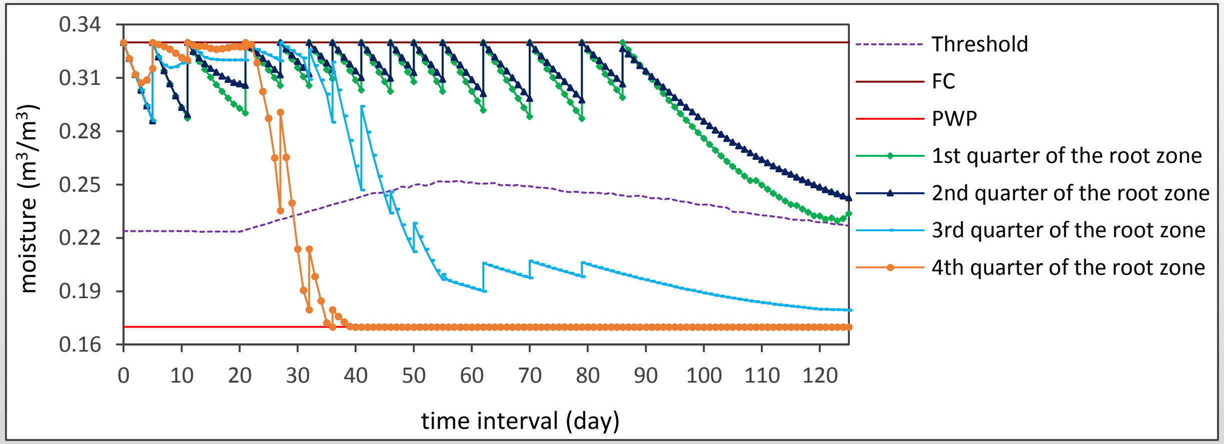
First longitudinal section (0-100 m)



Second longitudinal section (100-150 m)



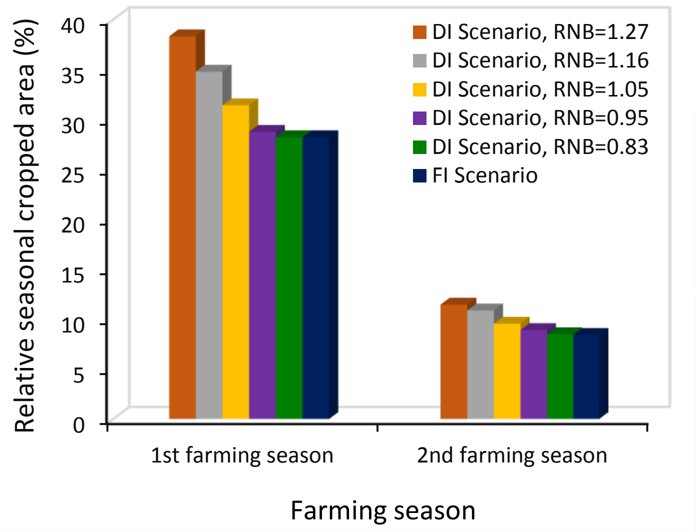
Third longitudinal section (150-180 m)

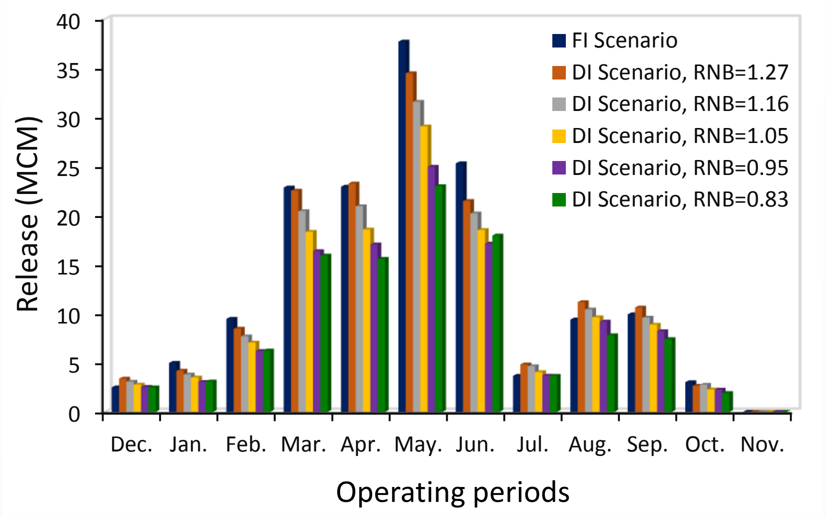


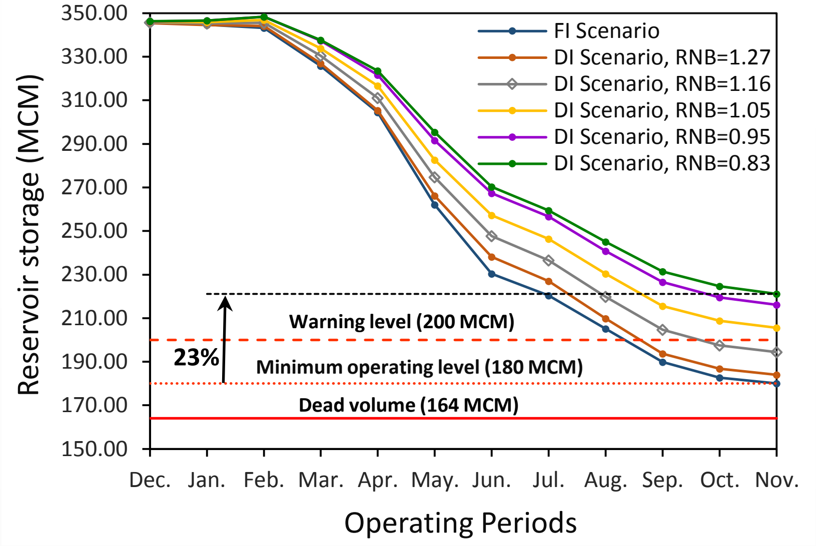
Fourth longitudinal section (180-200 m)

Results

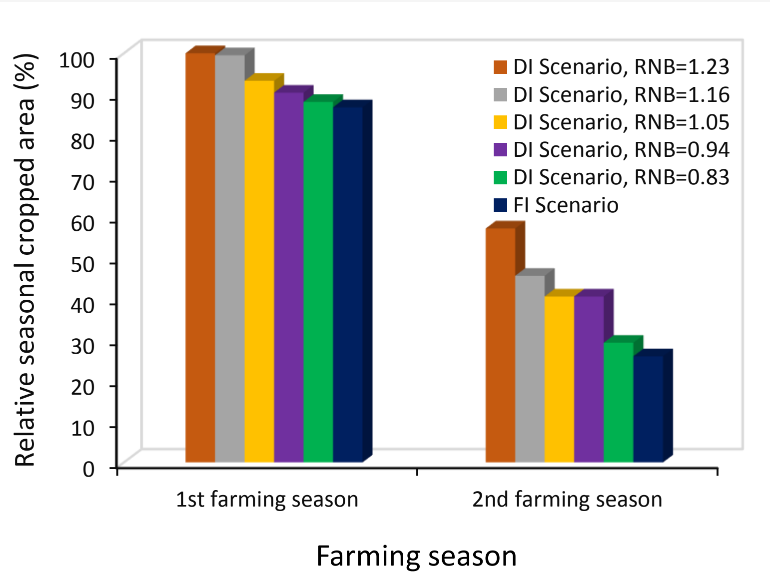
Hydrological condition: Dry — Initial storage: 25% of maximum capacity

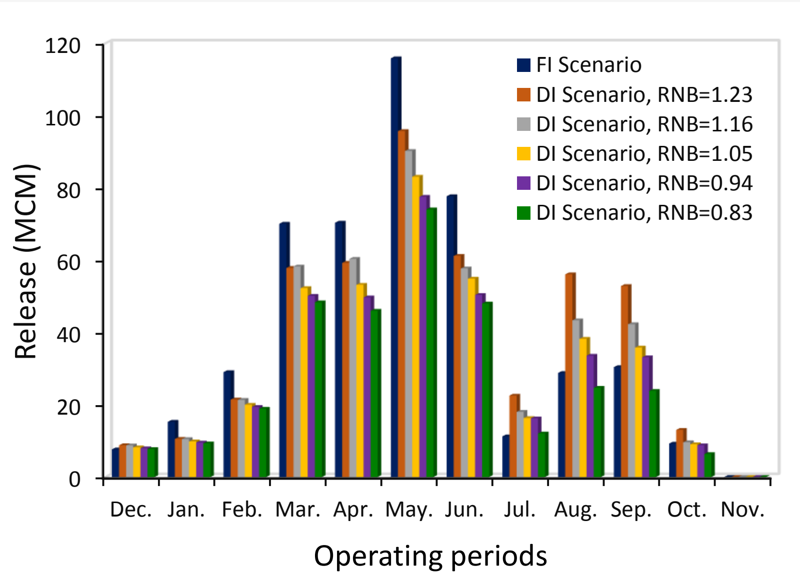


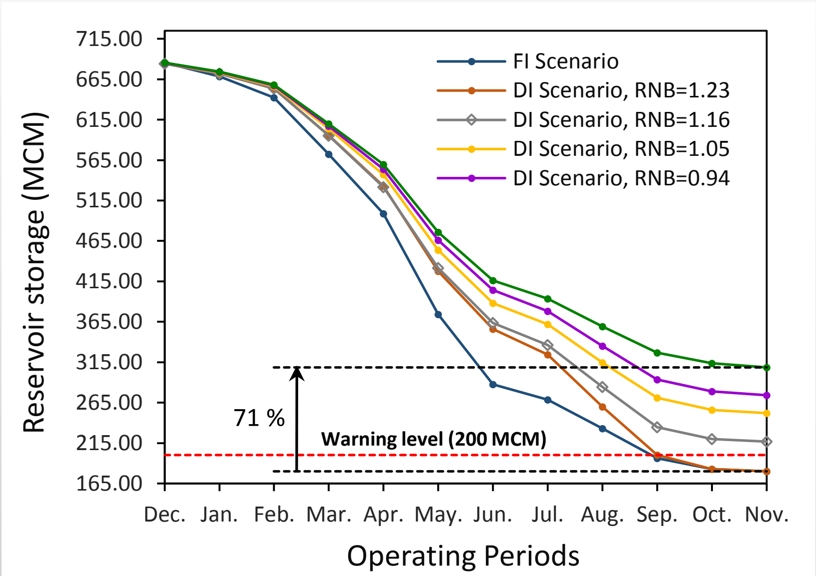




Hydrological condition: Dry — Initial storage: 50% of maximum capacity

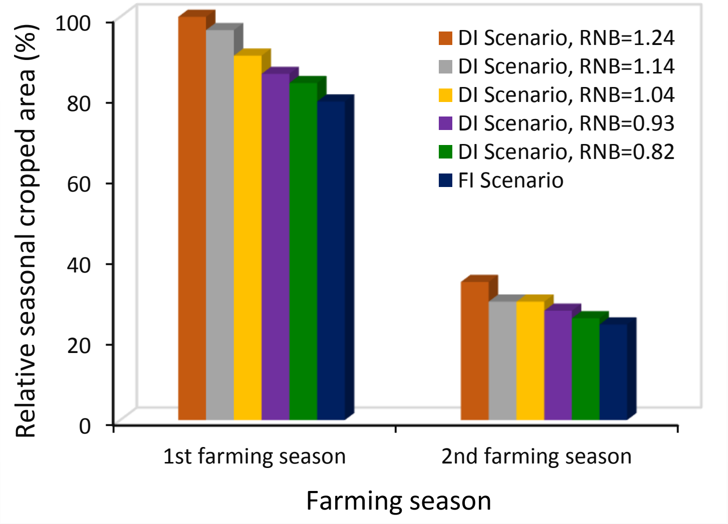


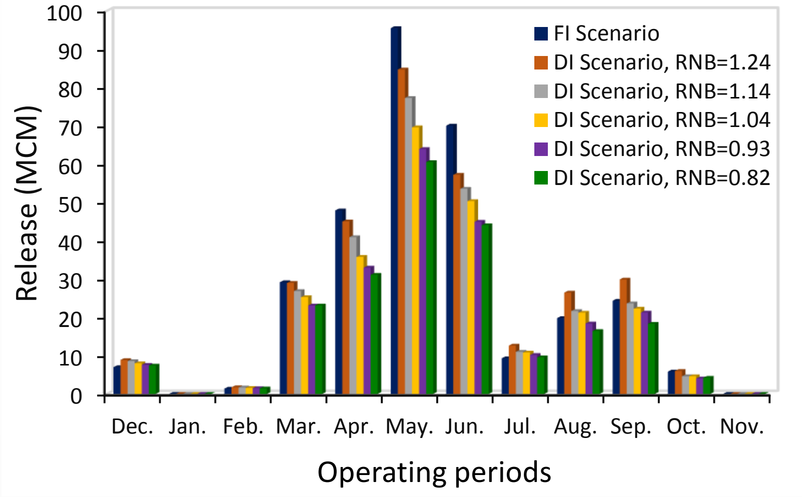


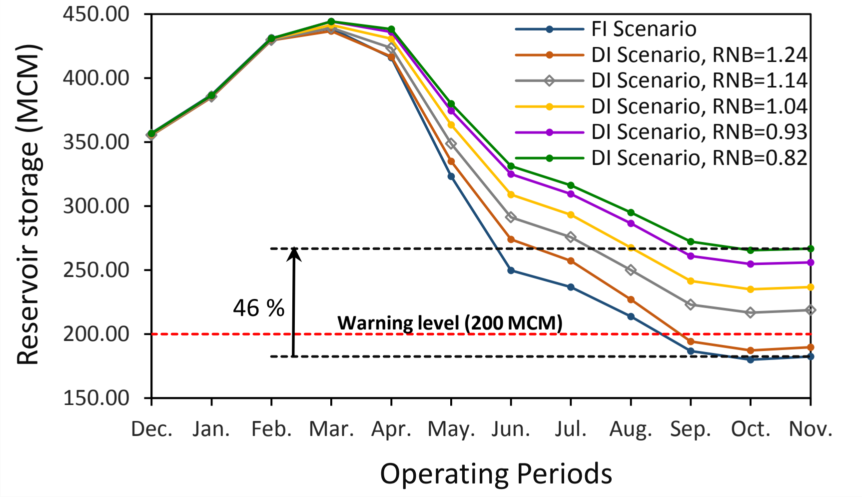


Results

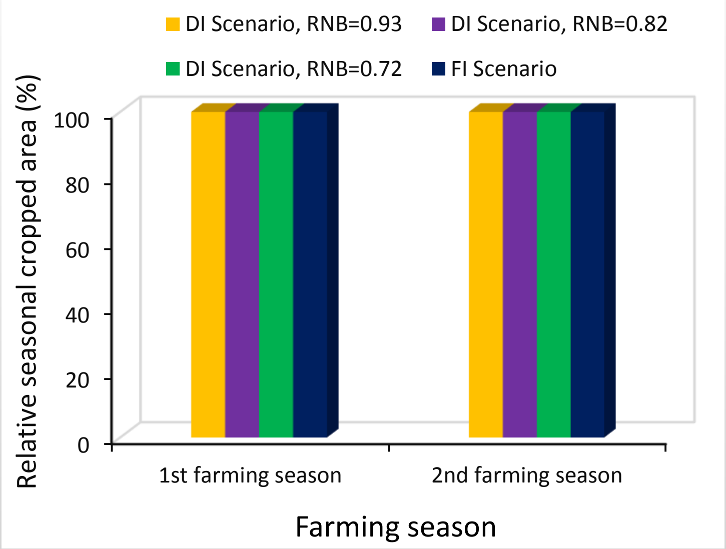
Hydrological condition: Normal Initial storage: 25% of maximum capacity

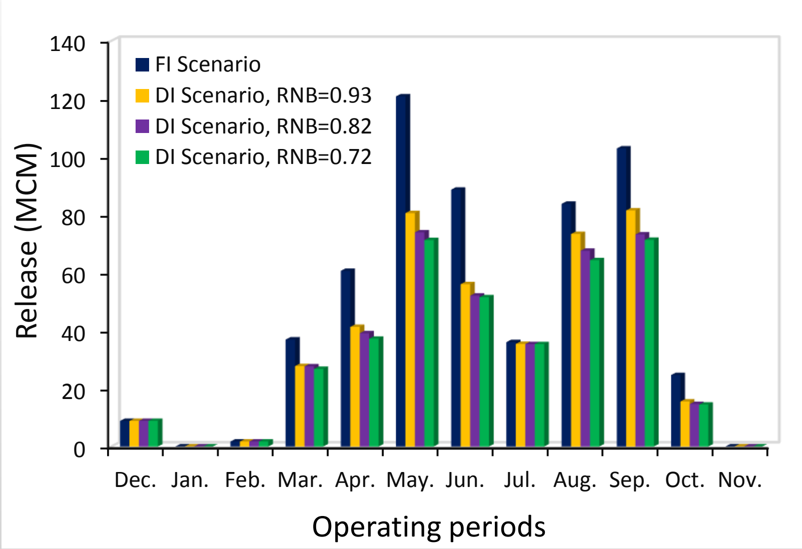


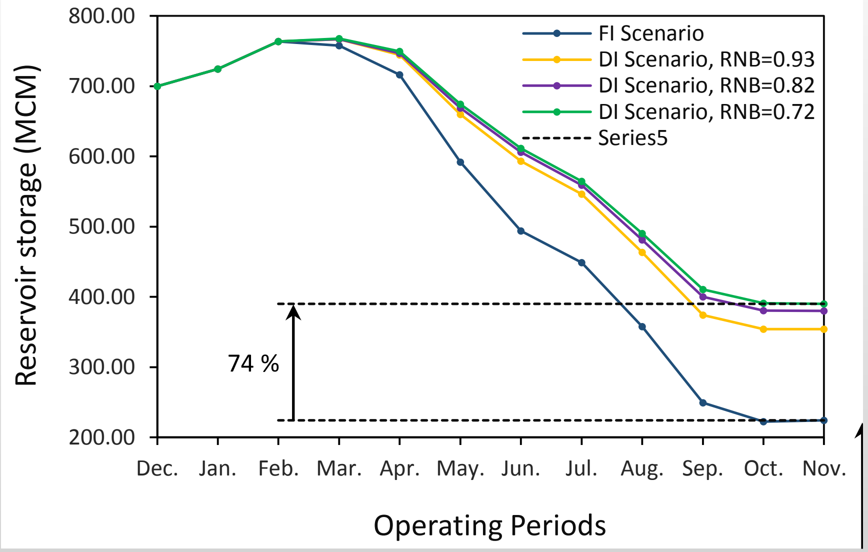




Hydrological condition: Normal Initial storage: 50% of maximum capacity

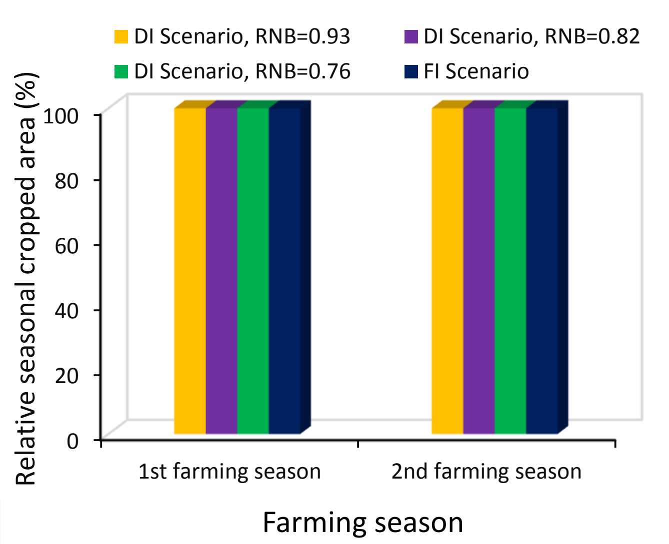


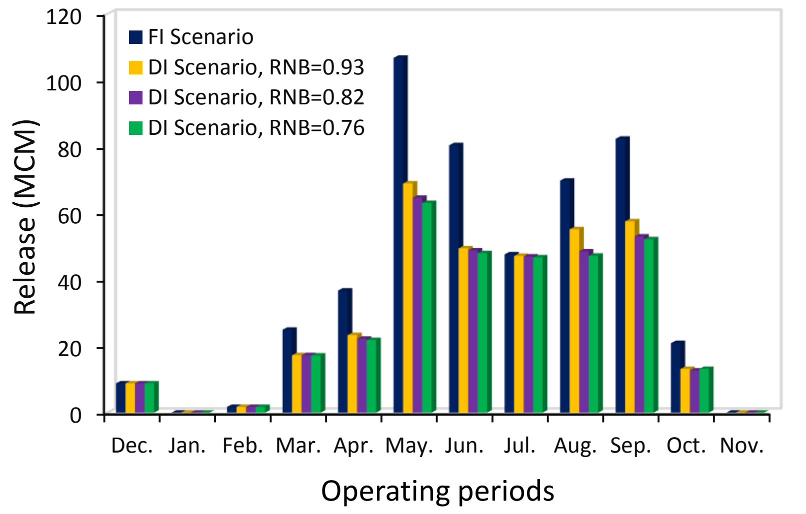


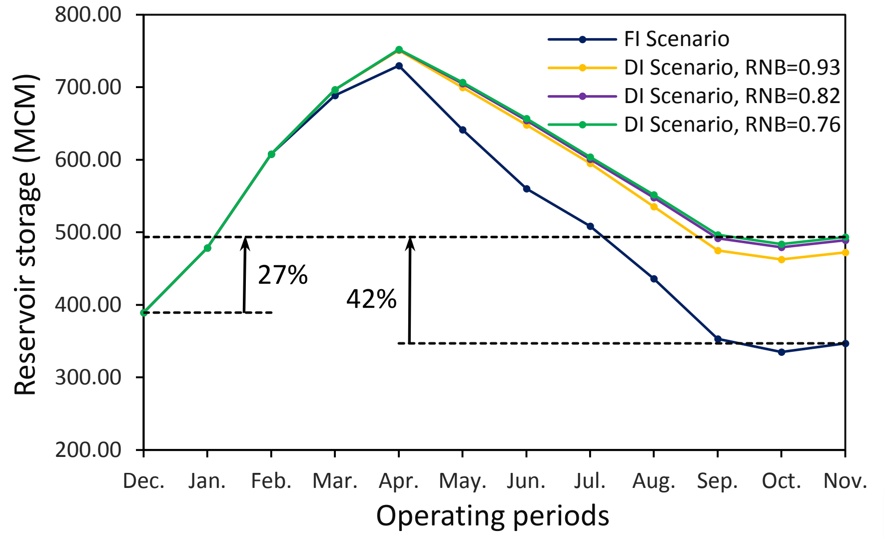


Results

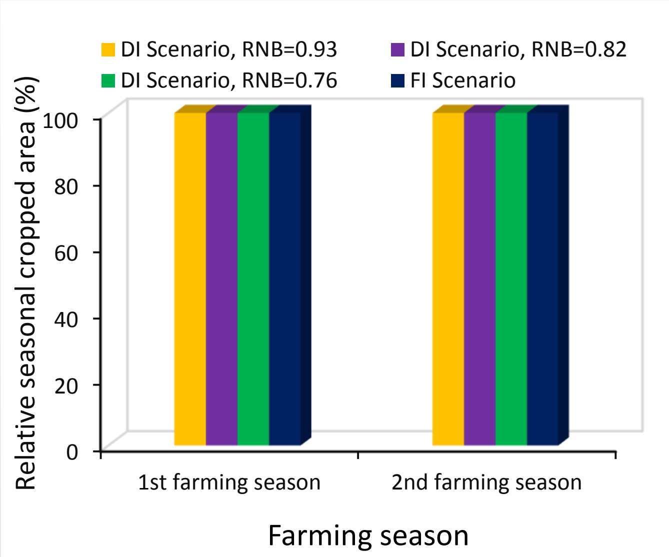
Hydrological condition: Wet   Initial storage: 25% of maximum capacity

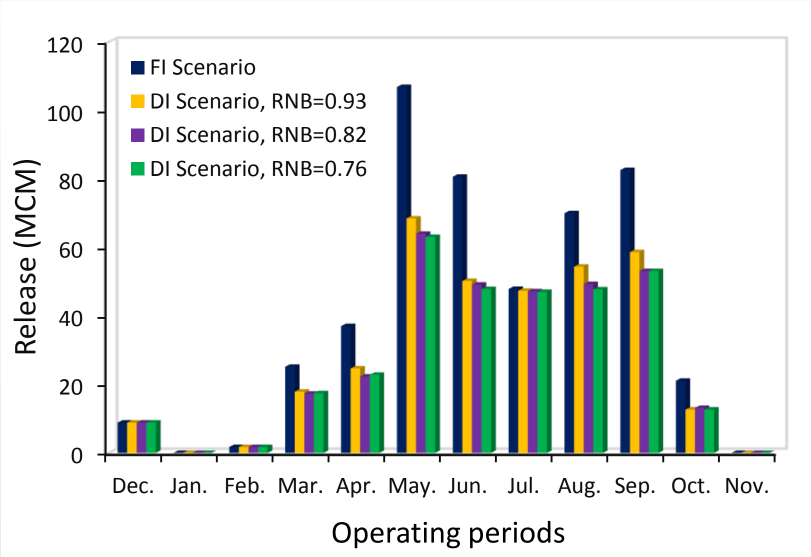


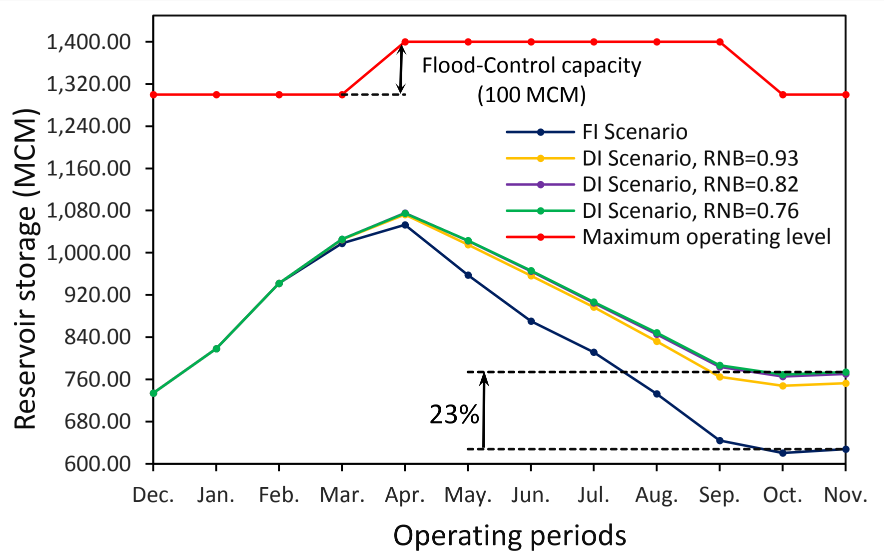




Hydrological condition: Wet   Initial storage: 50% of maximum capacity







Results

Optimal irrigation scheduling for FI and DI scenarios under normal hydrological condition

Winter wheat		Date	11/22	03/03	03/21	04/11	04/21	05/02	05/09	05/16	05/23	05/29	06/04	06/10	-	-	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps m^{-1})	1.8	1.4	1.3	1.2	1.3	1.2	1.3	1.3	1.3	1.4	1.4	1.4	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	60.0	145.0	190.0	270.0	190.0	245.0	190.0	190.0	190.0	145.0	145.0	145.0	-	-	-	-	-	-	-	-	-	-
	DI	Inflow rate (lps m^{-1})	1.8	1.6	1.5	1.3	1.5	1.4	1.5	1.5	1.5	1.6	1.6	1.6	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	60.0	76.1	98.8	149.5	98.8	126.0	98.8	98.8	98.8	76.1	76.1	76.1	-	-	-	-	-	-	-	-	-	-
Barley		Date	11/22	03/01	03/20	04/11	04/21	05/02	05/09	05/16	05/23	05/30	-	-	-	-	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps m^{-1})	1.8	1.4	1.4	1.1	1.3	1.2	1.3	1.3	1.3	1.3	-	-	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	60.0	145.0	145.0	360.0	190.0	245.0	190.0	190.0	190.0	190.0	-	-	-	-	-	-	-	-	-	-	-	-
	DI	Inflow rate (lps m^{-1})	1.8	1.6	1.6	1.2	1.5	1.4	1.5	1.5	1.5	1.5	-	-	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	60.0	82.5	76.1	198	98.8	126.0	98.8	98.8	98.8	98.8	-	-	-	-	-	-	-	-	-	-	-	-
Maize(grain)-1		Date	02/09	02/21	03/02	03/13	03/23	04/12	04/21	05/02	05/09	05/16	05/23	05/30	06/07	-	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps)	0.9	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.7	0.7	0.7	0.7	0.6	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	100.0	150.0	150.0	150.0	190.0	425.0	260.0	425.0	260.0	260.0	260.0	260.0	360.0	-	-	-	-	-	-	-	-	-
	DI	Inflow rate (lps)	0.9	0.8	0.8	0.8	0.8	0.6	0.7	0.6	0.7	0.7	0.7	0.7	0.6	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	100.0	150.0	150.0	112.5	142.5	318.8	221.0	361.3	221.0	221.0	169.0	169.0	234.0	-	-	-	-	-	-	-	-	-
Tomato		Date	02/20	03/02	03/10	03/22	04/06	04/14	04/22	04/29	05/03	05/07	05/11	05/15	05/19	05/23	05/27	05/31	06/04	06/08	06/12	06/16	06/20	06/25
	FI	Inflow rate (lps)	0.9	1.0	0.9	0.9	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cutoff time (min)	100.0	70.0	100.0	100.0	150.0	190.0	260.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
	DI	Inflow rate (lps)	0.9	1.0	0.9	0.9	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Cutoff time (min)	100.0	70.0	100.0	80.0	120.0	152.0	208.0	120.0	135.0	135.0	135.0	135.0	135.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	112.5
Cucumber		Date	02/20	03/01	03/10	03/22	04/04	04/11	04/19	04/28	05/04	05/10	05/16	05/21	05/26	05/31	06/05	06/10	06/15	06/20	-	-	-	-
	FI	Inflow rate (lps)	0.9	1.0	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-
		Cutoff time (min)	100.0	70.0	100.0	100.0	150.0	190.0	190.0	190.0	150.0	190.0	190.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	-	-	-	-
Watermelon		Date	03/01	03/06	03/14	03/19	03/23	04/02	04/07	04/13	04/19	04/26	05/01	05/06	05/11	05/15	05/19	05/23	05/28	06/02	06/08	-	-	-
	FI	Inflow rate (lps)	0.9	1.0	1.0	1.0	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.9	0.8	0.9	0.8	0.8	0.8	-	-	-
		Cutoff time (min)	100.0	70.0	70.0	70.0	100.0	100.0	150.0	100.0	150.0	150.0	150.0	150.0	150.0	100.0	150.0	100.0	150.0	150.0	150.0	-	-	-
	DI	Inflow rate (lps)	0.9	1.0	1.0	1.0	0.9	0.9	0.8	1.0	0.8	0.8	0.8	0.8	0.8	1.0	0.8	1.0	0.8	0.8	0.8	-	-	-
		Cutoff time (min)	100.0	70.0	70.0	70.0	95.0	95.0	142.5	58.5	97.5	105.0	105.0	105.0	97.5	58.5	97.5	58.5	97.5	97.5	97.5	-	-	-
Bean		Date	07/11	07/14	07/22	07/31	08/07	08/13	08/18	08/23	08/28	09/03	09/09	09/15	09/22	09/29	10/06	-	-	-	-	-	-	-
	FI	Inflow rate (lps)	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-	-	-	-
		Cutoff time (min)	100.0	190.0	150.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	-	-	-	-	-	-	-
	DI	Inflow rate (lps)	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-	-	-	-
		Cutoff time (min)	100.0	190.0	150.0	152.0	152.0	152.0	152.0	152.0	152.0	152.0	152.0	152.0	161.5	161.5	161.5	-	-	-	-	-	-	-
Sorghum		Date	07/11	07/16	07/25	08/04	08/10	08/16	08/21	08/27	09/04	09/12	09/21	09/30	-	-	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.8	0.8	0.8	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	190.0	150.0	150.0	190.0	190.0	190.0	190.0	260.0	260.0	190.0	190.0	190.0	-	-	-	-	-	-	-	-	-	-
	DI	Inflow rate (lps)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.8	0.8	0.8	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	190.0	150.0	150.0	95.0	95.0	95.0	95.0	130.0	247.0	180.5	180.5	180.5	-	-	-	-	-	-	-	-	-	-
Sesame		Date	07/11	07/17	07/29	08/06	08/13	08/18	08/23	08/27	08/31	09/05	09/10	09/15	09/21	09/26	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps)	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	-	-	-	-	-	-	-	-
		Cutoff time (min)	100.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	190.0	-	-	-	-	-	-	-	-
Maize(grain)-2		Date	07/11	07/21	07/30	08/07	08/13	08/19	08/25	08/30	09/08	09/17	09/27	-	-	-	-	-	-	-	-	-	-	-
	FI	Inflow rate (lps)	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.7	0.6	0.7	0.6	-	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	190.0	150.0	190.0	190.0	190.0	260.0	190.0	260.0	360.0	260.0	360.0	-	-	-	-	-	-	-	-	-	-	-
	DI	Inflow rate (lps)	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.7	0.6	0.7	0.6	-	-	-	-	-	-	-	-	-	-	-
		Cutoff time (min)	190.0	150.0	190.0	180.5	180.5	247.0	180.5	156.0	216.0	130.0	180.0	-	-	-	-	-	-	-	-	-	-	-

Conclusion

- Under DI scenario by adopting each operational policy with RNB≥1, all of the main factors such as annual net profit, the area under cultivation, and reservoir storage increased.

- In dry hydrological condition due to the initial storage of the reservoir, storage enhancement approach must be intensified by choosing RNB≤1.

- In dry and normal hydrological conditions in order to make the annual reservoir water balance positive, the cropped area should be severely reduced.

- The flood-control capacity in the all assessed situations is free.

Thank you for attention