



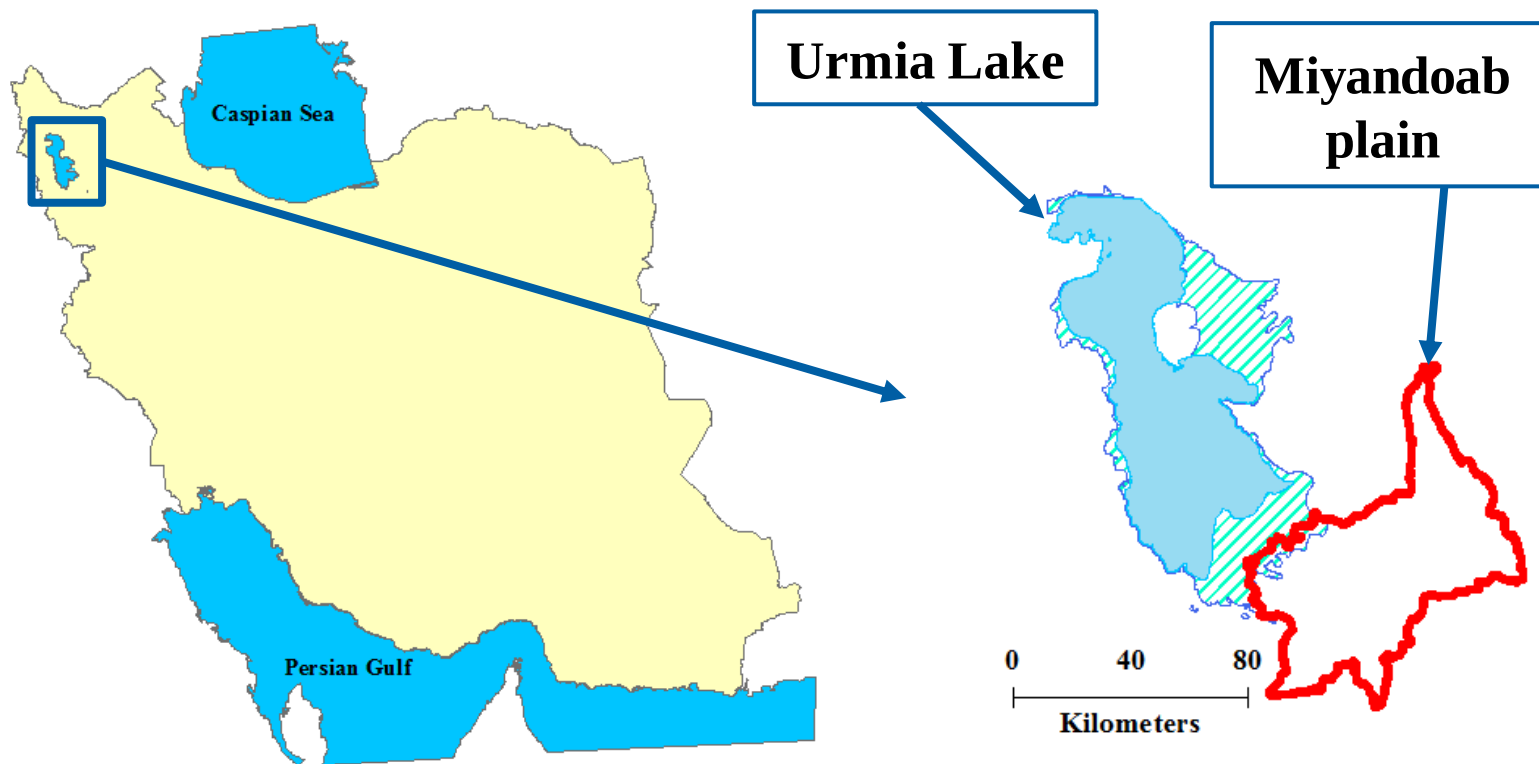
**Bayesian Belief Networks for the metamodeling of simulation-optimization model
to identify optimum water allocation scenario, Application in Miyandoab plain,
Urmia Lake basin, Iran**

Amirhossein Dehghanipour, Gerrit Schoups, Hossein Babazadeh, Majid Ehtiat, & Bagher Zahabioun



A computationally efficient decision-making model

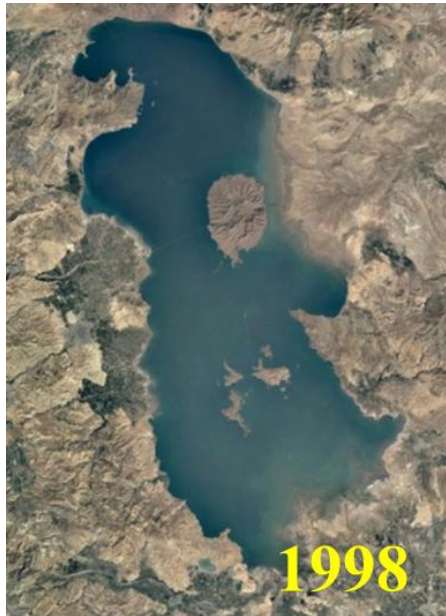
Develop a decision-making model in uncertain conditions to identify optimal strategies for reducing competition between agricultural and environmental water demand in the Miyandoab plain, one of the strategic agricultural areas in the Urmia Lake Basin in the semi-arid northwest of Iran.



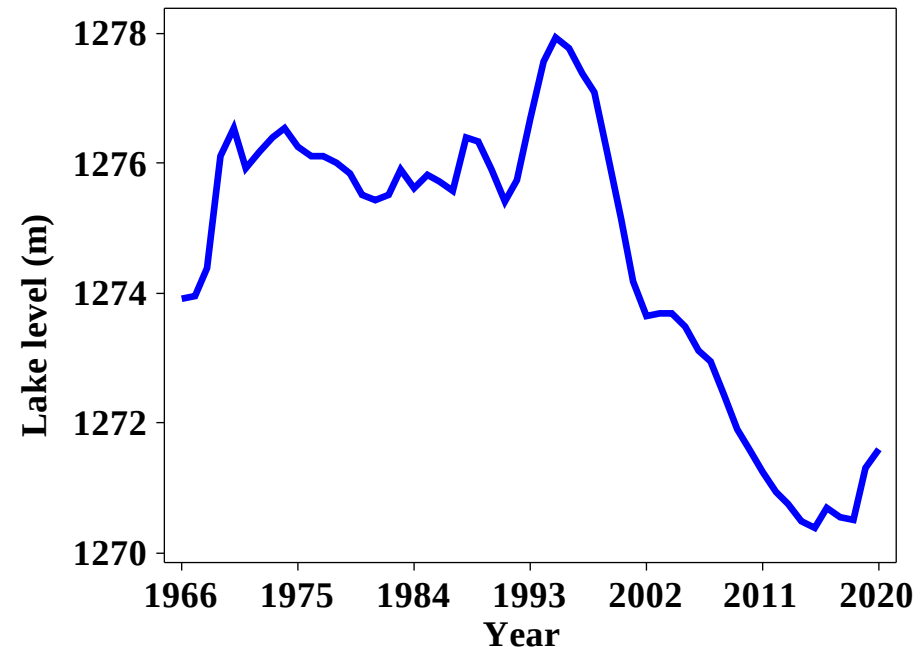
Motivation

Drought and water mismanagement led to complex water problems in the Urmia Lake basin:

- Decreasing environmental flows to Urmia Lake and shrinking of the lake.
- Increasing competition between environmental and agricultural demand.



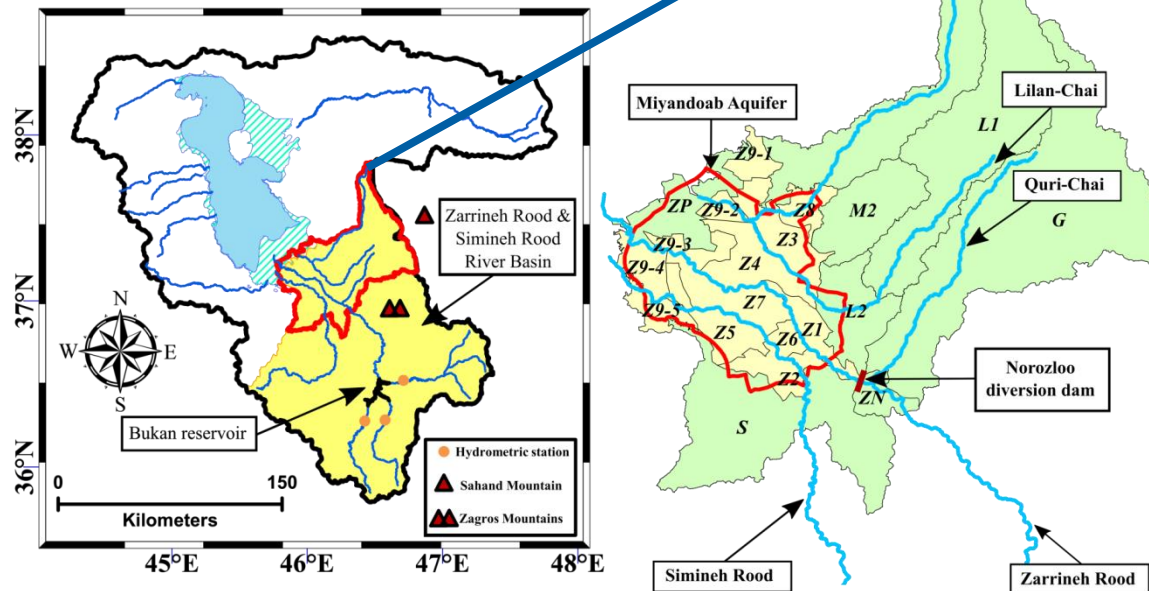
(Reference: Google Earth)



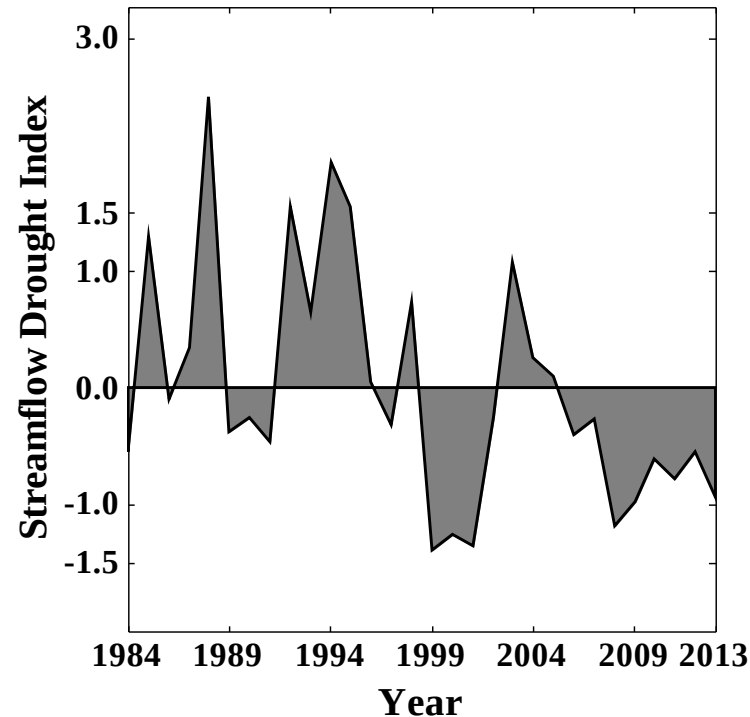
Miyandoab plain

- **Total area:** 4309 km²
- **Total irrigated area:** 100,000 hectares
- **Annual precipitation:** 290mm
- **Average temperature:** 14°C
- **Zarrineh Rood annual discharge:** 2000 MCM (40% of total inflow to Urmia lake)
- **Simineh Rood annual discharge:** 350 MCM (10% of total inflow to Urmia lake)
- **Bukan storage:** 808 MCM

(For more details, please see Dehganipour et al., 2019)



Historical hydrologic droughts in Miyandoab Plain



Classification	Identifier	Criterion	Years of occurrence
Non-drought	HD1	$0.0 \leq \text{SDI}$	1985, 1987, 1988, 1992, 1993, 1994, 1995, 1996, 1998, 2003, 2004, 2005
Mild drought	HD2	$-1.0 \leq \text{SDI} < 0.0$	1984, 1986, 1989, 1990, 1991, 1997, 2002, 2006, 2007, 2009, 2010, 2011, 2012, 2013
Moderate drought	HD3	$-1.5 \leq \text{SDI} < -1$	1999, 2000, 2001, 2008

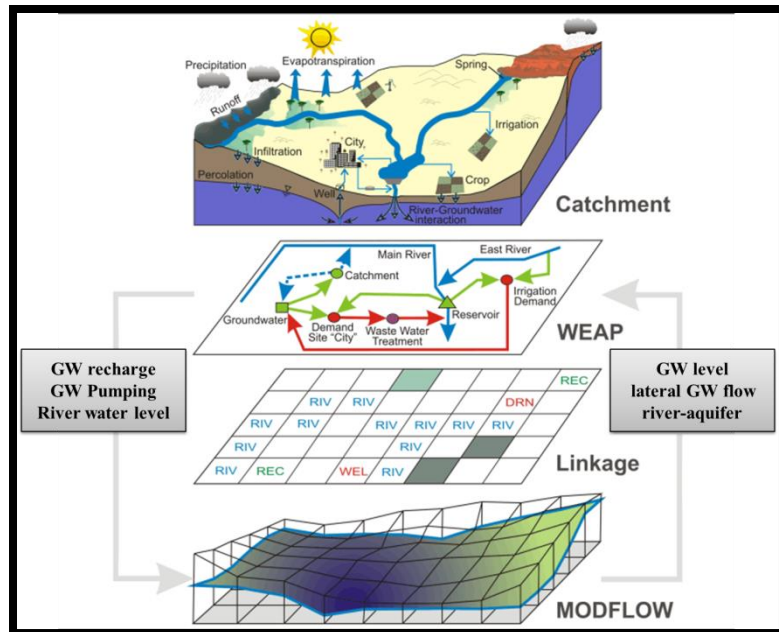
(For more details, please see Dehganipour et al., 2020)

Research process

Start

Development of a hydrological module by coupling between WEAP and MODFLOW

(For more details, please see Dehganipour et al., 2019)



(Reference: Maßmann et al., 2012)

Development of a multi-period simulation-optimization model

Objective Functions:

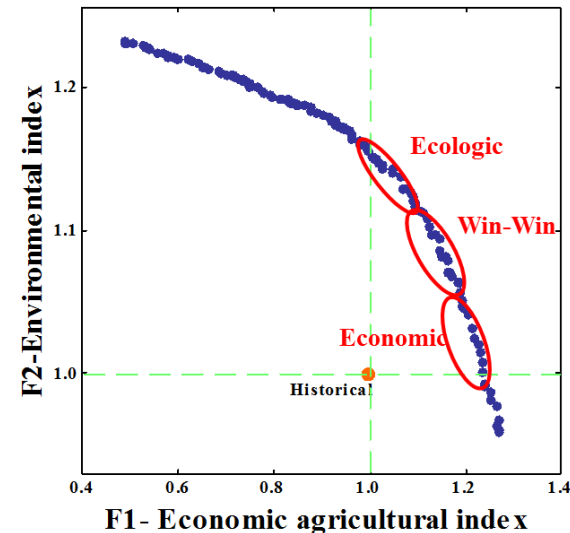
(1) Maximize Economic agricultural Index

F1= Function (annual average (agricultural net benefit))

(2) Maximize Environmental Index

F2= Function (annual average (Downstream flow to lake))

(For more details, please see Dehganipour et al., 2020)



Development of a decision-making model based on Bayesian Belief Network (BBN)

Development of a static BBN with annual scale

Evaluation of the effects of management strategies and drought conditions on environmental flow and agricultural profit.

Development of a dynamic BBN with monthly scale

Account for monthly dynamics of water demand and conjunctive use.

Application of simulated outputs from a multi-period simulation-optimization model to populate the CPTs in each BBN

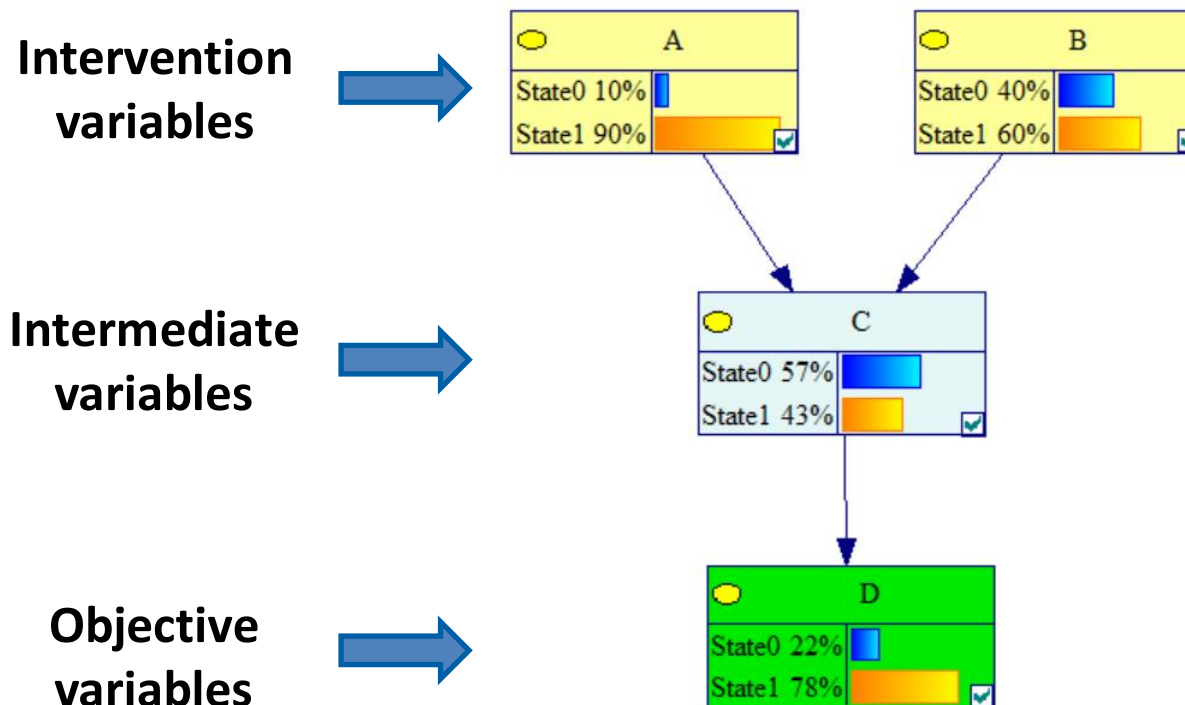
Finish

Bayesian Belief Networks (BBN)

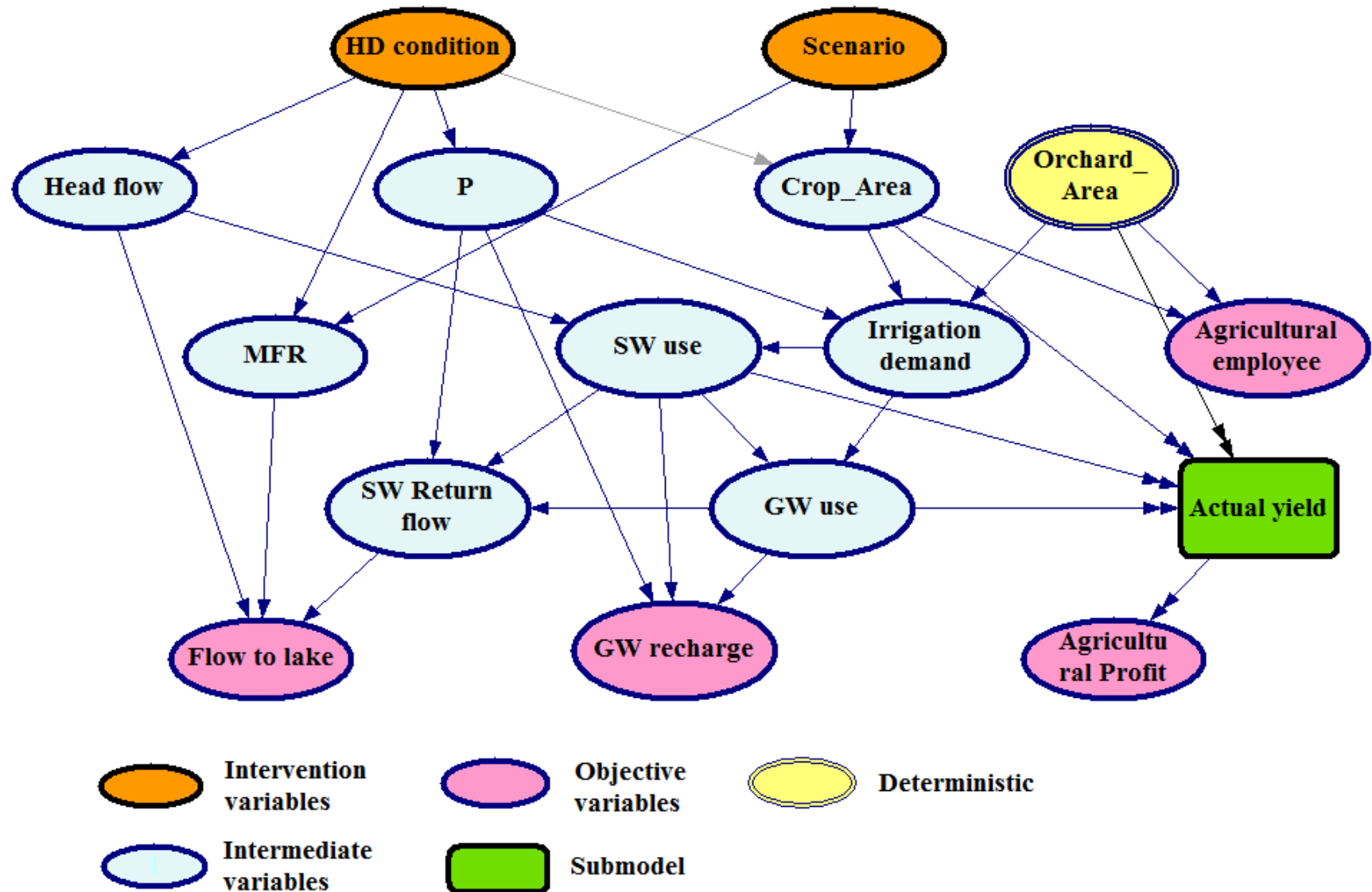
A BBN is a probabilistic graph that includes two main components.

(1) A directed acyclic graph (DAG): DAG includes a set of nodes and links that indicates dependent and independent relationships between model variables.

(2) Conditional Probability Tables (CPTs): In DAG, each node has a set of continuous or discrete states that CPTs express the beliefs regarding these states based on Bayes' law.



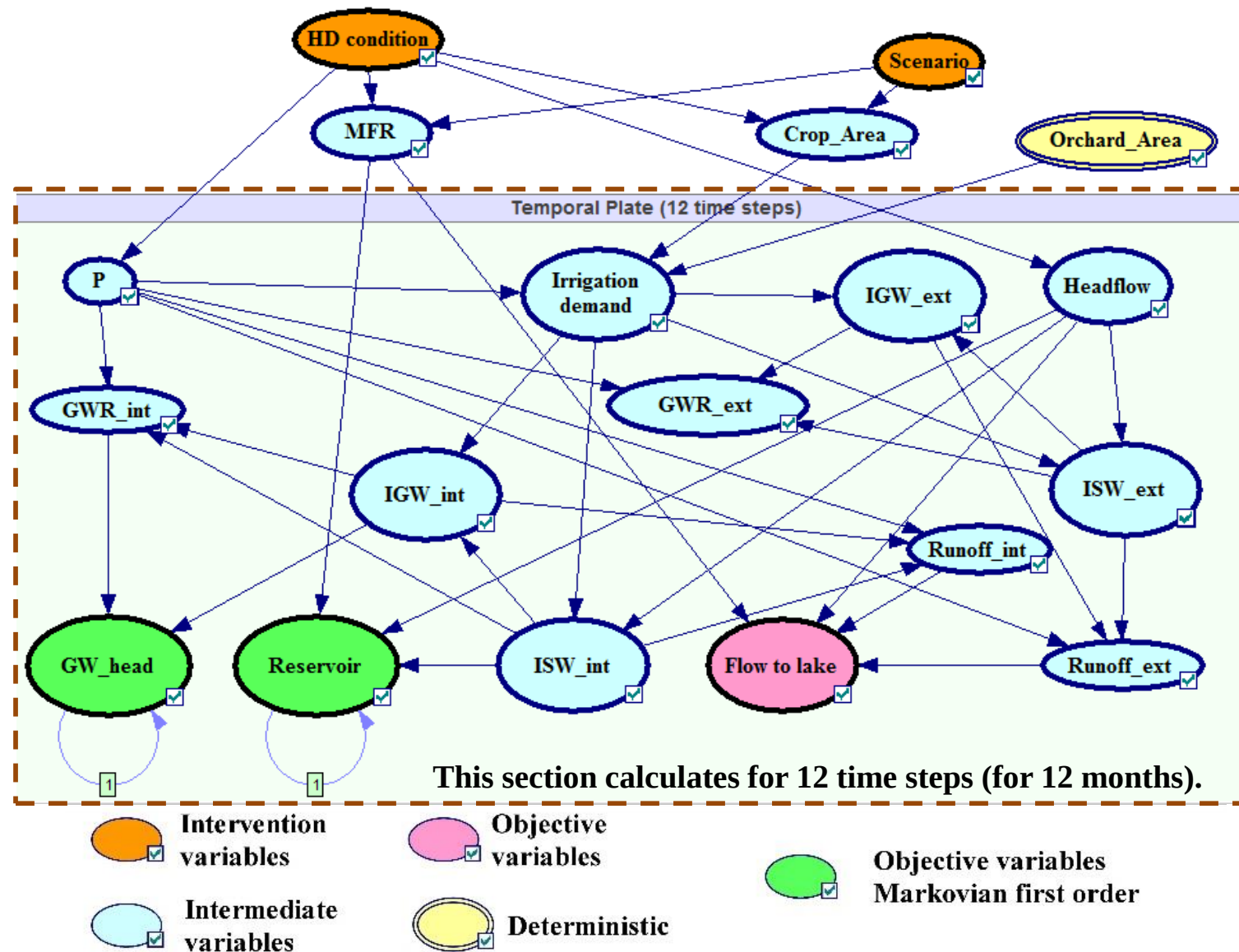
Static BBN



Static BBN

Group	Name	Explanation	States	Time scale
Intervention variables	HD condition	Hydrological Drought conditions based on Stream flow Drought Index (SDI)	HD1 ($0.0 \leq \text{SDI}$); HD2 ($-1.0 \leq \text{SDI} < 0.0$); HD3 ($-1.5 \leq \text{SDI} < -1$)	Annual
	Scenario	Based on Clustering of Pareto fronts	Ecologic; Win-Win; Economic	
Fixed variable	Orchard Area	(ha)	32090	
Intermediate variables	MFR	Minimum environmental flow ratio	0.2-0.4; 0.4-0.6; 0.6-0.8	
	Crop Area	(ha)	0-15342; 15342-30684; 30684-46026; 46026-61368; 61368-76710	
	P	Precipitation (mm)	150-246; 246-342; 342-437	
	Head flow	(MCM)	738-2665; 2665-4592; 4592-6520	
	Irrigation demand	(MCM)	240-397; 397-553; 553-709	
	SW use	Surface Water use (MCM)	200-676; 676-1151; 1151-1627	
	GW use	Groundwater use (MCM)	73-131; 131-190; 190-249	
	SW Return flow	(MCM)	140-404; 404-668; 668-932	
	Actual yield	(ton)	Sub-model in the static BBN	
Objective variables	Flow to lake	(MCM)	317-1477; 1477-2637; 2637-3797; 3797-4957; 4957-6118	
	GW recharge	(MCM)	56-156; 156-257; 257-357	
	Agricultural Profit	Million US Dollars	29-65; 65-101; 101-137; 137-173; 173-209	
	Agricultural employee	Man-Day	2587800-3007700; 3007700-3427700; 3427700-3847700; 3847700-4267600; 4267600-4687600	

Dynamic BBN

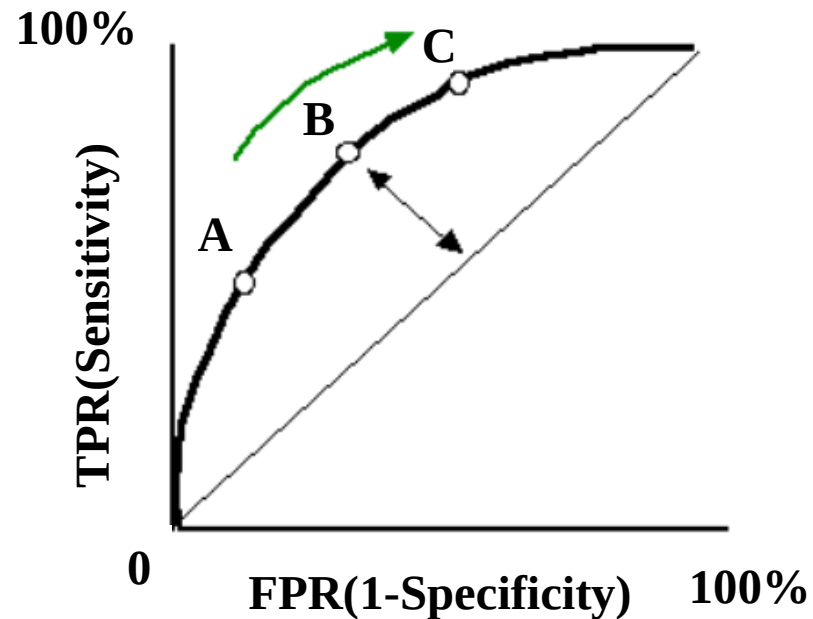
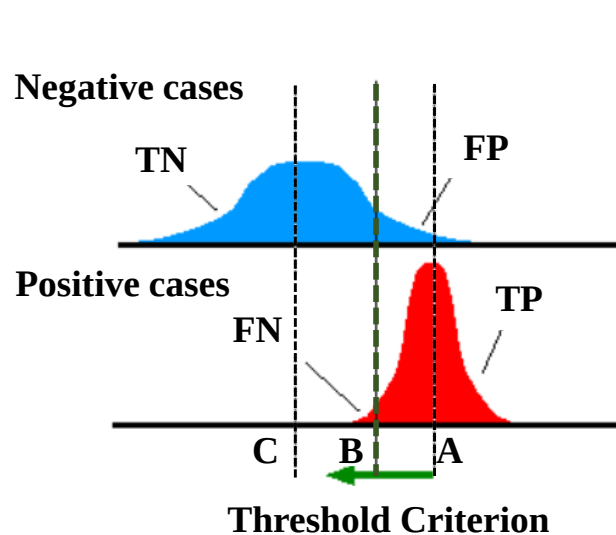


Dynamic BBN

Group	Name	Explanation	States	Time scale
Intervention variables	HD condition	Hydrological Drought conditions based on Stream flow Drought Index (SDI)	HD1 ($0.0 \leq \text{SDI}$); HD2 ($-1.0 \leq \text{SDI} < 0.0$); HD3 ($-1.5 \leq \text{SDI} < -1$)	Annual
	Scenario	Based on Clustering of Pareto fronts	Ecologic; Win-Win; Economic	
Fixed variable	Orchard Area	(ha)	32090	
Intermediate variables	MFR	Minimum environmental flow ratio	0.2-0.4; 0.4-0.6; 0.6-0.8	Monthly
	Crop Area	(ha)	0-15342; 15342-30684; 30684-46026; 46026-61368; 61368-76710	
	P	Precipitation (mm)	0-40; 40-80; 80-120	
	Head flow	(MCM)	0-600; 600-1200; 1200-1800	
	Irrigation demand	(MCM)	0-45; 45-90; 90-135	
	ISW_int	Surface Water(SW) use in internal zones (MCM)	0-80; 80-160; 160-240	
	IGW_int	Groundwater (GW) use in internal zones (MCM)	0-12; 12-24; 24-36	
	Runoff_int	Surface Runoff in internal zones (MCM)	0-40; 40-80; 80-120	
	GWR_int	GW recharge in internal zones (MCM)	0-9; 9-18; 18-27	
	ISW_ext	SW use in external zones (MCM)	0-25; 25-50; 50-75	
	IGW_ext	GW use in external zones (MCM)	0-12; 12-24; 24-36	
	Runoff_ext	Surface Runoff in external zones (MCM)	0-15; 15-30; 30-45	
Objective variables	Flow to lake	(MCM)	0-600; 600-1200; 1200-1800	
	Reservoir	Reservoir storage(MCM)	134-360.3; 360.3-586.7; 586.7-813	
	GW_head	GW head in internal zones (m)	1282.8-1286.7; 1286.7-1290.6; 1290.6-1294.5	
	GWR_ext	GW recharge in external zones (MCM)	0-5; 5-10; 10-15	

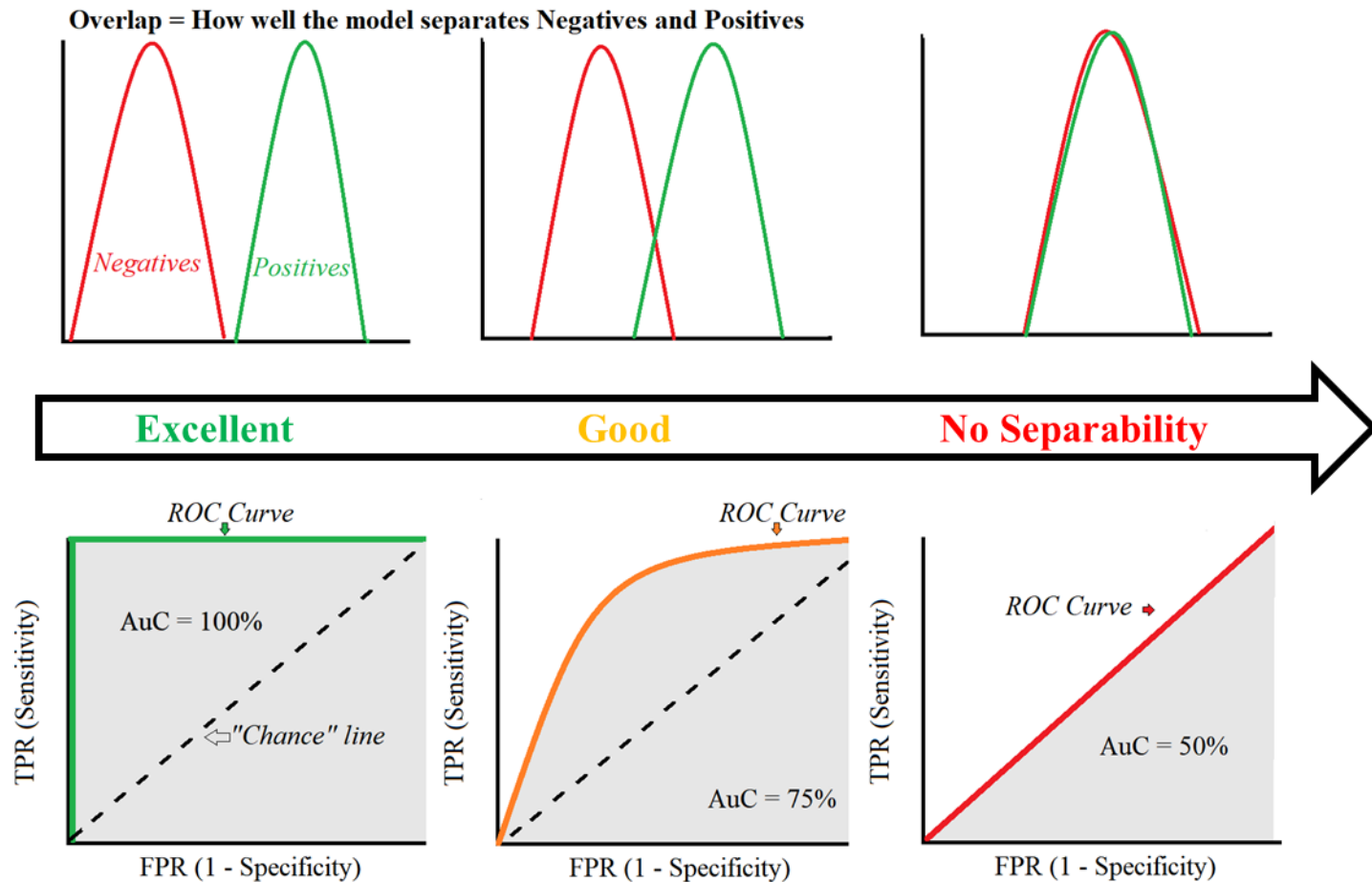
Cross-validation tests

Confusion matrix		Predicted	
		Positive	Negative
Real	Positive	True Positive (TP)	False negative (FN)
	Negative	False positive (FP)	True negative (TN)



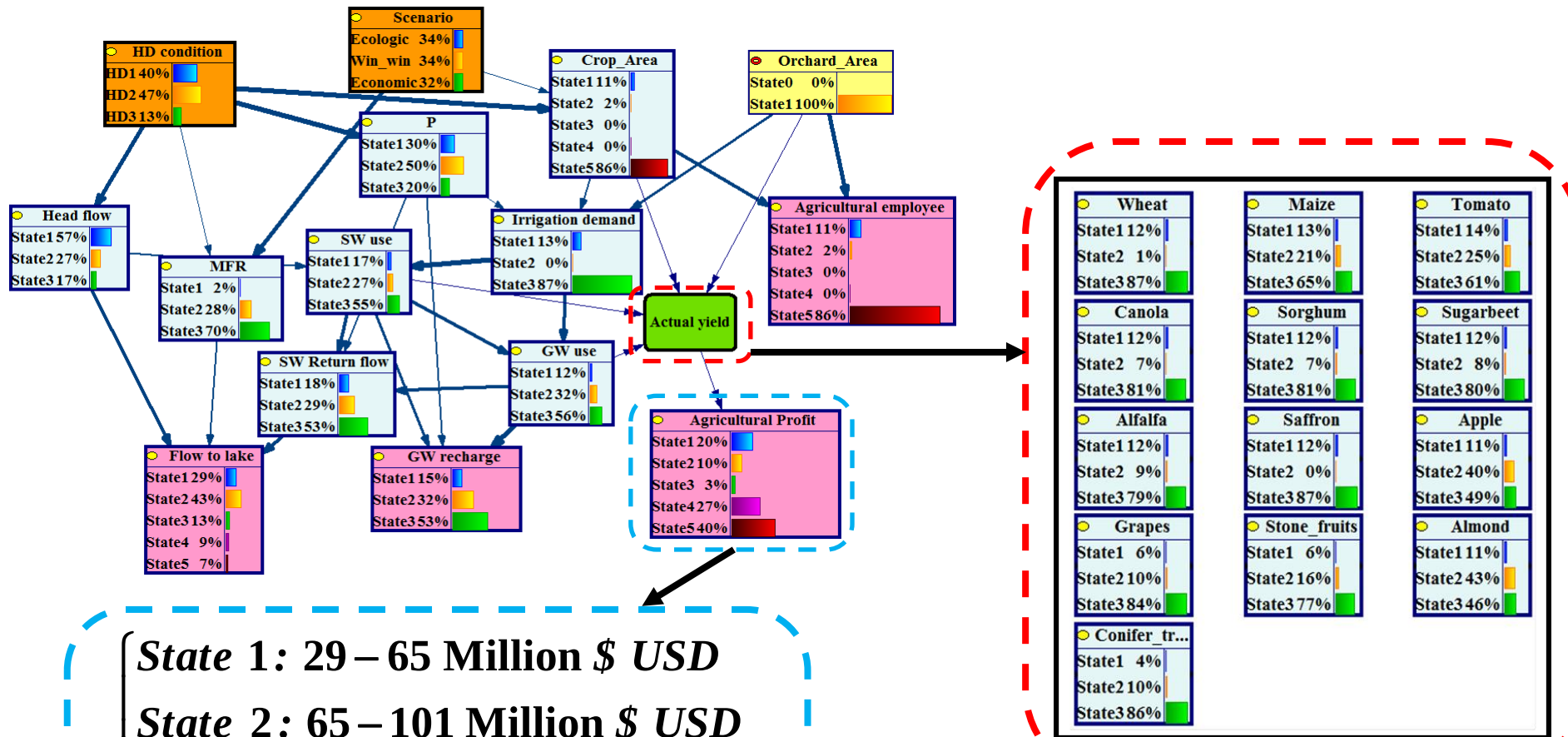
(Reference: <https://nl.wikipedia.org/wiki/ROC-curve>)

Cross-validation tests



(Reference: <https://www.datasciencecentral.com/profiles/blogs/roc-curve-explained-in-one-picture>)

The prior probability of static BBN



State 1: 29 – 65 Million \$ USD

State 2: 65 – 101 Million \$ USD

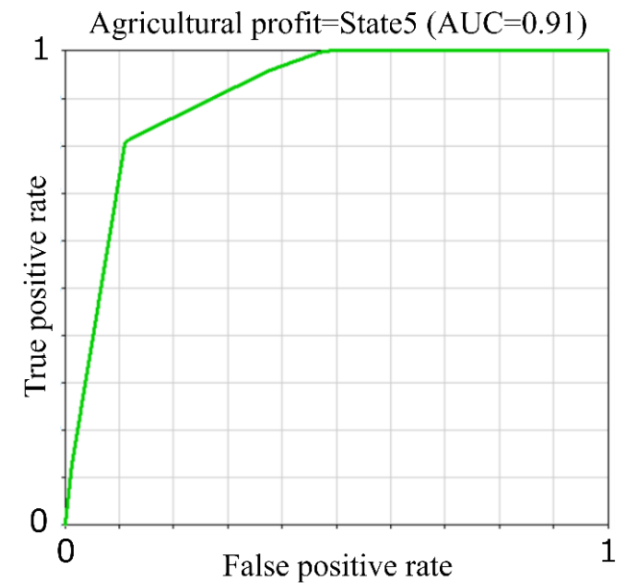
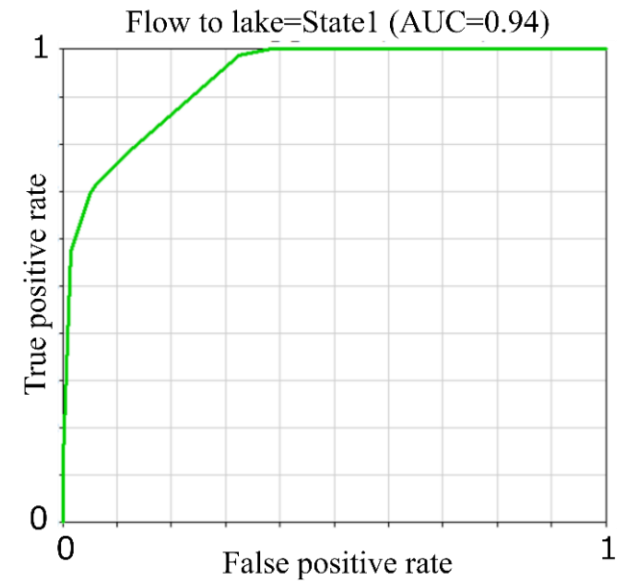
State 3: 101 – 137 Million \$ USD

State 4: 137 – 173 Million \$ USD

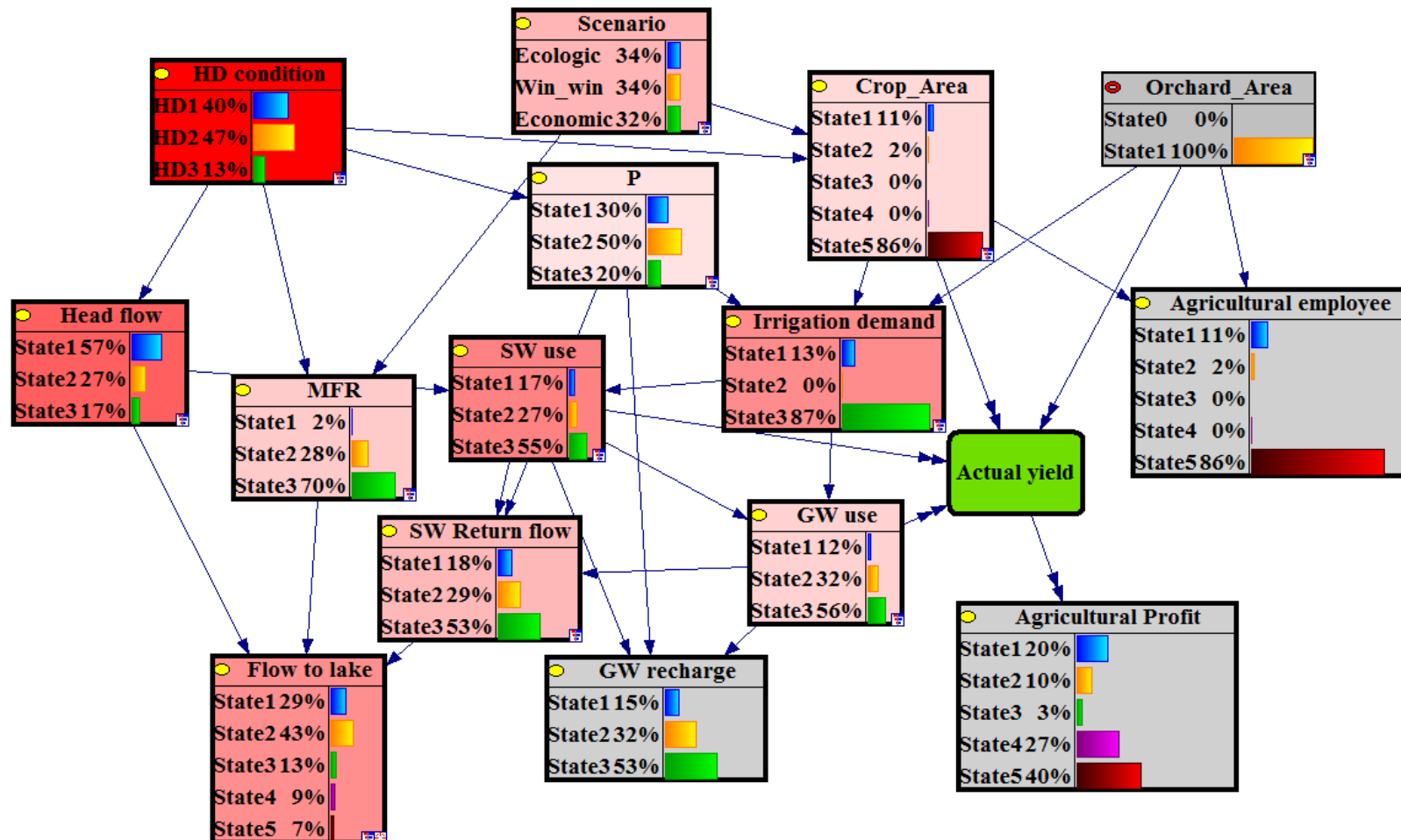
State 5: 173 – 209 Million \$ USD

Validation of static BBN

			Predicted				
			State 1	State 2	State 3	State 4	State 5
			State 1	State 2	State 3	State 4	State 5
Real	Flow to lake	State 1	383	57	0	0	0
		State 2	32	530	45	0	0
		State 3	0	23	165	20	0
		State 4	0	0	0	131	0
		State 5	0	0	0	24	0
	Agricultural profit	State 1	130	7	0	0	0
		State 2	16	46	0	0	0
		State 3	0	14	78	2	0
		State 4	0	0	11	357	61
		State 5	0	0	0	103	585



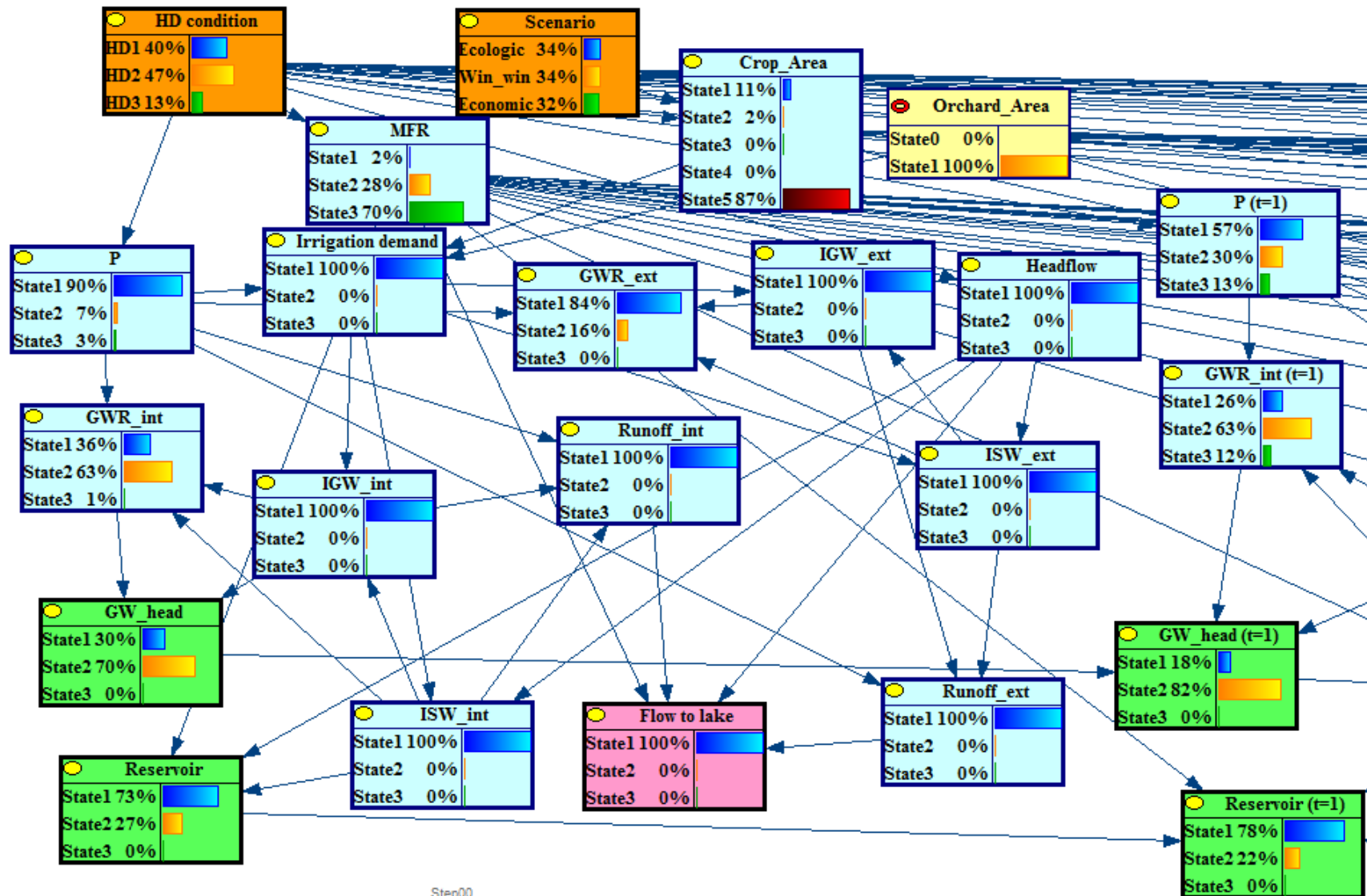
Sensitivity analysis of static BBN



The posterior probability of static BBN

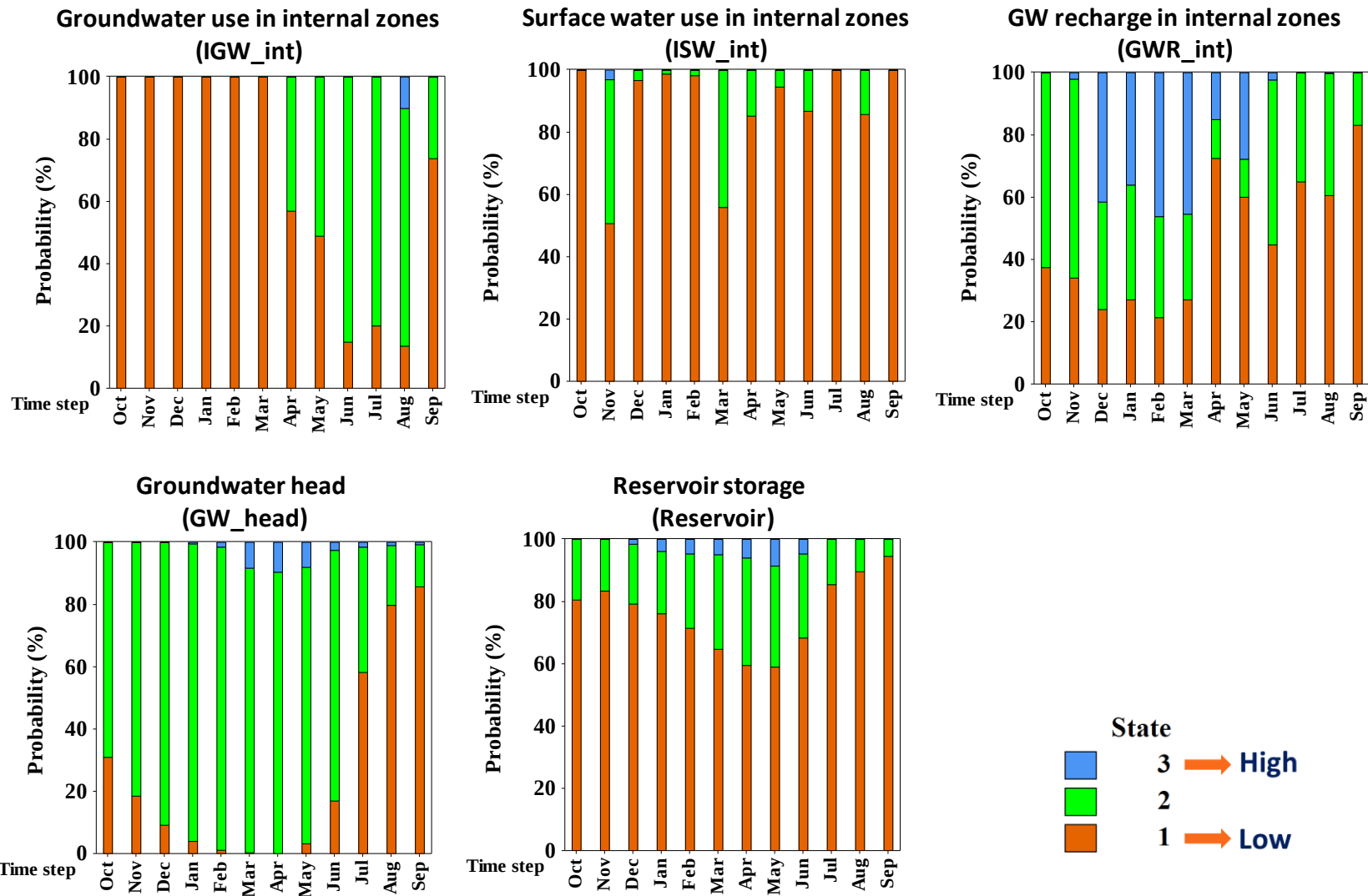
Scenario		Ecologic
HD condition		HD3
Crop area	State1 (0-15342)	100%
	State2 (15342-30684)	0
	State3 (30684-46026)	0
	State4 (46026-61368)	0
	State5 (61368-76710)	0
MFR	State1 (0.2-0.4)	0
	State2 (0.4-0.6)	1%
	State3 (0.6-0.8)	98%
Agricultural profit	State1 (29-65)	68%
	State2 (65-101)	28%
	State3 (101-137)	3%
	State4 (137-173)	0%
	State5 (173-209)	0%
Flow to lake	State1 (317-1477)	76%
	State2 (1477-2638)	24%
	State3 (2638-3798)	0%
	State4 (3798-4958)	0%
	State5 (4958-6118)	0%

The prior probability of dynamic BBN for the first time slice



The posterior probability of dynamic BBN

Intervention variables: (Scenario: Ecologic; HD condition: HD3)



Conclusions

- Develop the first decision-making models in uncertain conditions conceptualized based on BBN for meeting agricultural and environmental water demand in Miyandoab Plain.
- Use simulated outputs corresponding to the Pareto fronts from a multi-period simulation-optimization model to populate the CPTs in BBN and reduce the BBN training error.
- Cross-validation tests show that the developed BBNs is able to reproduce the behavior of the complex simulation-optimization model.
- Sensitivity analysis shows that drought conditions have the most significant impact on environmental flow to Urmia lake.
- Static and Dynamic BBN provide a computationally fast alternative for decision-making under uncertainty.

- *Dehghanipour, A. H., Zahabiyoun, B., Schoups, G., & Babazadeh, H. (2019). A WEAP-MODFLOW surface water-groundwater model for the irrigated Miyandoab plain, Urmia lake basin, Iran: Multi-objective calibration and quantification of historical drought impacts. Agricultural Water Management, 223, 105704.*
- *Dehghanipour, A. H., Zahabiyoun, B., Schoups, G., & Babazadeh, H. (2019). A WEAP-MODFLOW surface water-groundwater model for the irrigated Miyandoab plain, Urmia lake basin, Iran: Multi-objective calibration and quantification of historical drought impacts. Agricultural Water Management, 223, 105704.*
- *Maßmann, J., Johannes Wolfer, M. H., Schelkes, K., Hennings, V., Droubi, A., & Al-Sibai, M. (2012). WEAP-MODFLOW as a Decision Support System (DSS) for integrated water resources management: Design of the coupled model and results from a pilot study in Syria. Groundwater Quality Sustainability, 173.*



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