Applications of the modified SWAT model in karstic-influenced basins: some examples from karstic basins in Iran

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Why?

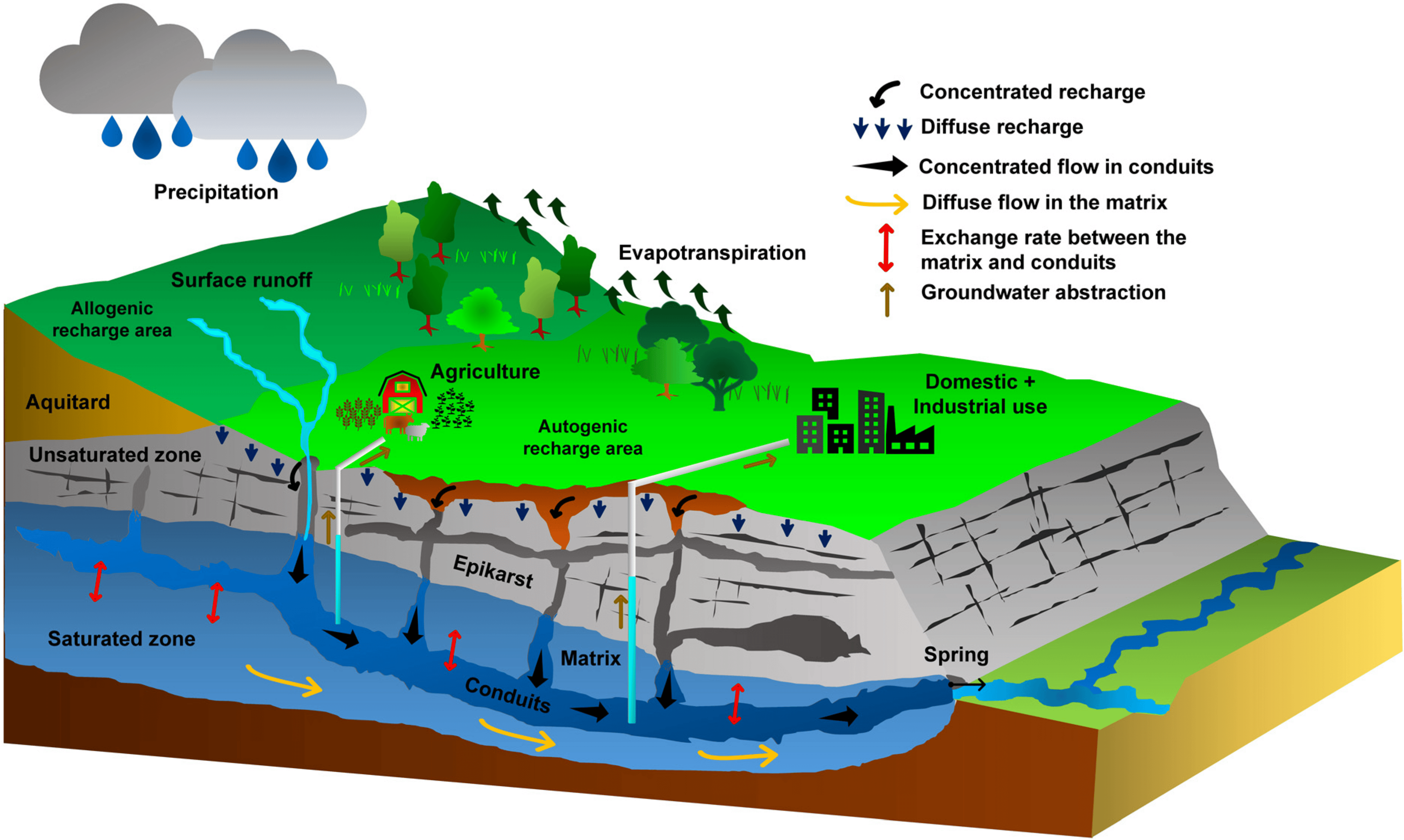
- About 25% of the world's population relies on water stored in karst aquifers
- Karst formations are unique in realm of hydrology
- High infiltration rate and complex recharge characteristics
- Random and undefined pattern on surface and riverbeds
- Hydrological modeling can be challenging

What is a karst formation?

Karst is a type of landscape where the dissolving of the bedrock has created sinkholes, sinking streams, caves, springs, and other characteristic features.

$$\underset{\text{air}}{CO_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{carbonic acid}}{H_2CO_3}$$

$$\underset{\text{limestone}}{CACO_3} + \underset{\text{carbonic acid}}{H_2CO_3} \longrightarrow \underset{\text{calcium bicarbonate}}{Ca(HCO_3)_2}$$



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Aims

- Modifying SWAT to have a better estimations for water budget
- Water Accounting assessments in karstic regions
- Interaction of surface and groundwater resources
- Improving groundwater module in SWAT
- Testing different approaches in model developments

Past works (SWAT and modified SWAT)

Study	Catchment (region[a], country/ km²)	SWAT modeling method	Streamflow testing time periods[b]	NSE Daily		NSE Monthly	
				Cal	Val	Cal	Val
Spruill et al. (2000)	Univ. of KY Research Site (Kentucky, U.S./5.5)	SWAT	Cal: 1995 Val: 1996	−0.04	0.19	0.58	0.89
Coffey et al. (2004)	Univ. of KY Research Site (Kentucky, U.S./5.5)	SWAT	Cal: 1995 Val: 1996	0.09	0.15	0.41	0.61
Afinowicz et al. (2005)	North Fork, Upper Guadalupe River (Texas, U.S./360)	Modified SWAT (modified surface runoff & recharge algorithms)	Cal: 1992–1996 Val: 1997-2003[c]	0.40	0.09	0.29	0.50
Benham et al. (2006)	Shoal Creek (Missouri, U.S./367)	SWAT	Cal: 1999-2000[c] Val: 2000-2001[c]	0.21	0.54	0.63	0.61
Baffaut and Benson (2009)	James River (Missouri, U.S./ 3,600)	Modified SWAT (accounted for sinkholes & losing stream recharge)	Cal: 1983–2000 Val: 2001–2007	0.33–0.56	0.24–0.56	[d]–	–
Salerno and Tartari (2009)	Lake Pusiano (Lombardy, Italy/ 52.5)	SWAT; supported with Wavelet Analysis (WA)	Cal: 2001–2003 Val: 1977–1982	0.61/ 0.66[e]	0.56/ 0.62[e]	–	–
Vale and Holman (2009)	Bosherston Lakes (Wales, UK/-)	SWAT	Cal: 1995–2005 Val: 1984–1994	0.67-0.74	0.56–0.74	–	–
Amatya and Jha (2011)[f]	Chapel Branch Creek (South Carolina, U.S./15.6)	SWAT	–	–	–	–	–
Jiang et al. (2011)	Shibetsu River (Island of Hokkaido, Japan/672)	SWAT	Cal: 2004–2006 Val: 2007–2008	0.58	0.51	−0.39/ 0.81[e]	0.23/ 0.89[e]
Nikolaidis et al. (2013)	Koiliaris River (Island of Crete, Greece/132 [g])	SWAT interface with two reservoir karst model	Cal: 2004–2006 Val: 2004–2007	0.43	0.62	0.61	0.77
Palazón and Navas (2013)	Linsoles River (Central Pyrenees, Spain/284)	SWAT	Cal:2003–2005	–	–	0.57	–
Palanisamy and Workman (2014)	Cane Run Creek (Kentucky, U.S./115.6)	SWAT & KarstSWAT (accounted for effects of sinkholes & springs)	Cal: 2001–2003 Val: 2004–2006 [h] Val: 2001–2006 [h]	−1.28-0.74 [h] 0.57–0.87 [h]	0.30–0.78 [h] 0.70–0.87 [h]	–	–
Wilson et al. (2014)	South Branch, Root River (Minnesota, U.S./301.8)	SWAT	Cal: 2004–2005 Val: 2006–2008	–	–	0.76	0.78
Gamvroudis et al. (2015)	Evrotas River (Peloponnesus, Greece/1,348)	SWAT	Cal: 2009–2011 Val: 2004–2009	0.59-0.80	0.54-0.80	–	–

Past works (SWAT and modified SWAT)

Jain et al. (2015)	Nueces River Headwaters (Texas, U.S./ 2,126)	SWAT	Cal: 1960–1977 Val: 1978–1994	–	–	0.79	0.74
Malagò et al. (2015)[i]	Scandanavian Peninsula (Norway, Sweden, Finland/ 10^6); Iberian Peninsula (Spain, Portugal/556,000)	SWAT	–	–	–	–	–
Mehdi et al. (2015)	Altmühl River (Bavaria, Germany/980)	SWAT	Cal: 1964–1974 Val: 1975–1984	–	–	0.80–0.83	0.59–0.87
Nerantzaki et al. (2015)	Koiliaris River (Island of Crete, Greece/ 130[g])	SWAT interface with two reservoir karst model	Val: 2010–2014	–	0.80	–	0.83
Malagò et al. (2016)	Island of Crete (Greece/8,336)	KSWAT; modified SWAT interface with two reservoir karst model	Cal: 1989-2000[j] Val: 1989-2000[j]	–	–	−2.38–0.83	−3.94–0.78
Tian et al. (2016)	Shibantang River (Guizhou, China/2,248)	SWAT	Cal: 2000–2004 Val: 2005–2010	-	-	0.78	0.76
Amin et al. (2017)[k]	Spring Creek (Pennsylvania, U.S./370)	SWAT & Topo-SWAT	Cal: 2002–2007 Val: 2008–2013	0.77/ 0.79[l]	0.68/ 0.73[l]	0.84/ 0.85[l]	0.83/ 0.82[l]
Vigiak et al. (2017)[i]	Danube River (parts of 19 European countries/800,000)	SWAT	–	–	–	–	–
Sunde et al. (2018)[m]	Hinkson Creek (Missouri, U.S./231)	SWAT	Cal: 2007-2012[c] Val: 2013-2017[c]	–	–	0.84	0.78
Wang et al. (2019)	Xianghualing River (Hunan, China/26.8)	SWAT & Modified SWAT interface with three reservoir karst model	Cal: 2016[c] Val: 2016[c]	0.63/ 0.83[l]	0.58/ 0.81[l]	–	–
Merriman et al. (2019)	Upper East River (Wisconsin, U.S./375.3)	SWAT	Cal: 2005–2014 Val: 2015–2016	–	–	0.86	0.84
Delavar et al. (2020)	Tashk-Bakhtegan (Fars, Iran/27,520)	SWAT-FARS; interface with WA+ water accounting framework	Cal: 1985–2006 Val: 2006–2014	–	–	0.56–0.73[n]	0.56–0.73[n]
Martínez-Salvador and Conesa-García (2020)	Upper Argos River (Murcia, Spain/510)	SWAT	Cal: 1976–2000 Val: 2001–2017	–	–	0.62	0.70
Nerantzaki et al. (2020)	Koiliaris River (Island of Crete, Greece/ 130[g])	SWAT & Karst-SWAT[o]	Cal: 2013–2017	0.59	–	0.81	–

Modifications

SWAT modifications for Karst

SWAT-ML

- This method is based on Baffaut and Benson (2009)
- A new parameter (X) was calibrated
- This parameter is non-dimensional and should be calibrated for karstic areas (HRUs)
- Return flow and delay time of infiltration were considred insignificant in karstic regions

SWAT-CF

- This method is based on crack flow module in SWAT
- Crack Flow (bypass flow) is used for vertisol soils
- Sol_CRK was calibrated in karstic areas (HRUs)
- There is no delay time and recharge directly goes to aquifer

SWAT-ML (Maharlu Lake)

For non-karstic areas (standard SWAT)

$$rchrg(j) = (1. - gw_{delay}(j)) * (sepbtm(j) + gwq_{ru}(j)) + gw_{delaye}(j) * rchrg1$$

For karstic areas

$$rchrg(j) = (1. - (exp(-1./((gw_{delay}(j))/X)))) * (sepbtm(j) + gwq_{ru}(j)) + (exp(-1./((gw_{delay}(j))/X))) * rchrg1$$

X can be calibrated for each HRU varies between (0, +∞)

This approach is similar to the approach described by **Baffaut and Benson (2009).**
Here, we have used the distributed approach.

SWAT-CF (Crack Flow)

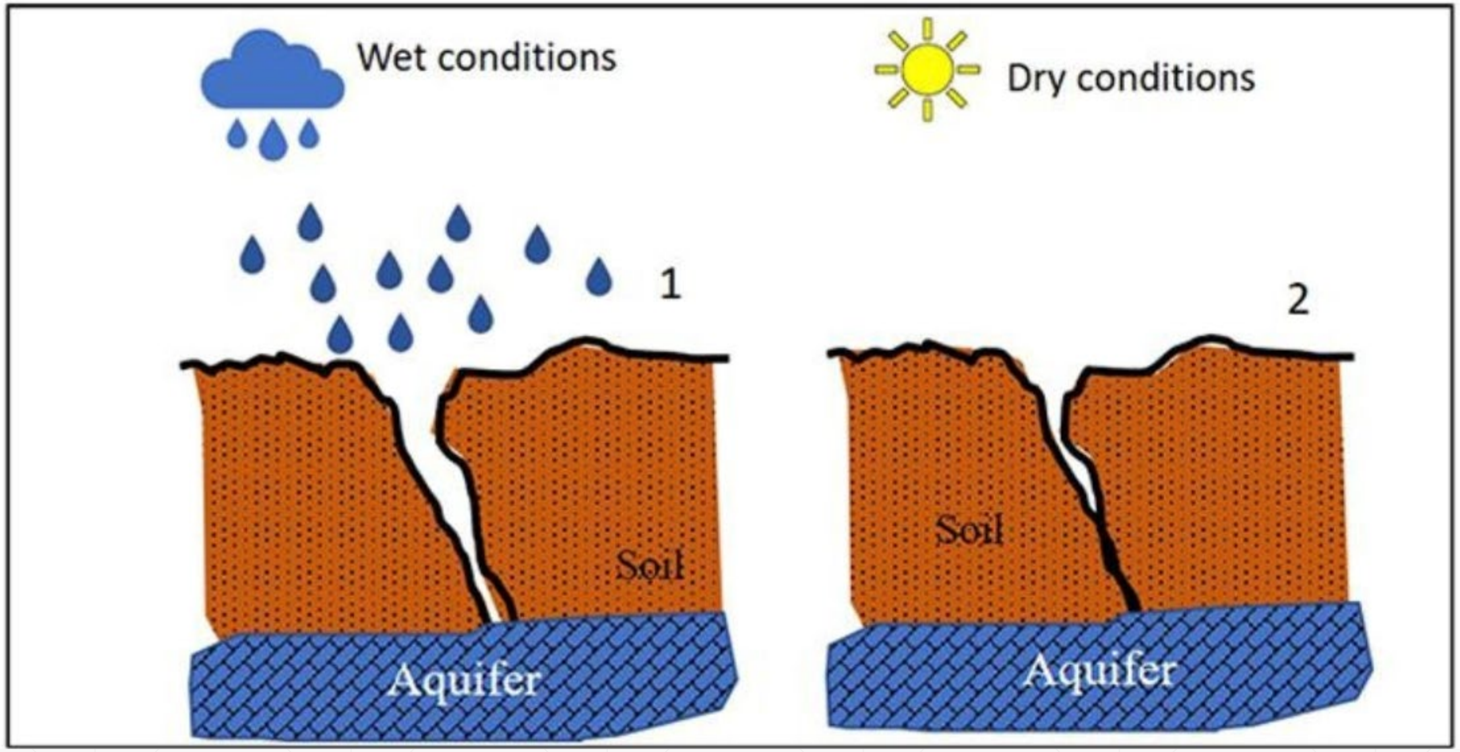
For karstic areas ICRK was activated

$$volcr(l,j) = crlag * volcr(l,j) + (1. - crlag) * volcrnew$$

Based on modifications, the sinks can be formed in wet conditions and always are active.

Sol_CRK was calibrated for karstic regions!

SWAT-Karst-MODFLOW!



Past works (SWAT and modified SWAT)

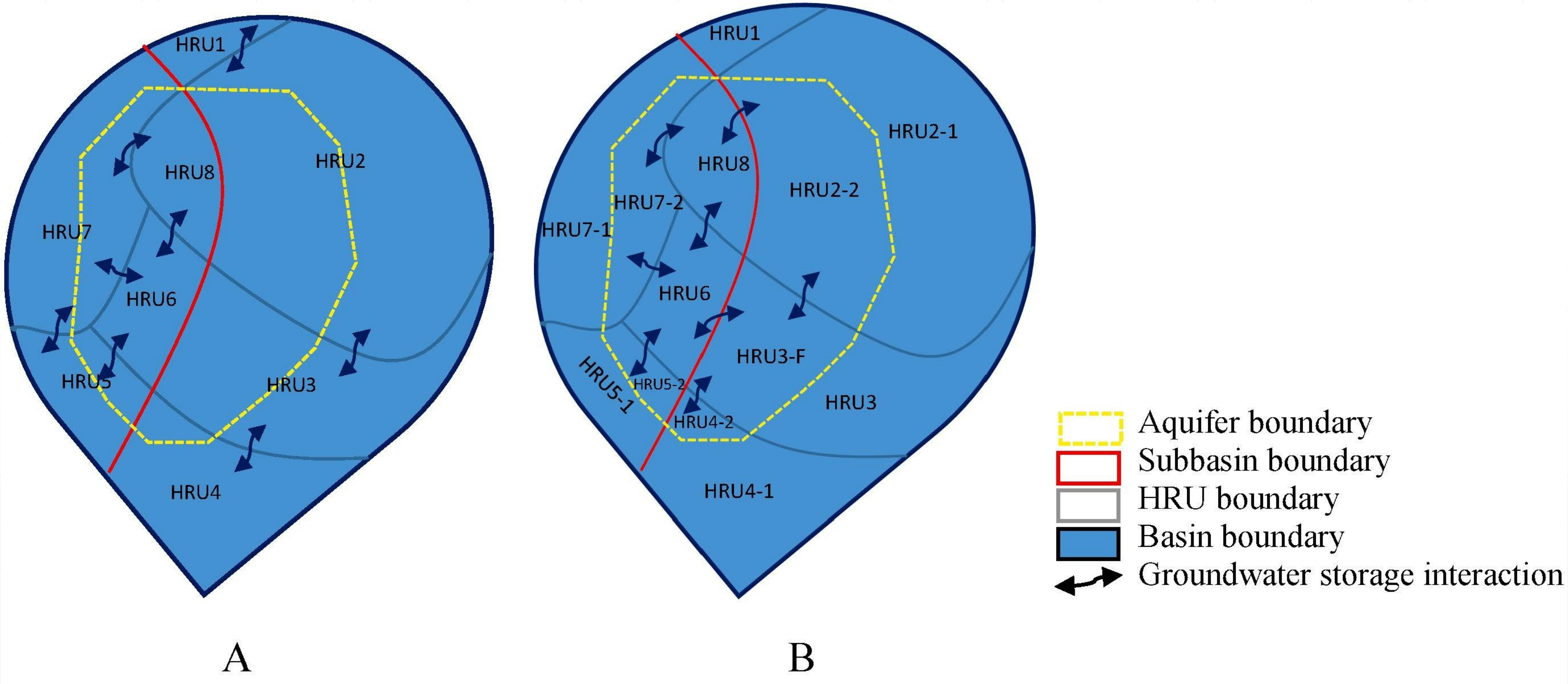
Catchment descriptions, SWAT models and simulation method for SWAT studies reporting applications of bypass (crack) or preferential flow.

Study	Catchment (region, country/km^2)	SWAT model	Bypass (crack) or preferential flow method
Arnold et al. (2005)	Riesel Y-2 (Texas, U.S./0.5)	SWAT	Vertisol shrink/swell bypass flow module[a]
Fu et al. (2014)	Harp Lake (Ontario, Canada/5.4)	SWAT-Canadian Shield (SWAT-CS)	Continuous macropore & infiltration module
Fu et al. (2015)	Harp Lake (Ontario, Canada/5.4)	SWAT-Canadian Shield (SWAT-CS)	Continuous macropore & infiltration module
Baffaut et al. (2015)	Goodwater Creek (Missouri, U.S./73)	Modified SWAT	Claypan infiltration & lateral flow function
Zhang et al. (2016)	Harp Lake (Ontario, Canada/5.4[b])	SWAT-CS[enm]	Continuous macropore & infiltration module
Rahbeh et al. (2019)	Zarqa River (Jordan/3,900[c])	SWAT	Ad hoc representation of preferential flow
Delavar et al. (2020)	Tashk-Bakhtegan (Fars, Iran/27,520)	SWAT-FARS	Vertisol shrink/swell bypass flow module

More modifications

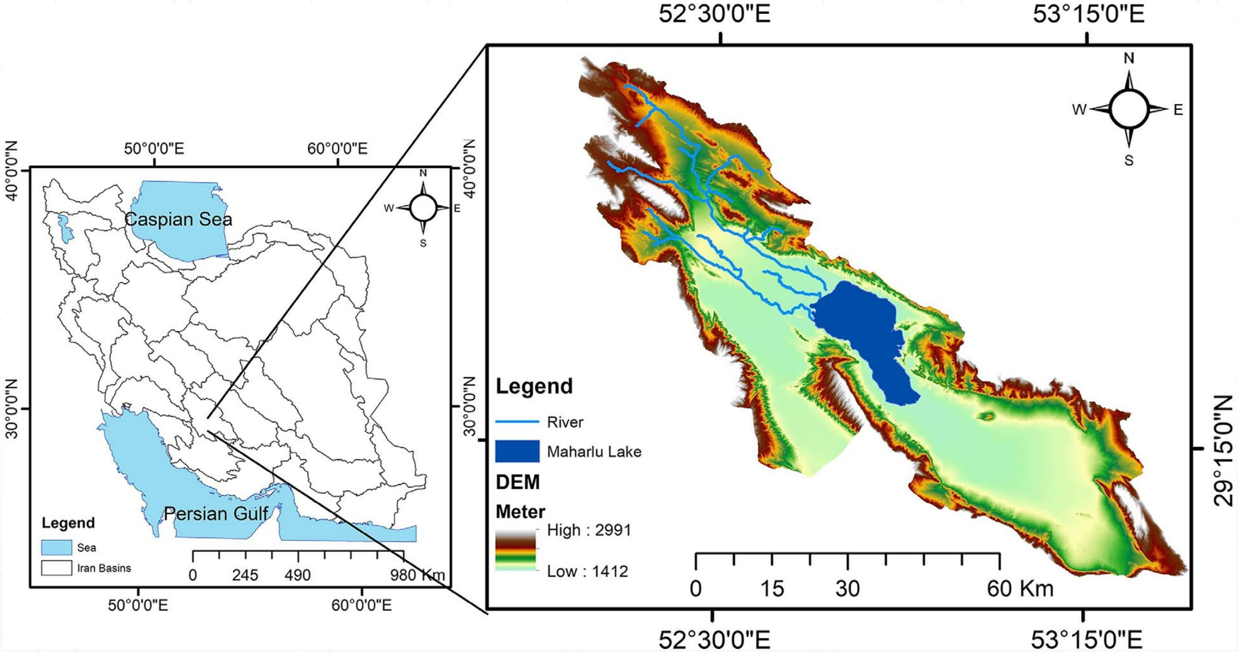
Aquifer presentation

Defining aquifer boundaries within subbasins and connecting HRUs which are in one aquifer



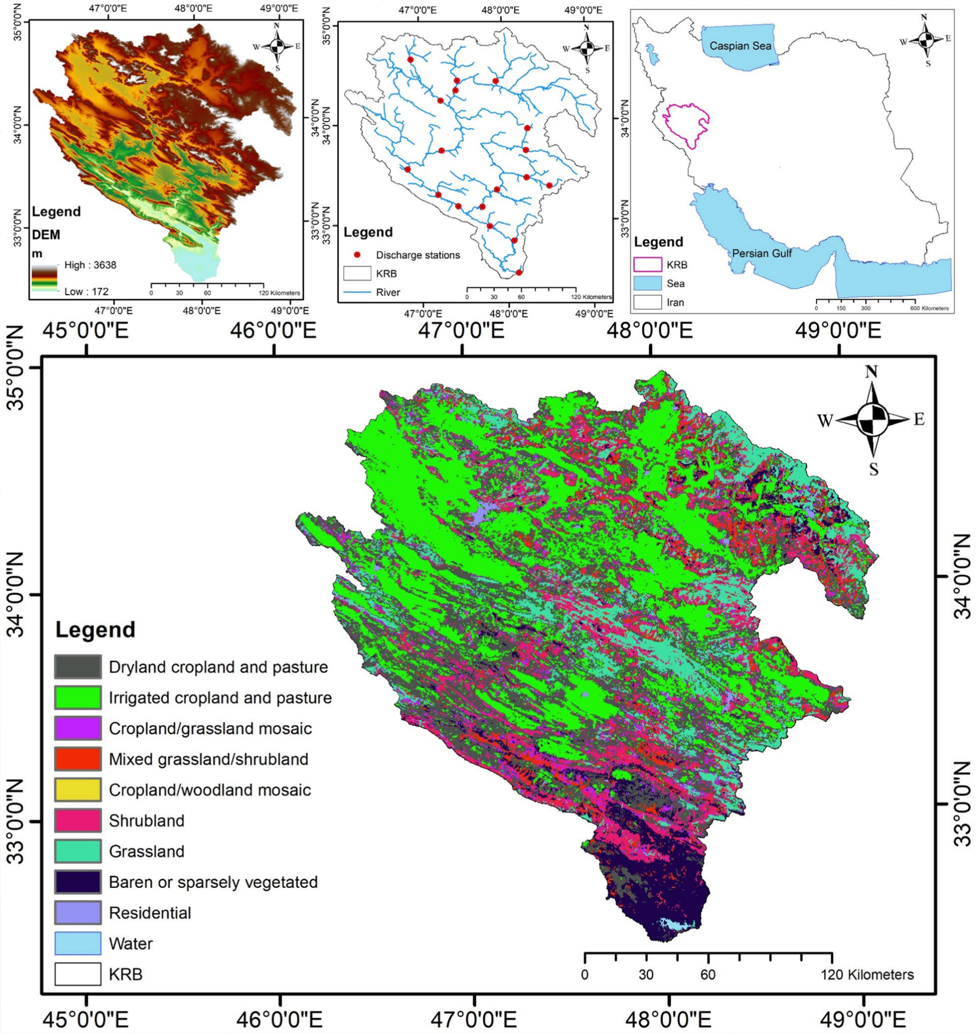
Study area

Maharlu lake basin and Karkeh river basin



4,270 sq-km

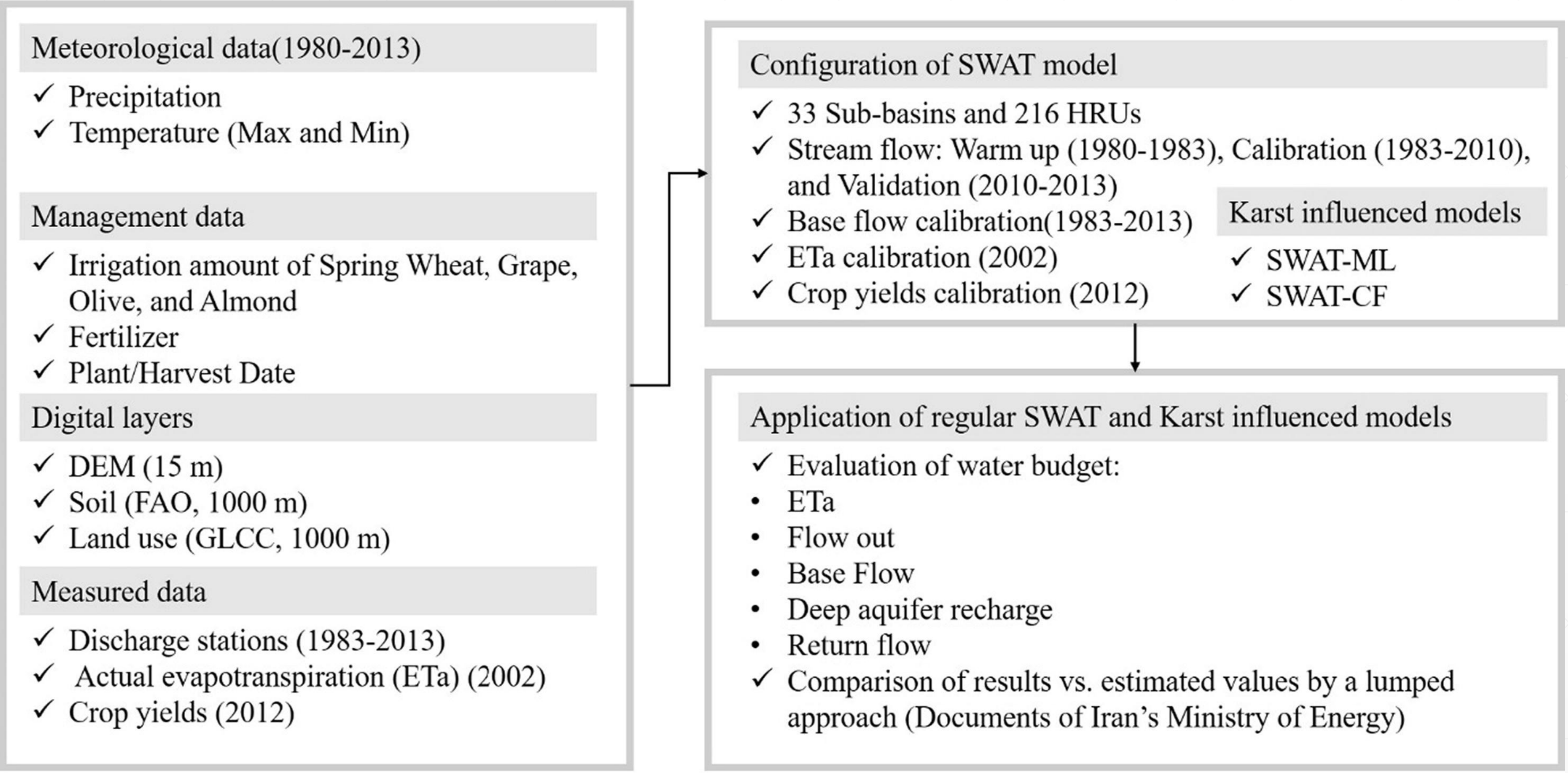
42,267 sq-km



Calibration

Multi-objective calibration:

Runoff
ET
Crop yields
Base flow
Amount of recharge
Groundwater table



Results

Almost no changes in river discharge calibration at Maharlu Lake basin

Results of calibration and validation of SWAT, SWAT-ML, and SWAT-CF model.

		R^2			NS		
Station		SWAT	SWAT-ML	SWAT-CF	SWAT	SWAT-ML	SWAT-CF
Nahre Azam	Calibration	0.68	0.71	0.72	0.52	0.66	0.55
	Validation	0.73	0.75	0.79	0.6	0.64	0.65
Rode Khoshk	Calibration	0.72	0.75	0.75	0.72	0.77	0.69
	Validation	0.81	0.80	0.69	0.78	0.77	0.77
Bagh Safa	Calibration	0.6	0.64	0.55	0.6	0.62	0.65
	Validation	0.65	0.67	0.61	0.66	0.67	0.69

Values of simulated product yield (kg / ha).

Plant	Yield (Kg/ha)	
	Observed	Simulated
Wheat	5322	4638
Olive	1461	1699
Grape	3325	3035

Comparison of simulated annual ETa (mm) values with observed ETa (mm) for 2002 (Andaryani et al., 2019).

	Wheat	Olive	Grape
SWAT	491	836	296
Observed	390	920	380

All related parameters were calibrated (and crop.dat parameters) (available in published papers)

Results

Significant changes in other water budget components

Evaluation of average infiltration values in a Karstic HRU with all Models.

Model	Infiltration (mm)	Deep aquifer recharge (mm)
SWAT-ML	282	11
SWAT-CF	238	16
SWAT	184	4

Comparison coefficient of determination of calibrated baseflow by each model vs. observed baseflow.

	R^2			NSE		
Discharge Stations	SWAT	SWAT-ML	SWAT-CF	SWAT	SWAT-ML	SWAT-CF
Nahre Azam	0.58	0.61	0.57	0.61	0.69	0.61
Rode Khoshk	0.66	0.71	0.7	0.62	0.7	0.67
Bagh Safa	0.31	0.37	0.33	0.45	0.46	0.45

The values of main components of the water budget in the study area. All figures are calibrated into MCM (Million Cubic Meter).

Approach	Precipitation	ETa	Runoff	Deep Aquifer Infiltration	Baseflow	Return Flow
SWAT	614	412.6	52	144	26.2	43
SWAT-ML	614	386.9	52.3	159	24.3	73
SWAT-CF	614	392.7	52	153	25.1	69
Ministry of Energy	614	345.5	52.9	197	23.6	61

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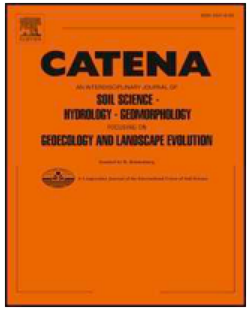

Development of alternative SWAT-based models for simulating water budget components and streamflow for a karstic-influenced watershed

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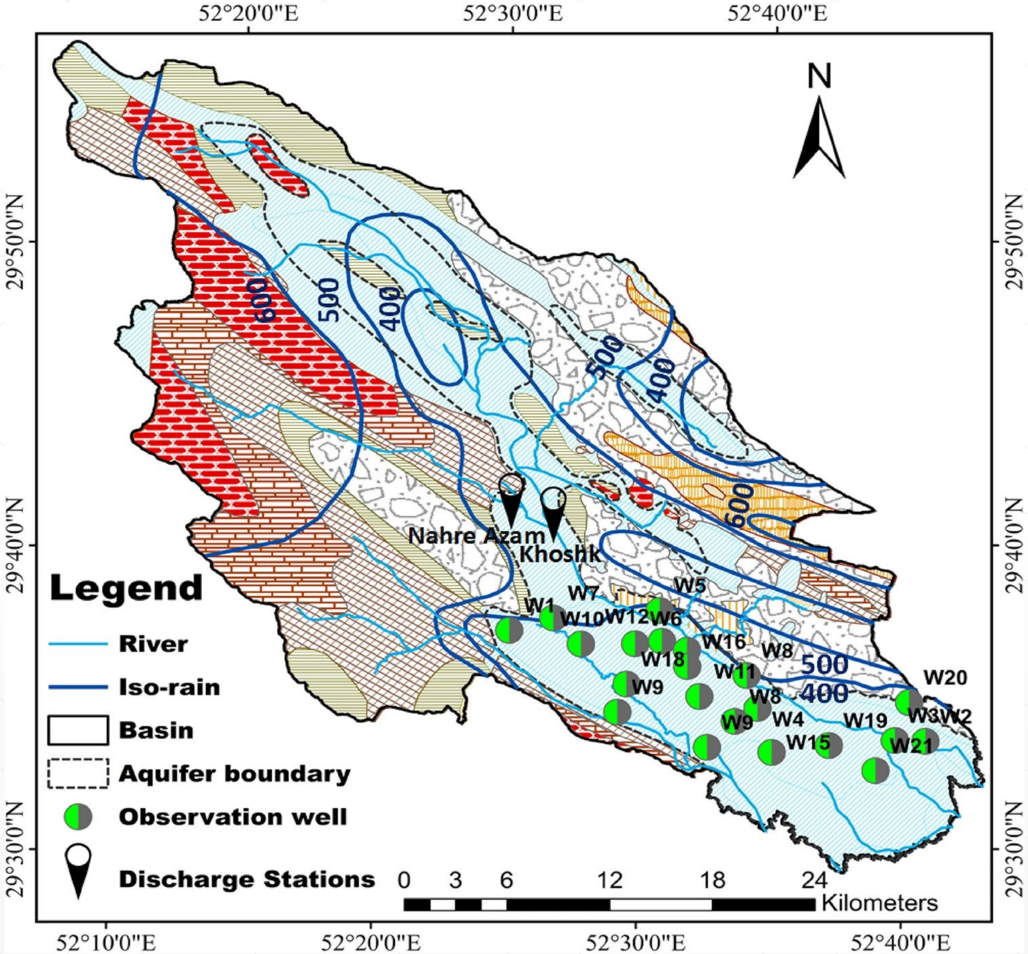
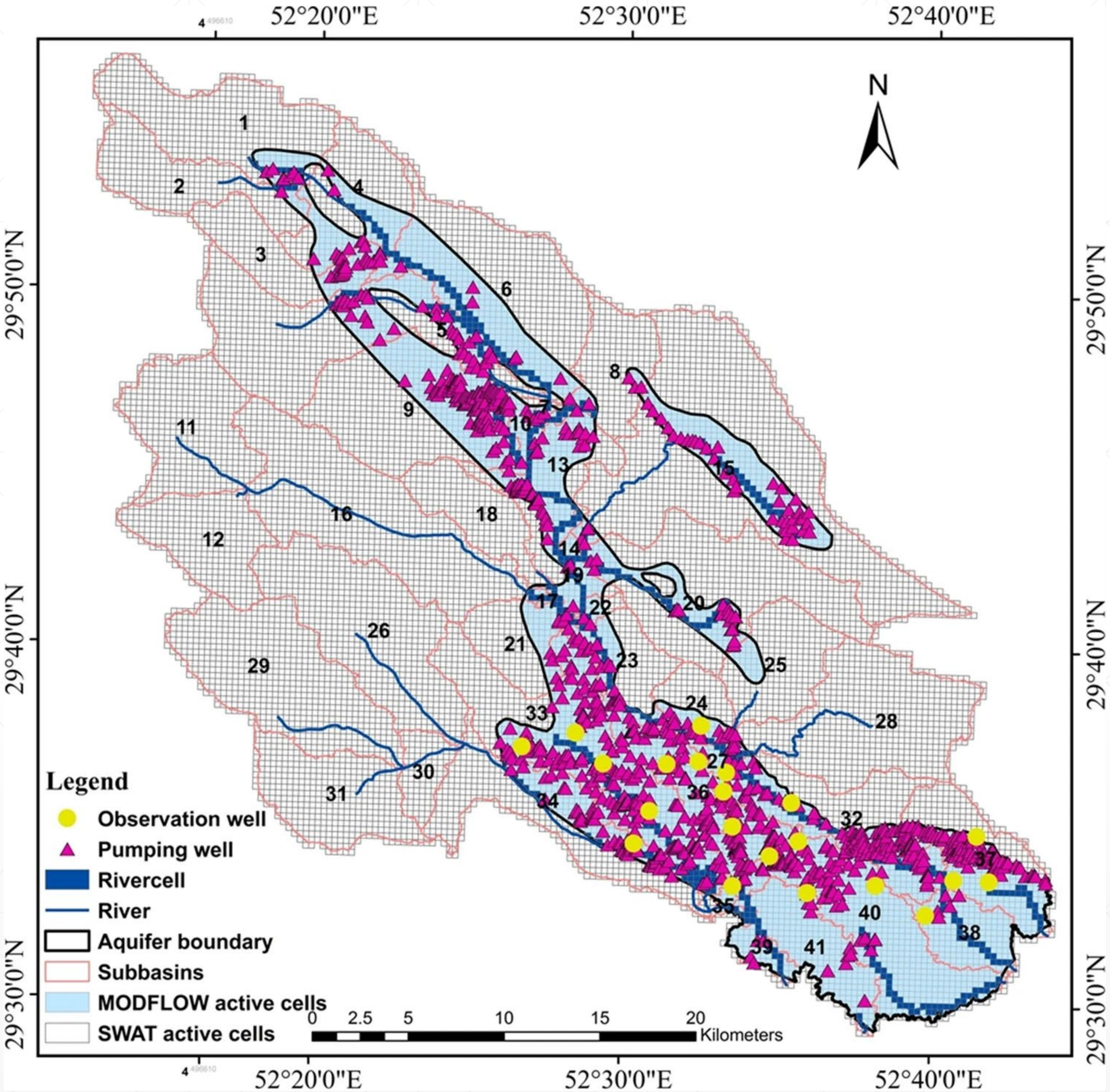
[e] *Sustainability Research Centre, University of the Sunshine Coast, Sunshine Coast, QLD 4556, Australia*

Results

SWAT-MODFLOW-CF





Results

SWAT-MODFLOW-CF

Table 4 Results of calibration and validation of surface water using the implemented models

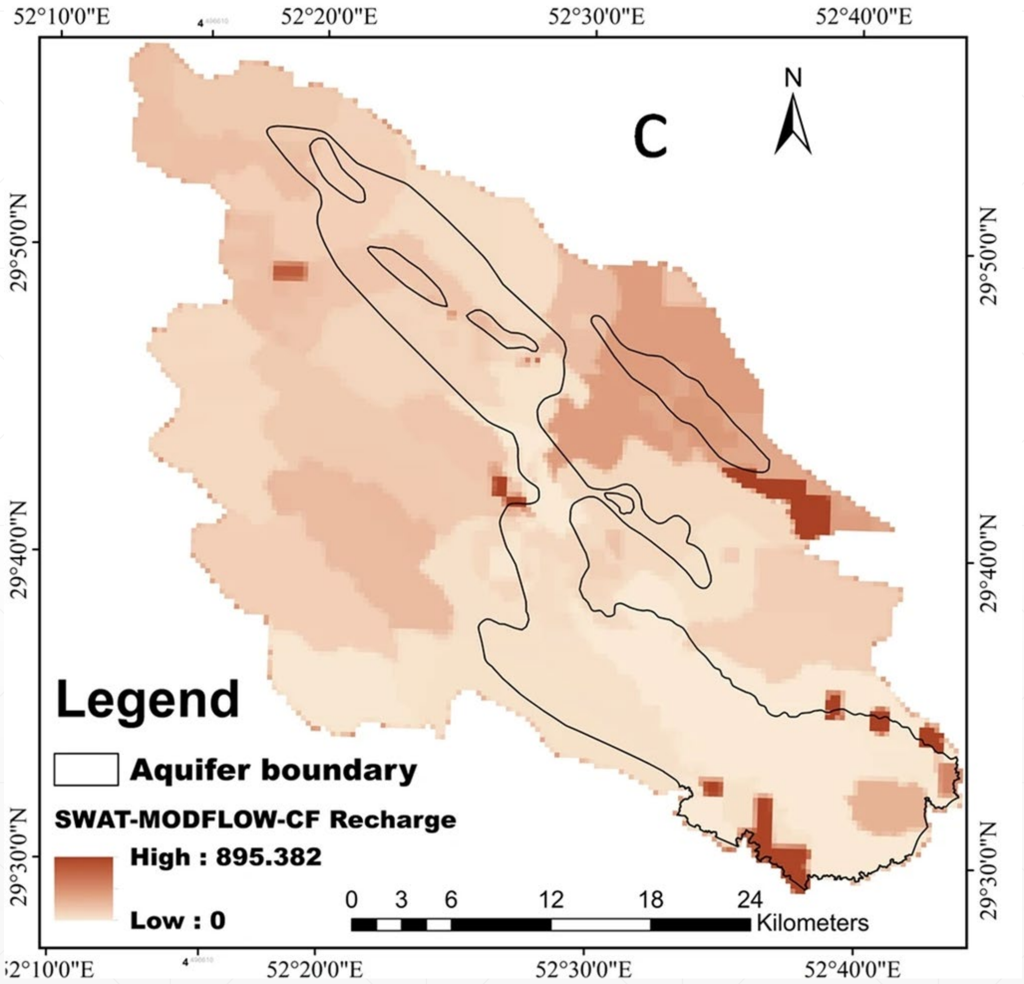
Discharge station		SWAT-M0DFLOW	SWAT-MODFLOW-CF	
		Calibration	Calibration	Validation
Khoshk	R^2	0/66	0/70	0/76
	NSE	0/62	0/66	0/64
Nahre Azam	R^2	0/70	0/75	0/8
	NSE	0/60	0/73	0/71

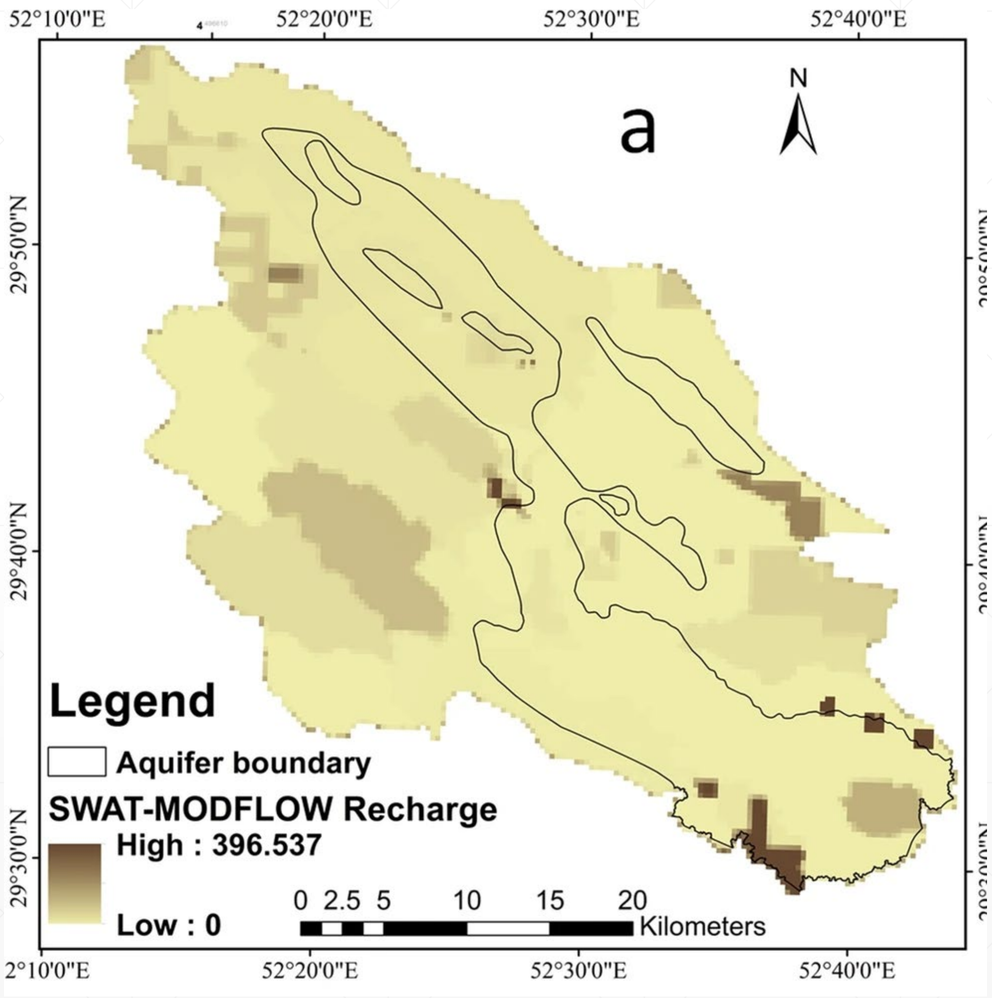
Table 5 Results of calibration and validation of groundwater level using the implemented models

Error coefficient	SWAT-MODFLOW	SWAT-MODFLOW-CF	
	Calibration	Calibration	Validation
RMSE	1/77	1/33	2/47
MAE	1/23	1/01	2/39

Results

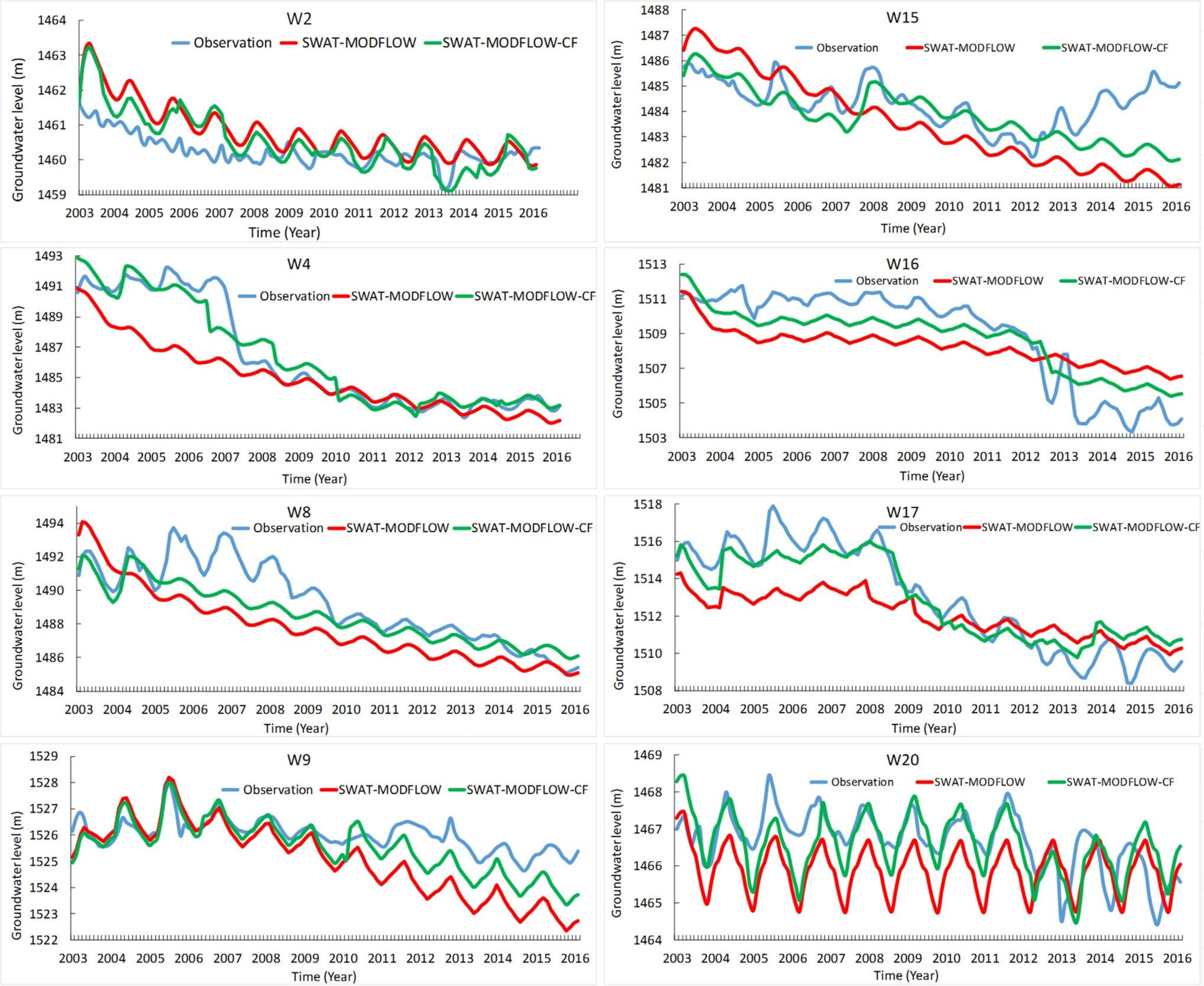
Amount of recharge





Results

Groundwater Level



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REPORT

Compilation simulation of surface water and groundwater resources using the SWAT-MODFLOW model for a karstic basin in Iran

Haniyeh Salmani[1] · Saman Javadi[2] · Mohammad Reza Eini[2,3] · Golmar Golmohammadi[4]

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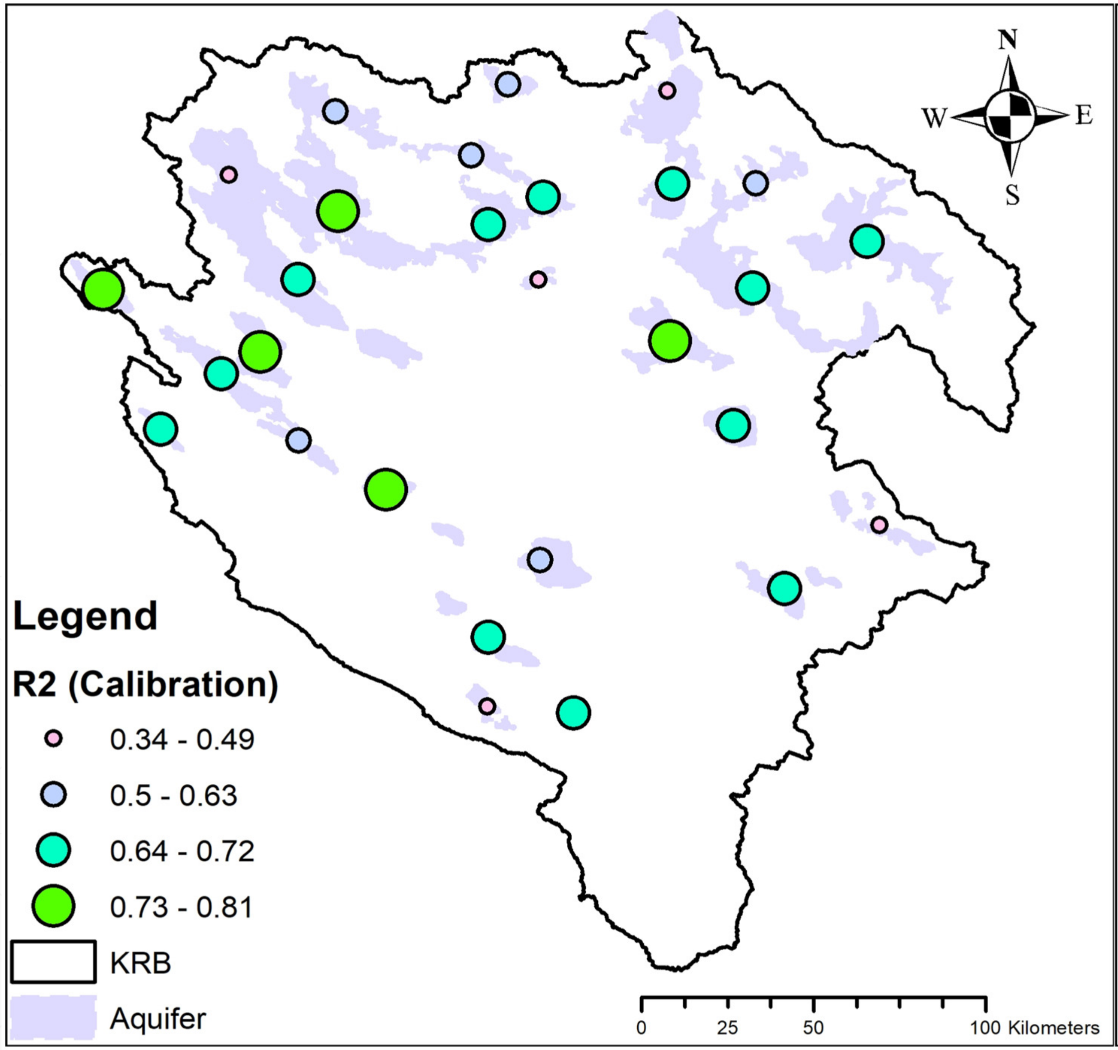
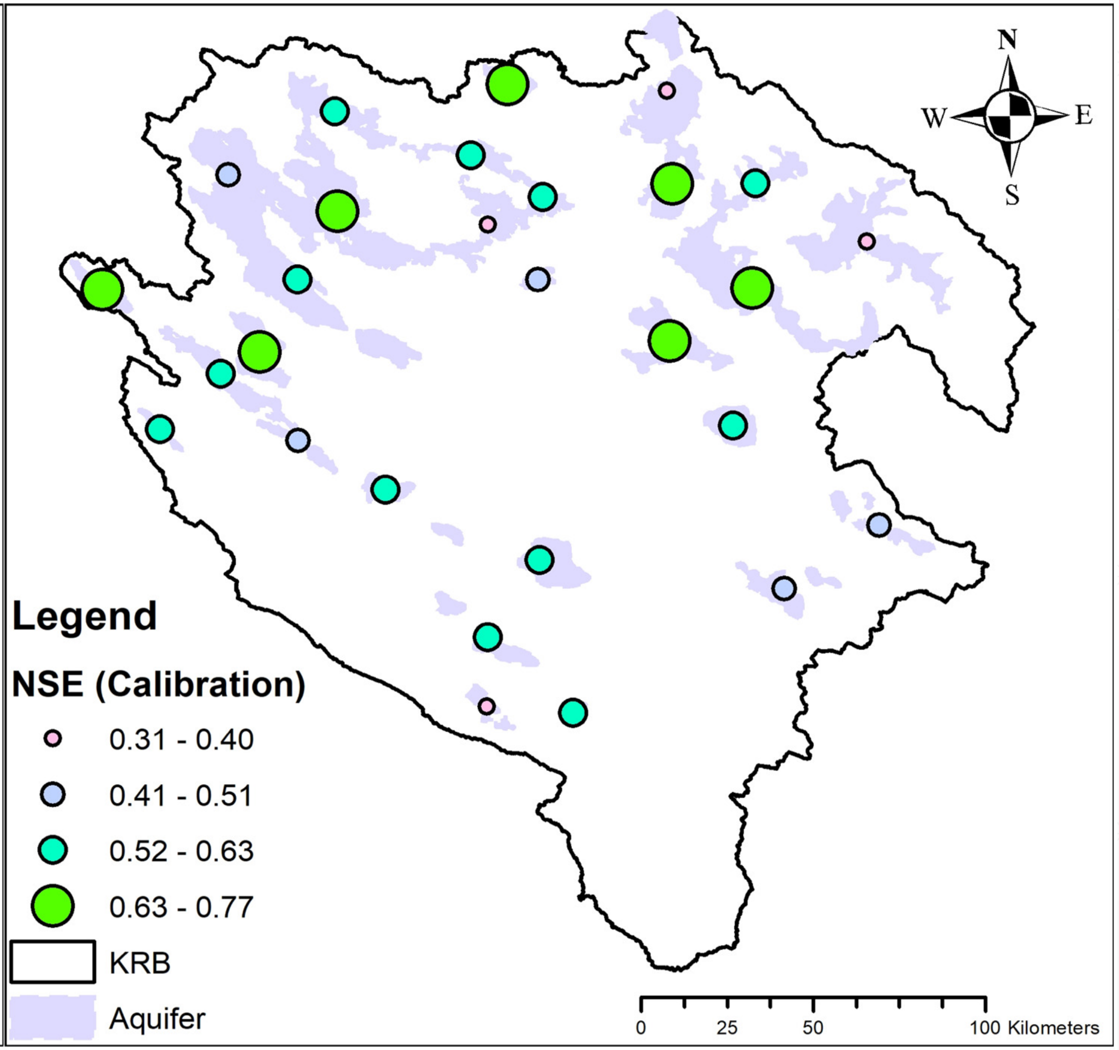
Water Accounting Assessments
Large scale basin (17 aquifers)





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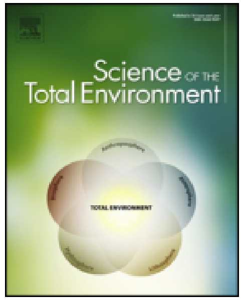

Model-based water accounting for integrated assessment of water resources systems at the basin scale

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Summary

- SWAT have been used in karstic basins with different accuracies
- SWAT can be modified with different approaches in karstic regions
- In semi-dry regions, the difference between modified SWAT and SWAT can be seen in infiltration and ET amounts
- In different regions, according to the karst features, SWAT can be altered differently (e.g. riverbed)

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Thanks for your attention!

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