Supplementary materials (SM)

Multi-model approach to quantify groundwater level prediction uncertainty using an ensemble of global climate models and multiple abstraction scenarios

Syed Md. Touhidul Mustafa [1,*], Md Moudud Hasan[1], Ajoy Kumar Saha[1], Rahena Parvin Rannu[1], Els Van Uytven[2], Patrick Willems [1,2] and Marijke Huysmans [1]

* Correspondence to: Syed Md Touhidul Mustafa (syed.mustafa@vub.be)

Supplementary materials (SM)

Supplementary materials (SM)-1: Study area

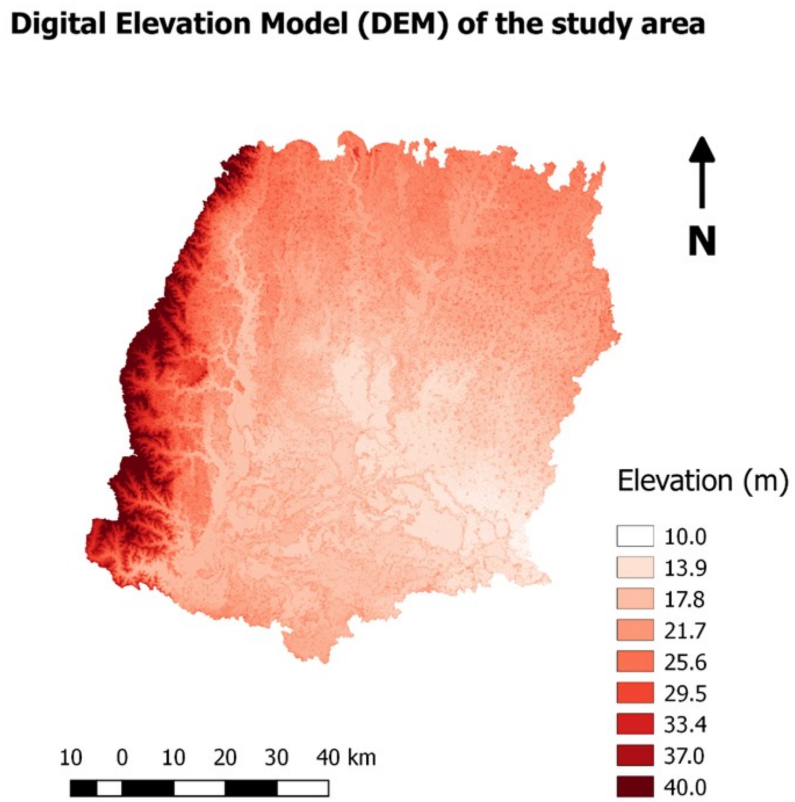

Figure SM-1: Digital Elevation Model (DEM) of the study area.

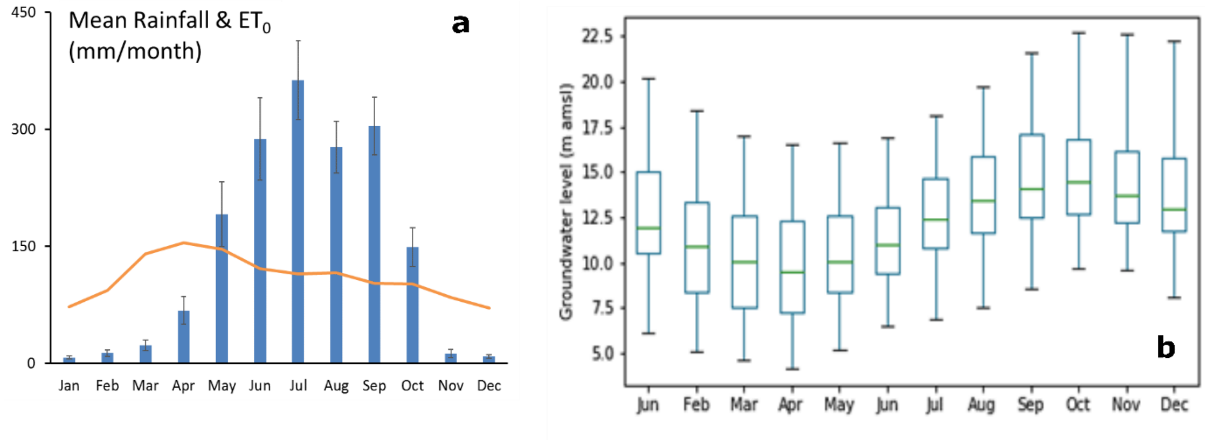

Figure SM-2: a: Average monthly ET_0 amounts (calculated, line) and average monthly precipitation amounts (measured, bars), b: groundwater level (measured, box-plots) distribution of the study area. The boxplot shows the variation of groundwater level in different observation wells in the study area. The green line in the middle of the box represents the median value of the mean monthly groundwater level.

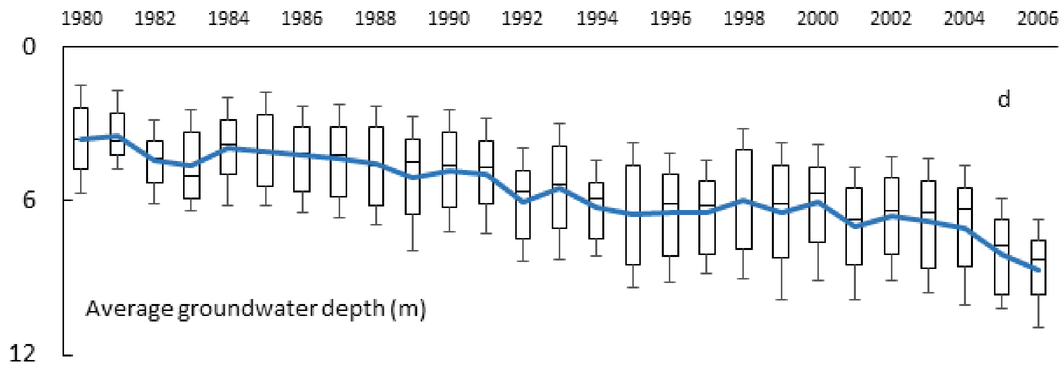

Figure SM-3: Time series of annual groundwater depth of the study area (box plots), including average (blue line).

Supplementary materials (SM)-2: alternative conceptual groundwater flow models

Table SM-1: List of alternative conceptual models developed based on different layer types and boundary conditions.

Sl. No.	Layer type	Boundary condition	Model ID
1		Boundary condition-1 (B1)	L1B1
2		Boundary condition-2 (B2)	L1B2
3	One-layered (L1)	Boundary condition-3 (B3)	L1B3
4		Boundary condition-4 (B4)	L1B4
5		Boundary condition-5 (B5)	L1B5
6		Boundary condition-1 (B1)	L2B1
7		Boundary condition-2 (B2)	L2B2
8	Two-layered (L2)	Boundary condition-3 (B3)	L2B3
9		Boundary condition-4 (B4)	L2B4
10		Boundary condition-5 (B5)	L2B5
11		Boundary condition-1 (B1)	L3B1
12		Boundary condition-2 (B2)	L3B2
13	Three-layered (L3)	Boundary condition-3 (B3)	L3B3
14		Boundary condition-4 (B4)	L3B4
15		Boundary condition-5 (B5)	L3B5

Table SM-2: List of optimized parameters of one-layered models with optimized value.

		Parameters		
		Horizontal hydraulic conductivity, Hk (m/s)	Specific yield, Sy (-)	Specific storage, Ss (m^{-1})
Initial value		1.05×10^{-03}	0.25	9.40×10^{-05}
Range		7×10^{-10} to 6×10^{-03}	0.02 to 0.35	4.92×10^{-05} to 2.56×10^{-03}
Optimized value	L1B1	6.00×10^{-03}	0.35	2.56×10^{-03}
	L1B2	6.00×10^{-03}	0.35	2.56×10^{-03}
	L1B3	6.00×10^{-03}	0.35	1.39×10^{-04}
	L1B4	6.00×10^{-03}	0.35	4.92×10^{-05}
	L1B5	4.45×10^{-03}	0.35	4.92×10^{-05}

Table SM-3: List of optimized parameters of two-layered models with optimized value.

Layer	Parameters	Initial value	Range		Optimized value				
			Minimum	Maximum	L2B1	L2B2	L2B3	L2B4	L2B5
Top layer	1. Horizontal hydraulic conductivity (m s^{-1})	4.6×10^{-06}	7×10^{-10}	4.6×10^{-06}	2.54×10^{-08}	2.59×10^{-06}	4.42×10^{-09}	1.10×10^{-08}	4.94×10^{-08}
	2. Vertical hydraulic conductivity (m s^{-1})	9.9×10^{-08}	7×10^{-11}	4.6×10^{-07}	1.18×10^{-08}	1.10×10^{-08}	1.05×10^{-08}	1.20×10^{-08}	1.03×10^{-08}
	3. Specific yield (-)	0.18	0.02	0.19	0.19	0.19	0.19	0.19	0.19
	4. Specific storage(m^{-1})	1.74×10^{-03}	9.19×10^{-04}	2.56×10^{-03}	9.19×10^{-04}	9.19×10^{-04}	9.19×10^{-04}	9.19×10^{-04}	9.19×10^{-04}
Bottom layer	5. Horizontal hydraulic conductivity (m s^{-1})	1.25×10^{-03}	3×10^{-04}	6×10^{-03}	5.28×10^{-03}	2.91×10^{-03}	6.00×10^{-03}	6.00×10^{-03}	5.45×10^{-03}
	6. Vertical hydraulic conductivity (m s^{-1})	1.25×10^{-04}	3×10^{-05}	6×10^{-04}	6.00×10^{-04}	6.00×10^{-04}	6.00×10^{-04}	6.00×10^{-04}	5.63×10^{-04}
	7. Specific yield (-)	0.25	0.10	0.35	0.35	0.35	0.35	0.35	0.35
	8. Specific storage(m^{-1})	9.40×10^{-05}	4.92×10^{-05}	1.02×10^{-03}	1.02×10^{-03}	4.54×10^{-04}	5.19×10^{-04}	5.48×10^{-04}	5.72×10^{-04}

Table SM-4: List of optimized parameters of three-layered models with optimized value.

Layer	Parameters	Initial value	Range		Optimized value				
			Minimum	Maximum	L3B1	L3B2	L3B3	L3B4	L3B5
Top layer	1. Horizontal hydraulic conductivity (m s^{-1})	4.6×10^{-06}	7×10^{-10}	4.6×10^{-06}	8.26×10^{-09}	4.18×10^{-09}	8.44×10^{-08}	2.54×10^{-06}	3.76×10^{-06}
	2. Vertical hydraulic conductivity (m s^{-1})	9.9×10^{-08}	7×10^{-11}	4.6×10^{-07}	1.10×10^{-08}	1.17×10^{-08}	9.97×10^{-09}	1.05×10^{-08}	9.69×10^{-09}
	3. Specific yield (-)	0.18	0.02	0.19	0.19	0.19	0.17	0.19	0.19
	4. Specific storage(m^{-1})	1.74×10^{-03}	9.19×10^{-04}	2.56×10^{-03}	1.36×10^{-03}	9.19×10^{-04}	9.19×10^{-04}	9.19×10^{-04}	1.14×10^{-03}
Middle layer	5. Horizontal hydraulic conductivity (m s^{-1})	3×10^{-04}	2×10^{-07}	3×10^{-04}	2.40×10^{-04}	2.55×10^{-04}	3.00×10^{-04}	3.56×10^{-05}	3.00×10^{-04}
	6. Vertical hydraulic conductivity (m s^{-1})	3×10^{-05}	2×10^{-08}	8×10^{-05}	7.97×10^{-05}	5.07×10^{-06}	5.07×10^{-06}	8.00×10^{-05}	8.00×10^{-05}
	7. Specific yield (-)	0.25	0.10	0.32	0.32	0.32	0.32	0.32	0.32
	8. Specific storage(m^{-1})	5.74×10^{-04}	1.28×10^{-04}	1.3×10^{-03}	1.02×10^{-03}	1.02×10^{-03}	1.02×10^{-03}	1.02×10^{-03}	1.02×10^{-03}
Bottom layer	9. Horizontal hydraulic conductivity (m s^{-1})	1.25×10^{-03}	5.8×10^{-04}	6×10^{-03}	2.99×10^{-03}	4.53×10^{-03}	6.00×10^{-03}	6.00×10^{-03}	5.35×10^{-03}
	10. Vertical hydraulic conductivity (m s^{-1})	1.25×10^{-04}	3×10^{-05}	6×10^{-04}	6.00×10^{-04}	6.00×10^{-04}	1.49×10^{-04}	6.00×10^{-04}	6.00×10^{-04}
	11. Specific yield (-)	0.32	0.15	0.35	0.35	0.31	0.35	0.35	0.35
	12. Specific storage(m^{-1})	9.40×10^{-05}	4.92×10^{-05}	2.03×10^{-04}	2.03×10^{-04}	2.03×10^{-04}	2.03×10^{-04}	2.03×10^{-04}	2.03×10^{-04}

Table SM-5: Model evaluation statistics for calibration and validation period.

Model ID	Calibration period				Validation period			
	RMSE (m)	σ^2	NSE	PBIAS (%)	RMSE (m)	σ^2	NSE	PBIAS (%)
L1B1	2.27	5.15	0.55	-5.34	2.62	6.84	0.45	-7.83
L1B2	2.26	5.09	0.55	-5.49	2.72	7.40	0.41	-10.29
L1B3	2.27	5.15	0.55	-5.91	2.71	7.33	0.42	-10.23
L1B4	2.19	4.79	0.58	-4.91	2.70	7.29	0.42	-9.69
L1B5	2.31	5.32	0.53	-6.38	2.74	7.50	0.40	-11.32
L2B1	2.15	4.61	0.60	2.26	2.60	6.76	0.46	2.81
L2B2	2.25	5.05	0.56	4.59	2.59	6.68	0.47	3.48
L2B3	2.02*	4.08*	0.64*	2.53	2.66	7.05	0.44	2.94
L2B4	2.03	4.12	0.64*	2.17	2.56	6.54	0.48	0.45*
L2B5	2.04	4.16	0.63	1.12*	2.50*	6.25*	0.50*	0.49
L3B1	2.48	6.14	0.46	-1.44	2.66	7.05	0.44	4.63
L3B2	2.17	4.70	0.59	3.37	2.71	7.33	0.42	4.27
L3B3	2.08	4.31	0.62	2.57	2.70	7.29	0.42	4.21
L3B4	2.07	4.28	0.62	2.74	2.89	8.35	0.33	8.10
L3B5	2.12	4.49	0.61	2.38	2.57	6.59	0.47	2.04

*Best value

Table SM-6: Comparison of performance of BMA mean prediction with the best model and ensemble median for both calibration and validation period.

Method	Calibration period				Validation period			
	RMSE (m)	σ2	NSE	PBIAS (%)	RMSE (m)	σ2	NSE	PBIAS (%)
Best Model*	2.02	4.08	0.64	2.53	2.56	6.54	0.48	0.45
Median	2.01	4.05	0.65	0.87	2.53	6.41	0.49	2.01
BMA	1.97	3.89	0.66	0.00	2.30	5.31	0.58	0.00

*Best model based on AIC, AICc, BIC and KIC value.

Supplementary materials (SM)-3: Climatic models

Table SM-7: Ensemble of climate models used in this study

Institution	Climate model run		
Commonwealth Scientific and Industrial Research Organization/ Bureau of Meteorology (CSIRO-BOM)	ACCESS1.0	r1i1p1	RCP 8.5
Beijing Climate Center, China Meteorological Administration	BCC-CSM1.1m	r1i1p1	RCP 4.5, RCP 8.5
College of Global Change and Earth System Science, Beijing Normal University	BNU-ESM	r1i1p1	RCP 4.5
Canadian Centre for Climate Modelling and Analysis	CanESM2	r1/r2/r4/r5i1p1	RCP 4.5, RCP 8.5
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC-CESM	r1i1p1	RCP 8.5
	CMCC-CMS	r1i1p1	RCP 4.5, RCP 8.5
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (CNRM/CERFACS)	CNRM-CM5	r1i1p1	RCP 4.5, RCP 8.5
Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)	CSIRO-Mk3.6.0	r10i1p1	RCP 4.5, RCP 8.5
EC-EARTH consortium	EC-EARTH	r12i1p1	RCP 4.5
Geophysical Fluid Dynamics Laboratory	GFDL-ESM2G	r1i1p1	RCP 8.5
	GFDL-ESM2M	r1i1p1	RCP 8.5
NASA Goddard Institute for Space Studies	GISS-E2-H	r6i1p3	RCP 4.5
	GISS-E2-R	r6i1p1/p3	RCP 4.5
Met Office Hadley Centre	HadGEM2-ES	r1i1p1	RCP 8.5
Institute for Numerical Mathematics	INM-CM4	r1i1p1	RCP 4.5, RCP 8.5

Institute Pierre-Simon Laplace	IPSL-CM5A-LR	r2i1p1	RCP 4.5, RCP 8.5
	IPSL-CM5A-MR	r1i1p1	RCP 4.5, RCP 8.5
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC-ESM	r1i1p1	RCP 4.5, RCP 8.5
	MIROC5	r1i1p1	RCP 8.5
	MIROC5	r2/r3i1p1	RCP 4.5, RCP 8.5
Max Planck Institute for Meteorology (MPI-M), Germany	MPI-ESM-LR	r1i1p1	RCP 4.5, RCP 8.5
Meteorological Research Institute	MRI-CGCM3	r1i1p1	RCP 4.5, RCP 8.5

Table SM-8: 25th, 50th, 75th percentile changes in monthly precipitation amount, minimum, mean and maximum daily temperature and potential evapotranspiration for April and September (all GHSs combined, 1975-2035)

	April			September		
	25th	50th	75th	25th	50th	75th
Monthly precipitation amount (%)	-19.80	-8.20	11.70	-0.60	11.10	17.00
Minimum daily temperature (°C)	1.33	1.74	2.00	1.06	1.35	1.72
Mean daily temperature (°C)	0.98	1.40	1.87	0.79	1.28	1.68
Maximum daily temperature (°C)	0.57	1.24	1.91	0.65	1.28	1.67
Evapotranspiration (%)	-1.60	1.50	3.60	-1.10	1.00	3.40

Supplementary materials (SM)-4: Trend analysis

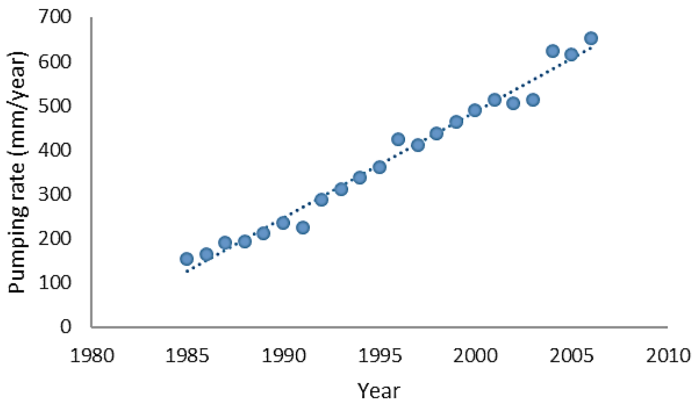

Figure SM-4: General groundwater abstraction trend in the study area from 1985 to 2006.

Table SM-9: Annual groundwater level trend in 50 observation wells for different abstraction scenarios (P_{Linear}, $P_{Constant}$, $P_{Reduced\_30}$) and recharge scenarios (Low, High) in the baseline (1985–2006) and simulated future (2026–2047) period.

Observation Wells	Baseline period	Simulated future period					
		P_{Linear}		$P_{Constant}$		$P_{Reduced\_30}$	
		Low	High	Low	High	Low	High
	Slope (m/year)						
BOG001	-0.15*	-0.34*	-0.31*	-0.08*	-0.06	-0.04	-0.04
BOG004	-0.49*	-1.01*	-0.95*	-0.46*	-0.37*	-0.25*	-0.14
BOG009	-0.15*	-0.36*	-0.34*	-0.11*	-0.07	-0.06*	-0.03
BOG013	-0.25*	-0.49*	-0.47*	-0.21*	-0.17*	-0.12*	-0.07
BOG014	-0.05*	-0.09*	-0.09*	-0.04*	-0.03	-0.02	-0.02
JOY003	-0.06*	-0.07*	-0.08*	-0.03	-0.03	-0.02	-0.01
JOY005	-0.21*	-0.41*	-0.40*	-0.15*	-0.13	-0.09	-0.05
NAO001	-0.07	-0.22*	-0.20*	-0.07*	-0.04*	-0.04*	-0.01
NAO002	-0.08*	-0.16*	-0.16*	-0.03*	-0.02	-0.02	-0.01
NAO004	-0.08	-0.13*	-0.13*	-0.01	-0.01	-0.01	-0.01
NAO008	-0.08*	-0.11*	-0.11*	-0.01	-0.01	-0.01	-0.01
NAO009	-0.10	-0.13*	-0.13*	-0.01	-0.01	-0.01	-0.01
NAO013	-0.06	-0.06*	-0.06*	-0.01	-0.01	-0.01	-0.01
NAO014	-0.12	-0.18*	-0.17*	-0.03*	-0.03	-0.02	-0.02

Observation Wells	Baseline period	Simulated future period					
		P_{Linear}		$P_{Constant}$		$P_{Reduced\_30}$	
		Low	High	Low	High	Low	High
	Slope (m/year)						
NAO015	-0.19	-0.40*	-0.38*	-0.06	-0.03	-0.03	-0.01
NAO018	-0.23	-0.38*	-0.36*	-0.14*	-0.09	-0.08*	-0.05
NAO019	-0.15	-0.30*	-0.27*	-0.06*	-0.03	-0.03	-0.01
NAO020	-0.19	-0.35*	-0.33*	-0.04	-0.02	-0.02	-0.01
NAO021	-0.25	-0.50*	-0.44*	-0.22*	-0.14*	-0.13*	-0.06
NAO022	-0.14	-0.32*	-0.28*	-0.08*	-0.03	-0.03	-0.01
NAO023	-0.24	-0.57*	-0.52*	-0.27*	-0.18*	-0.16*	-0.07
NAO024	-0.40	-1.15*	-1.09*	-0.55*	-0.38*	-0.32*	-0.13*
NAO026	-0.14	-0.25*	-0.24*	-0.03	-0.02	-0.02	-0.01
NAO027	-0.14	-0.27*	-0.26*	-0.05*	-0.02	-0.02	-0.01
NAO031	-0.30*	-0.25*	-0.23*	-0.40*	-0.33*	-0.27*	-0.21*
NAO035	-0.18*	-0.15*	-0.14*	-0.11*	-0.09*	-0.08*	-0.05
NAO036	-0.23	-0.25*	-0.23*	-0.15*	-0.11*	-0.10*	-0.07
NAO040	-0.15*	-0.18*	-0.17*	-0.05*	-0.04	-0.03	-0.03
NAO043	-0.27	-0.29*	-0.28*	-0.26*	-0.20*	-0.18*	-0.12*
NAO047	-0.14*	-0.29*	-0.28*	-0.05*	-0.03	-0.03	-0.03
NAO048	-0.18*	-0.36*	-0.34*	-0.06*	-0.05	-0.04	-0.04
RAJ001	-0.23	-1.54*	-1.30*	-0.44*	-0.23*	-0.23*	-0.05
RAJ002	-0.26	-1.15*	-0.99*	-0.44*	-0.26*	-0.24*	-0.06
RAJ003	-0.20	-0.98*	-0.84*	-0.34*	-0.19*	-0.18*	-0.04
RAJ004	-0.29	-1.66*	-1.41*	-0.57*	-0.32*	-0.30*	-0.07
RAJ005	-0.29	-3.35*	-2.87*	-0.89*	-0.53*	-0.46*	-0.12*
RAJ006	-0.50	-2.29	-2.80*	-1.01*	-0.53*	-0.48*	-0.10*
RAJ015	-0.39	-2.74*	-2.28*	-0.83*	-0.47*	-0.43*	-0.11
RAJ020	-0.67	-3.89*	-3.68*	-1.88*	-1.54*	-1.13*	-0.79*
RAJ021	-0.72	-3.80*	-3.57*	-1.65*	-1.30*	-0.99*	-0.65*
RAJ024	-0.66	-3.89*	-3.71*	-1.84*	-1.48*	-1.10*	-0.76*
RAJ030	-0.47	-1.59*	-1.49*	-0.76*	-0.51*	-0.42*	-0.18*
RAJ031	-0.63	-1.96*	-1.92*	-1.12*	-0.78*	-0.62*	-0.29*
RAJ035	-0.37	-3.29*	-2.74*	-0.86*	-0.48*	-0.44*	-0.09*

Observation Wells	Baseline period	Simulated future period					
		P_{Linear}		$P_{Constant}$		$P_{Reduced\_30}$	
		Low	High	Low	High	Low	High
	Slope (m/year)						
RAJ036	-0.38	-3.40*	-2.91*	-0.98*	-0.60*	-0.52*	-0.16*
RAJ038	-0.41	-3.41*	-2.95*	-1.02*	-0.63*	-0.55*	-0.18*
RAJ041	-0.33	-2.54*	-2.15*	-0.65*	-0.35*	-0.34*	-0.07
RAJ042	-0.21	-1.47*	-1.23*	-0.39*	-0.21*	-0.21*	-0.04
RAJ043	-0.22	-2.00*	-1.67*	-0.50*	-0.27*	-0.27*	-0.05
RAJ046	-0.90	-1.72	-2.29	-1.37*	-1.02*	-0.74*	-0.43*

*The trend is significant at 0.05 level.