Article

Determining Regional-Scale Groundwater Recharge with GRACE and GLDAS

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Abstract: Groundwater recharge (GR) is a key component of regional and global water cycles and is a critical flux for water resource management. However, recharge estimates are difficult to obtain at regional scales due to the lack of an accurate measurement method. Here, we estimate GR using Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) data. The regional-scale GR rate is calculated based on the groundwater storage fluctuation, which is, in turn, calculated from the difference between GRACE and root zone soil water storage from GLDAS data. We estimated GR in the Ordos Basin of the Chinese Loess Plateau from 2002 to 2012. There was no obvious long-term trend in GR, but the annual recharge varies greatly from 30.8 to 66.5 mm yr^{-1}, 42% of which can be explained by the variability in the annual precipitation. The average GR rate over the 11-year period from GRACE data was 48.3 mm yr^{-1}, which did not differ significantly from the long-term average recharge estimate of 39.9 mm yr^{-1} from the environmental tracer methods and one-dimensional models. Moreover, the standard deviation of the 11-year average GR is 16.0 mm yr^{-1}, with a coefficient of variation (*CV*) of 33.1%, which is, in most cases, comparable to or smaller than estimates from other GR methods. The improved method could provide critically needed, regional-scale GR estimates for groundwater management and may eventually lead to a sustainable use of groundwater resources.

Keywords: Water table fluctuation; Water storage fluctuation; Loess Plateau; Ordos Basin; Interannual groundwater recharge; GRACE

Table 1. The annual water storage variations in Wanjiazhai reservoirs on the Loess Plateau in 2003-2016, Data based on the Yellow River Water Resources Bulletin (http://www.yellowriver.gov.cn/other/hhgb/).

Year	Water Storage Variable ($10^8 m^3$)	Water Equivalent (mm)
2003	0.65	0.20
2004	−0.94	−0.29
2005	−1.11	−0.35
2006	1.70	0.53
2007	0.25	0.08
2008	−0.94	−0.29
2009	0.03	0.01
2010	−1.09	−0.34
2011	−0.18	−0.06
2012	1.36	0.43
2013	−0.36	−0.11
2014	0.52	0.16
2015	−1.42	−0.44

Table 2. Table S2: Annual sediment runoff records at Tongguan hydrological station with a drainage area 680000 km^2, Data based on the Yellow River Sediment Bulletin (http://www.yellowriver.gov.cn/nishagonggao/).

Year	Sediment Runoff ($10^8 t$)	Water Equivalent (mm)
2006	2.47	0.36
2007	2.50	0.37
2008	1.30	0.19
2009	1.10	0.16
2010	1.30	0.19
2011	1.30	0.19
2012	2.10	0.31
2013	3.00	0.44
2014	0.70	0.10
2015	0.60	0.09
2016	1.10	0.16

Table 3. Statistics of precipitation, TWSA, SWSA, GWSA from 2002 to 2012 in the Ordos Basin.

	Precipitation (mm yr^{-1})	TWSA (mm)	SWSA (mm)	GWSA (mm)
Min	346.3	−107.10	−41.4	−108.7
Max	585.6	126.40	77.7	71.3
Mean	472.1	−2.11	−0.92	−2.11
Std	70.2	37.00	21.5	33.70

Table 4. The month of peak TWSA, SWSA, and GWSA in each year and the decline period of GWSA.

	Year	TWSA	SWSA	GWSA	Decline Period of GWSA
	2002	9	7	3*	6 to 10
	2003	11	10	11	4 to 7
	2004	11	9	11	12※ to 6
	2005	11	10	3*	12※ to 7
	2006	9	9	3*	4 to 9
	2007	10	10	4*	4 to 9
	2008	10	10	3*	5 to 9
	2009	9	9	2*	4 to 9
	2010	9	9	2*	3 to 8
	2011	12	11	5*	3 to 10
	2012	9	9	2*	6 to 9
Mean		10	9.4	2.1*	3.3 to 8.4

* represent the month in the next year. '※' represent the month in the next year.

Table 5. Groundwater recharge estimated via method of Henry et al. (2011) and our method.

	Year	Net Recharge or Amplitude of GWSA (mm yr^{-1})	Recharge of This Study (mm yr^{-1})
	2002	9.6	37.3
	2003	50.8	64.2
	2004	45.3	66.5
	2005	19.7	32.8
	2006	10.8	30.8
	2007	26.7	50.8
	2008	27.6	47.7
	2009	24.7	59.7
	2010	25.4	37.6
	2011	46.7	56.6
	2012	23.7	47.3
Mean		28.3	48.3

Note: Net recharge or Amplitude of GWSA is the ground water recharge estimated from the method of Henry et al. (2011).

Table 6. Groundwater recharge in the Ordos Basin estimated with different methods from different studies [47,50,126,51–55,57,105,125].

Location	Topographic	Land Use	Method	R (mm yr^{-1})	Reference
Guyuan	Terrace region	Natural sparse small grass	CMB	100	
Guyuan	Terrace region	Winter wheat	CMB	55	[50]
Xifeng	Loess Plain	Apple orchard 7 years	CMB	33	
Ansai	Terrace	Cultivated terrace	CMB	43	
Ansai	Gulley	Cultivated behind check-dam	CMB	67	
Ansai	Hillslope	Tree plantation	CMB	56	[51]
Ansai	Hillslope	Shrub plantation	CMB	92	
Ansai	Hillslope	Natural forest	CMB	19	
Etuokeqi	Plain		CMB	11.7	
Duguitala town	Plain		CMB	6.6	
Ordos city	Plain		CMB	5.2	[52]
Yulin city	Plain		CMB	10.1	
Yan'an city	Plain		CMB	12.3	
Weinan city	Plain		CMB	17.2	
zhengning	Loess-tableland	Farm land	CMB	55-71	[53]
Luochuan	Loess-plain	Wheat/maize	Cl-peak	39-44	
Luochuan	Loess-plain	20-year apple orchard	Cl-peak	36-40	
Luochuan	Loess-plain	30-year apple orchard and then cut	Cl-peak	59-67	
Luochuan	Loess-plain	Wheat/maize	CMB	47	
Luochuan	Loess-plain	20-year apple orchard	CMB	42	[47]
Luochuan	Loess-plain	30-year apple orchard and then cut	CMB	65	
Luochuan	Loess-plain	Wheat/maize	Nitrate-peak	38	
Luochuan	Loess-plain	20-year apple orchard	Nitrate-peak	38	
Luochuan	Loess-plain	30-year apple orchard and then cut	Nitrate-peak	46	
Luochuan		Wheat	model	17	[125]
Changwu	Table land	Apple orchard	model	9.3	[126]
Changwu	Table land	Winter wheat	model	18.3	
Changwu	Upper hillslope	Grass	^{3}H	20	
Changwu	Middle hillslope	Grass	^{3}H	22	[57]
Changwu	Lower hillslope	Grass	^{3}H	27	
Changwu	Upper hillslope	Grass	^{3}H	33.7	
Changwu	Middle hillslope	Grass	^{3}H	34.1	
Changwu	Lower hillslope	Grass	^{3}H	38.2	

Changwu	Table land	Maize	^{3}H	33.1	
Changwu	Table land	Wheat	^{3}H	38.6	
Qingjian	Hillslope	7-year jujube	^{3}H	33.8	
Qingjian	Hillslope	16-year jujube	^{3}H	39.7	Unpublished data
Qingjian	Hillslope	7-year grass	^{3}H	31.6	
Qingjian	Hillslope	16-year grass	^{3}H	37.3	
Yanan	Hillslope	Apple orchard	^{3}H	65	
Pengyang	Table land	Maize	^{3}H	51.2	
Pengyang	Valley	Millet	^{3}H	30.9	
Pingding	Plain	Maize	^{3}H	64.2	
Pingding	Plain	Maize	^{3}H	73.1	
Pingding	Plain	Maize	^{3}H	71.3	
Pingding	Plain	Maize	^{3}H	50.0	
Pingding	Plain	Maize	^{3}H	70.1	
Pingding	Plain	Framland	^{3}H	68	[105]
Western Ordos Basin	Plain	Grass	CMB	0.17	
Western Ordos Basin	Plain	Grass	CMB	3.26	
Western Ordos Basin	Plain	Grass	CMB	0.11	
Western Ordos Basin	Plain	Grass	CMB	0.18	[54]
Western Ordos Basin	Plain	Grass	CMB	0.22	
Western Ordos Basin	Plain	Grass	CMB	0.3	
Western Ordos Basin	Plain	Grass	CMB	0.32	
Wulanmu			UD	68	
Subei			UD	97	
Wuding			UD	110	
Muolin			UD	47	
Yanhaizi			UD	54	[57]
Taoli			UD	36	
Dosit			UD	48	
Damiao			UD	33	
Yanchi			UD	80	

Note: CMB is Cloride Mass Balance method; UD is Unsaturated-zone Darcian method; ^{3}H is the tritium peak method; model is method using Hydrus-1D; Cl-peak, Nitrate-peak is Cloride peak method and Nitrate peak method, respectively.