Contribution of global groundwater depletion since 1900 to sea-level rise

Leonard F. Konikow[1]

Received 20 June 2011; revised 29 July 2011; accepted 30 July 2011; published 2 September 2011.

[1] Removal of water from terrestrial subsurface storage is a natural consequence of groundwater withdrawals, but global depletion is not well characterized. Cumulative groundwater depletion represents a transfer of mass from land to the oceans that contributes to sea-level rise. Depletion is directly calculated using calibrated groundwater models, analytical approaches, or volumetric budget analyses for multiple aquifer systems. Estimated global groundwater depletion during 1900–2008 totals ~4,500 km^3, equivalent to a sea-level rise of 12.6 mm (>6% of the total). Furthermore, the rate of groundwater depletion has increased markedly since about 1950, with maximum rates occurring during the most recent period (2000–2008), when it averaged ~145 km^3/yr (equivalent to 0.40 mm/yr of sea-level rise, or 13% of the reported rate of 3.1 mm/yr during this recent period). **Citation:** Konikow, L. F. (2011), Contribution of global groundwater depletion since 1900 to sea-level rise, *Geophys. Res. Lett.*, *38*, L17401, doi:10.1029/2011GL048604.

1. Introduction

[2] Water budgets form the foundation of informed water management strategies, including design of water supply infrastructure and assessment of water needs of ecosystems [*Healy et al.*, 2007]. As part of assessing water budgets, periodic assessments of changes in aquifer storage should be undertaken [*U.S. Geological Survey*, 2002]. Groundwater depletion, herein defined as a reduction in the volume of groundwater in storage in the subsurface, not only can have negative impacts on water supply, but also can lead to land subsidence, reductions in surface water flows and spring discharges, and loss of wetlands [*Bartolino and Cunningham*, 2003; *Konikow and Kendy*, 2005]. Groundwater depletion is becoming recognized as an increasingly serious global problem that threatens sustainability of water supplies [e.g., *Schwartz and Ibaraki*, 2011].

[3] Water budgets are also critical in understanding sea-level rise (SLR) [e.g., *Milly et al.*, 2003; *Lettenmaier and Milly*, 2009]. *Milne et al.* [2009] note that complete closure of a globally integrated sea-level budget contains many uncertainties, including land-based water storage, and further state, "… it remains important to understand better the magnitudes and error budgets of the various processes that contributed to sea-level change during [the 20th century]."

[4] In a classic paper describing the source of water derived from wells, *Theis* [1940] clarified that withdrawals are balanced by some combination of removal of groundwater from storage (depletion), increases in recharge, and/or decreases in groundwater discharge. Furthermore, over time, the fraction of pumpage derived from storage will generally decrease as a system approaches a new equilibrium condition [e.g., see *Alley et al.*, 1999, Figure 14].

[5] The extracted groundwater can subsequently follow any number of pathways through the hydrologic cycle, and most pathways that don't involve a return to the groundwater system have relatively short travel times and relatively small storage capacities [*Alley et al.*, 2002; *Oki and Kanae*, 2006]. But because the oceanic volume is so large relative to other pools or stocks, the ultimate volumetric sink for essentially all depleted groundwater is the oceans. If the removal of groundwater from storage in the continental subsurface is sufficiently large and persistent, it can represent a substantial transfer of water mass from the land to the oceans, and thereby represent a measureable contributor to long-term SLR [*Sahagian et al.*, 1994; *Gornitz et al.*, 1997; *Konikow and Kendy*, 2005; *Huntington*, 2008; *Milly et al.*, 2010]. The principal difficulty in testing this hypothesis has been a lack of reliable data on large-scale, long-term, groundwater depletion.

[6] The goal of this study was to quantitatively assess the magnitude of long-term groundwater depletion by developing the first comprehensive aquifer-based estimate of changes in groundwater storage using direct volumetric accounting. The results have value both for assessing freshwater resources and to help understand, assess, and reduce uncertainty in factors contributing to global SLR.

2. Previous Estimates

[7] *Margat et al.* [2006, p. 19] estimate that global groundwater mining (i.e., depletion that is essentially nonrecoverable) occurs at a rate of 27 km^3/yr (0.075 mm of SLR). *Gornitz* [2001, p. 103] estimates that groundwater mining can contribute 0.10 to 0.30 mm/yr to SLR. *Wada et al.* [2010] estimate that the rate of global groundwater depletion is 283 km^3/yr (~0.8 ± 0.1 mm/yr of SLR), stating that this represents 25% of the currently reported rate of SLR of 3.1 mm/yr.

[8] The first two estimates are based on a limited number of direct aquifer evaluations. The estimate of *Wada et al.* [2010] is derived using an indirect, flux-based water budget approach that assumes that groundwater depletion is equal to the difference between natural recharge and withdrawals—an approach that is not based on observations of groundwater conditions. Recharge values are derived from global-scale modeling designed to estimate "diffuse" recharge from climatic data and soil properties [*Döll and Fiedler*, 2008]. This methodology does not calculate recharge from

[1]U.S. Geological Survey, Reston, Virginia, USA.

surface-water bodies, nor adjust depletion estimates in accordance with *Theis*' [1940] principles, which are applicable regardless of climate (*Wada et al.* [2010] only allow this for humid climates). Even in the Nubian Aquifer system—the classical example of a fossil groundwater aquifer having no modern recharge—about 25% of the total withdrawals in 1998 were offset by (and derived from) reductions in natural discharge from the system (such as to springs and oases) [*CEDARE*, 2001]. The global modeling approach to estimating natural recharge also does not account for "non-natural" non-diffuse recharge, such as leakage from canals, sewers, or pipelines, or from artificial recharge—none of which depend on climate and soil characteristics inherent in their recharge estimation model. Hence, the flux-based water budget approach of *Wada et al.* [2010] can substantially overestimate groundwater depletion.

[9] Problems with the approach of *Wada et al.* [2010] are illustrated by examining their results for areas in the US where depletion data exist. Figure 2 of *Wada et al.* [2010] shows highest rates of depletion in four areas in the US (red zones, rated at 300–1000 mm/yr of depletion), which appear to include the Los Angeles and San Diego areas of southern California. In the Los Angeles area, depletion is closely tracked by local agencies. These data and analyses (see auxiliary material) indicate that from 1961 to 2008 the cumulative change in storage was an increase of ~0.20 km^3, and in 2000 was a decrease of ~0.04 km^3/yr.[1] This corresponds to a rate of depletion of less than 20 mm over the area of resolution of the map of *Wada et al.* [2010]. In the San Diego area, there is no large-scale development of groundwater, and no reported depletion problems of significance.

[10] The few available estimates of global groundwater depletion rates for the end of the 20th century vary by about an order of magnitude. The variability, weaknesses, and uncertainties in the previous estimates support the need for a more comprehensive analysis.

3. Sea-Level Rise

[11] The average rate of global SLR in the 20th century was 1.7 ± 0.5 mm/yr and the rate may be accelerating in recent years [*Church and White*, 2006; *Bindoff et al.*, 2007; *Lettenmaier and Milly*, 2009]. For 1961–2003 the average rate of SLR was 1.8 ± 0.5 mm/yr and for 1993–2003 had increased to an estimated rate of 3.1 ± 0.7 mm/yr [*Bindoff et al.*, 2007]. *Munk* [2002] notes that after accounting for thermal expansion and melting, there remains "a residual of 12 cm of 20th century rise to be accounted for." Groundwater depletion is one of several anthropogenic land-based factors affecting SLR through mass transfers; uncertainty in their magnitudes contribute to uncertainty in balancing the SLR budget [*Huntington*, 2008]. Better numbers are needed to constrain the residual of the SLR budget.

4. Methods

[12] Groundwater depletion cannot be measured directly, but rather must be measured through a variety of indirect approaches. Changes in groundwater storage can be viewed from a perspective of either pools (volumes in storage, or stocks) or fluxes [*Alley et al.*, 2002]. One can thus estimate groundwater depletion directly by analyzing sequential changes in volume stored or indirectly from the residual of fluxes in and out of the system. The volumetric approach typically requires estimates of changes in head (groundwater levels) over time and of storativity coefficients, as demonstrated by *McGuire et al.* [2003], although gravity measurements can also be used to directly estimate changes in water mass (and hence volume) stored in an area, as illustrated by the analyses of *Rodell et al.* [2009], *Tiwari et al.* [2009], and *Famiglietti et al.* [2011]. These volumetric approaches have the advantage that the change in hydraulic head (water level) or mass integrates the effects of all inflow and outflow fluxes and obviates the need to identify and quantify specific types of fluxes. A flux-based estimate requires a detailed water budget approach that includes estimates of all inflows and outflows (recharge and discharge). All such fluxes cannot be estimated with high accuracy and precision over large areas, and the residual (the change in storage) typically represents a small difference between relatively large and uncertain numbers. The volumetric approach is therefore preferable, and this study develops and primarily uses estimates based on volumetric approaches and direct observations of aquifer characteristics. More details about the specific methods used in this study, their reliability, and how estimates were derived for each specific aquifer or area are included in the auxiliary material.

[13] One or more methods are applied to specific aquifers to estimate long-term depletion, including:

[14] 1. Integrate measurements of changes in groundwater levels over time and area, combined with estimates of storativity [e.g., *McGuire et al.*, 2003].

[15] 2. Estimate large-scale water loss from gravity changes over time as measured by GRACE satellite [e.g., *Rodell et al.*, 2009].

[16] 3. Use deterministic groundwater flow models that are calibrated to long-term observations of heads [e.g., *Faunt et al.*, 2009].

[17] 4. For confined aquifer systems, apply the method of *Konikow and Neuzil* [2007], estimates of specific storage, thickness of the confining unit, and head changes in the adjacent aquifer, to estimate the depletion from confining units.

[18] 5. Use pumpage data in conjunction with a water budget analysis to estimate depletion [e.g., *Kjelstrom*, 1995].

[19] 6. Assume that the ratio of depletion to pumpage in a control area or time can be extrapolated to a larger area or time [e.g., *Gornitz et al.*, 1997].

[20] 7. If data are not available through 2008, extrapolate rates of depletion through the end of the study period using the observed rates calculated for the most recent multi-year period, and adjust rates for extrapolation accordingly if recent observed water-level changes or pumpage data do not support a linear extrapolation.

[21] 8. Calculate a volume of subsidence in areas where land subsidence is caused by groundwater withdrawals; this serves as a cross-check and constraint on calculated depletion volumes.

[22] In the study approach, seasonal variability is intentionally ignored to better identify the long-term signal. The intent was to complete as comprehensive a census as possible (see auxiliary material for descriptions of representative

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048604.

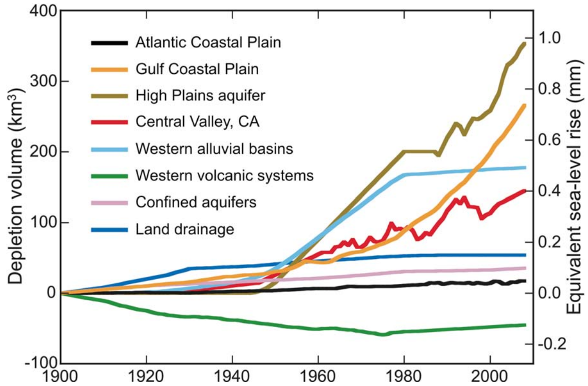

Figure 1. Cumulative net groundwater depletion in major aquifer systems or groups in the United States, 1900–2008.

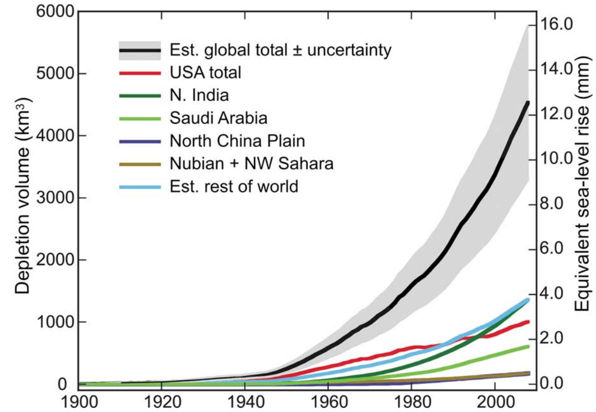

Figure 2. Estimated cumulative global groundwater depletion, 1900–2008.

assessments and summary results for all 46 evaluated cases), but insufficient data were available for some areas outside the USA where depletion is known to exist (see discussions by *Sahagian* [2000], *Milly et al.* [2010], and in the auxiliary material). Depletion for these areas is estimated indirectly; efforts should continue to improve the estimates with direct volumetric calculations.

5. Results

[23] Depletion volumes and rates in the USA (Figure 1) are calculated in 41 separate aquifer systems or subareas using comprehensive calibrated groundwater simulation models, analytical approaches, or volumetric budget analyses and plotted for 8 major systems or groups (Table 1 and Table S1 in the auxiliary material). During 1900–2000, there was ~800 km^3 of net cumulative depletion of groundwater in the USA—equivalent to a sea-level rise of ~2.2 mm (Table 1). Depletion in the USA increased ~25 percent during the next 8 years—to a cumulative total of ~1,000 km^3 (~2.8 mm of sea-level rise).

[24] Estimating global groundwater depletion is more problematic. There are five groundwater systems outside the USA with large volumes of depletion for which there are data to allow a reliable quantitative estimate to be made (Figure 2 and Table 1). The relative magnitudes of USA and global withdrawals and the fraction of total withdrawals represented

Table 1. Long-Term Cumulative Net Groundwater Depletion[a]

	Primary Methods[b]	Number of Sub-areas	Total Net Volumetric Groundwater Depletion[c] (km^3) 1900–2000	Total Net Volumetric Groundwater Depletion[c] (km^3) 1900–2008	Total Net Depletion as Equivalent Sea-Level Rise[d] (mm) 1900–2000	Total Net Depletion as Equivalent Sea-Level Rise[d] (mm) 1900–2008
			USA Aquifer Systems			
Atlantic Coastal Plain	1, 3, 4, 7	7	14.4	17.2	0.040	0.048
Gulf Coastal Plain	3, 7, 8	5	198.6	266.0	0.550	0.737
High Plains (Ogallala) Aquifer	1	1	258.6	353.3	0.716	0.979
Central Valley, California	2, 3	1	113.4	144.8	0.314	0.401
Western Alluvial Basins	1, 3, 5, 6, 7	19	175.1	177.5	0.485	0.492
Western Volcanic Systems	1, 3, 5, 6, 7	3	−47.9	−45.0	−0.133	−0.125
Deep Confined Bedrock Aquifers	3, 4, 6, 7	4	33.0	35.6	0.091	0.099
Agricultural and Land Drainage	1	1	54.0	54.0	0.150	0.150
TOTAL (all USA systems)		41	799.2	1003.0	2.214	2.779
			Non-USA Aquifer Systems			
Nubian Aquifer System	3, 5, 7	1	79.5	98.4	0.220	0.272
North Western Sahara Aquifer System	5	1	52.7	70.3	0.146	0.195
Saudi Arabia Aquifers	3, 5, 7	1	358.6	467.7	0.993	1.295
North China Plain	1, 3, 7	1	130.3	170.3	0.361	0.472
Northern India and Adjacent Areas	2, 6	1	937.5	1361.0	2.597	3.770
TOTAL Non-USA Aquifer Systems		5	1559.5	2168.0	4.317	6.004
TOTAL (all evaluated systems)		46	2358.0	3171.0	6.531	8.783
TOTAL GLOBAL ESTIMATE			3371.0	4534.0	9.339	12.560

[a]A more detailed breakdown, showing analyses for all separate areas contributing to the totals shown in Table 1, is included in the auxiliary material.
[b]Codes for methods correspond to ordered listing in Methods discussion (1 = water-level change; 2 = gravity; 3 = flow model; 4 = confining unit analysis; 5. water budget; 6 = pumpage data; 7 = partial record extrapolation; 8 = subsidence).
[c]Negative values indicate an increase in the volume of groundwater in storage and an equivalent drop in sea level.
[d]Conversion based on an ocean surface area of 3.61×10^8 km^2 [*Duxbury et al.*, 2000].

Table 2. Estimated Average Volumetric Rates of Groundwater Depletion for Selected Time Periods[a]

	Average Volumetric Rate of Groundwater Depletion (km^3/yr)								
	1900–2000	1900–2008	1900–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2008
Atlantic Coastal Plain	0.144	0.159	0.078	0.261	0.282	0.136	0.333	0.038	0.349
Gulf Coastal Plain	1.985	2.463	0.620	1.242	1.577	2.894	4.838	6.202	8.430
High Plains (Ogallala) Aquifer	2.586	3.271	0.311	6.100	6.192	6.192	2.003	3.823	11.830
Central Valley, California	1.134	1.340	0.522	2.900	0.998	2.361	2.870	−0.398	3.919
Western USA Alluvial Basins	1.751	1.643	0.692	4.408	4.598	4.248	0.427	0.373	0.292
Western Volcanic Systems	−0.479	−0.417	−0.902	−0.592	−0.307	−0.045	0.307	0.356	0.355
Deep Confined Bedrock Aquifers	0.330	0.329	0.371	0.258	0.429	0.529	0.105	0.123	0.323
Agricultural and Land Drainage	0.540	0.500	0.824	0.421	0.383	0.355	0.111	0.009	0.000
TOTAL (all USA systems)	7.992	9.289	2.515	15.00	14.15	16.67	10.99	10.53	25.50
TOTAL Non-USA Aquifer Systems	15.59	20.07	0.939	8.225	14.63	24.77	42.76	60.77	76.14
TOTAL (all evaluated systems)	23.58	29.40	3.454	23.22	28.78	41.44	53.76	71.30	101.6
TOTAL GLOBAL ESTIMATE	33.71	41.98	4.940	33.21	41.16	59.26	76.87	102.0	145.3

[a]A more detailed breakdown, showing analyses for all separate areas contributing to the totals shown in Table 2, is included in the auxiliary material.

by depletion are used to estimate global depletion in the rest of the world. Global depletion is estimated from USA values using correlation-based extrapolations, similar to the approach of *Gornitz* [2001]. This results in an estimate of total global groundwater depletion of ~3,400 km^3 during the 20th century, and 4,500 km^3 from 1900–2008, equivalent to a sea-level rise of 9.3 and 12.6 mm, respectively (Tables 1 and S1). This is equivalent to volumetric rates of depletion of 34 km^3/yr during the 20th century and 42 km^3/yr for 1900–2008 (Tables 2 and S2), and rates of equivalent SLR of 0.093 mm/yr and 0.12 mm/yr for those same two time periods (Table 3). These average rates are substantially lower than the rate given by *Wada et al.* [2010]. As an identifiable, separate, semi-independent hydrologic process, the volume and rate of estimated long-term global groundwater depletion can explain 6 to 7 percent of the observed SLR since 1900.

[25] An estimate of the uncertainty associated with each method for computing the depletion in each particular system is discussed in the auxiliary material, and ranges from about ±20 percent to ±40 percent, depending on the method and data availability for each system. These uncertainty estimates were integrated over all systems to yield an approximate error band of ±27 percent for the total global depletion values (Figure 2).

[26] The multi-year average rates of groundwater depletion varied considerably with time, but in general were relatively low prior to 1950 and clearly highest during 2001–2008 (Tables 2, 3, and S2). However, in some USA systems, peak depletion rates occurred during the 1950s and 1960s, and subsequently slowed due to self-limiting controls (such as reduced withdrawals due to higher pump lifts and energy costs), improved water management practices and regulations, and artificial recharge programs. The 2001–08 rate of groundwater depletion (145 km^3/yr, or 0.40 mm/yr of equivalent SLR) can account for 22 percent of the long-term average SLR rate of 1.8 mm/yr and 13 percent of the more recent (1993–2003) and higher rate of SLR of 3.1 mm/yr.

6. Conclusions

[27] This study improves and constrains the quantification of estimates of global groundwater depletion. The cumulative global groundwater depletion from 1900–2008 totaled ~4,500 km^3 from 1900–2008, equivalent to a sea-level rise of 12.6 mm. As an identifiable, separate, semi-independent hydrologic process, the volume and rate of estimated long-term global groundwater depletion balances 6 to 7 percent of the observed SLR since 1900.

[28] Even though increases in storage of large volumes of surface water in reservoirs have the opposite effect on sea level than does groundwater depletion, so that the net effect of terrestrial changes in liquid water storage are smaller than from the individual components, it is still important to understand the contribution of each process. During the 21st century, their relative magnitudes may shift, so the net effect of changes in terrestrial water storage may be different than during the 20th century. Surface water storage will probably stabilize because of reservoir sedimentation and slowing of construction of new large dams [*Huntington*, 2008]. On the other hand, data from this study indicate that the rate of groundwater depletion is still accelerating (though ultimately it tends to be self-limiting).

[29] This better understanding and quantification of the contribution of groundwater depletion to sea-level rise should facilitate an improved understanding of 20th century sea-level rise and more confidence in predictions of 21st century sea-level changes. The comprehensive census of depletion in the USA is based primarily on direct calculations of volumetric changes in groundwater storage. Global estimates for the rest of the world are less reliable. Additional assessments are needed for systems around the world

Table 3. Estimated Rates of Sea-Level Rise From Groundwater Depletion for Selected Time Periods

	Average Rate of Sea-Level Rise From Groundwater Depletion (mm/yr)								
	1900–2000	1900–2008	1900–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2008
TOTAL (all USA systems)	0.022	0.026	0.007	0.042	0.039	0.046	0.030	0.029	0.071
TOTAL (Non-USA Aquifer Systems)	0.043	0.056	0.003	0.023	0.041	0.069	0.118	0.168	0.211
TOTAL (all evaluated systems)	0.065	0.081	0.010	0.064	0.080	0.115	0.149	0.197	0.282
TOTAL GLOBAL ESTIMATE	0.093	0.116	0.014	0.092	0.114	0.164	0.213	0.282	0.403

with substantial known depletion to more accurately quantify these estimates and to complete a global census of groundwater depletion. Nevertheless, the data clearly indicate that groundwater depletion, as a distinct hydrologic factor, is a small but nontrivial and increasing contributor to SLR.

[30] **Acknowledgments.** I greatly appreciate the assistance of E. A. Achey, S. M. Feeney, D. P. McGinnis, and J. Donovan, who assisted with analyses and calculations for some of the aquifer systems. Helpful review comments from USGS colleagues J. R. Bartolino and T. G. Huntington are also greatly appreciated.

[31] The Editor thanks Tom Gleeson and an anonymous reviewer for their assistance in evaluating this paper.

References

Alley, W. M., T. E. Reilly, and O. L. Franke (1999), Sustainability of ground-water resources, *U.S. Geol. Surv. Circ.*, *1186*, 79 pp.

Alley, W. M., R. W. Healy, J. W. LaBaugh, and T. E. Reilly (2002), Flow and storage in groundwater systems, *Science*, *296*, 1985–1990, doi:10.1126/science.1067123.

Bartolino, J. R., and W. L. Cunningham (2003), Ground-water depletion across the Nation, *U.S. Geol. Surv. Fact Sheet*, *103-03*, 4 pp.

Bindoff, N. L., et al. (2007), Observations: Oceanic climate change and sea level, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 385–432, Cambridge Univ. Press, Cambridge, U. K.

CEDARE (2001), *Regional strategy for the Utilisation of the Nubian Sandstone Aquifer System, Volume III: Ground Water Model*, Cent. for Environ. and Dev. for the Arab Reg. and Eur., Cairo.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

Döll, P., and K. Fiedler (2008), Global-scale modeling of groundwater recharge, *Hydrol. Earth Syst. Sci.*, *12*, 863–885, doi:10.5194/hess-12-863-2008.

Duxbury, A. C., A. B. Duxbury, and K. A. Sverdrup (2000), *An Introduction to the World's Oceans*, 6th ed., McGraw-Hill, Boston, Mass.

Famiglietti, J. S., et al. (2011), Satellites measure recent rates of groundwater depletion in California's Central Valley, *Geophys. Res. Lett.*, *38*, L03403, doi:10.1029/2010GL046442.

Faunt, C. C., et al. (2009), Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley, in *Groundwater Availability of the Central Valley Aquifer, California*, edited by C. C. Faunt, *U.S. Geol. Surv. Prof. Pap.*, *1766*, 121–212.

Gornitz, V. (2001), Impoundments, groundwater mining, and other hydrologic transformation: Impacts on global sea level rise, in *Sea Level Rise: History and Consequences*, *Int. Geophys.*, vol. 75, edited by B. C. Douglas, M. S. Kearney, and S. P. Leatherman, chap. 5, pp. 97–119, Academic, San Diego, Calif., doi:10.1016/S0074-6142(01)80008-5.

Gornitz, V., C. Rosenzweig, and D. Hillel (1997), Effects of anthropogenic intervention in the land hydrologic cycle on global sea level rise, *Global Planet. Change*, *14*, 147–161, doi:10.1016/S0921-8181(96)00008-2.

Healy, R. W., T. C. Winter, J. W. LaBaugh, and O. L. Franke (2007), Water budgets: Foundations for effective water-resources and environmental management, *U.S. Geol. Surv. Circ.*, *1308*, 90 pp.

Huntington, T. G. (2008), Can we dismiss the effect of changes in land-based water storage on sea-level rise?, *Hydrol. Processes*, *22*, 717–723, doi:10.1002/hyp.7001.

Kjelstrom, L. C. (1995), Streamflow gains and losses in the Snake River and ground-water budgets for the Snake River Plain, Idaho and eastern Oregon, *U.S. Geol. Surv. Prof. Pap.*, *1408-C*, 47 pp.

Konikow, L. F., and E. Kendy (2005), Groundwater depletion: A global problem, *Hydrogeol. J.*, *13*(1), 317–320, doi:10.1007/s10040-004-0411-8.

Konikow, L. F., and C. E. Neuzil (2007), A method to estimate groundwater depletion from confining layers, *Water Resour. Res.*, *43*, W07417, doi:10.1029/2006WR005597.

Lettenmaier, D., and P. C. D. Milly (2009), Land waters and sea level, *Nat. Geosci.*, *2*, 452–454, doi:10.1038/ngeo567.

Margat, J., S. Foster, and A. Droubi (2006), Concept and importance of non-renewable resources, in *Non-renewable Groundwater Resources: A Guidebook on Socially-Sustainable Management for Water-Policy Makers*, *IHP-VI Ser. Groundwater*, vol. 10, edited by S. Foster, and D. P. Loucks, pp. 13–24, UNESCO, Paris.

McGuire, V. L., et al. (2003), Water in storage and approaches to groundwater management, High Plains Aquifer, 2000, *U.S. Geol. Surv. Circ.*, *1243*, 51 pp.

Milly, P. C. D., A. Cazenave, and M. C. Gennero (2003), Contribution of climate-driven change in continental water storage to recent sea-level rise, *Proc. Natl. Acad. Sci. U. S. A.*, *100*, 13,158–13,161, doi:10.1073/pnas.2134014100.

Milly, P. C. D., et al. (2010), Terrestrial water-storage contributions to sea-level rise and variability, in *Understanding Sea-Level Rise and Variability*, edited by J. A. Church et al., chap. 8, pp. 226–255, Wiley-Blackwell, Oxford, U. K., doi:10.1002/9781444323276.ch8.

Milne, G. A., W. R. Gehrels, C. W. Hughes, and M. E. Tamisiea (2009), Identifying the causes of sea-level change, *Nat. Geosci.*, *2*, 471–478, doi:10.1038/ngeo544.

Munk, W. (2002), Twentieth century sea level: An enigma, *Proc. Natl. Acad. Sci. U. S. A.*, *99*, 6550–6555, doi:10.1073/pnas.092704599.

Oki, T., and S. Kanae (2006), Global hydrological cycles and world water resources, *Science*, *313*, 1068–1072, doi:10.1126/science.1128845.

Rodell, M., I. Velicogna, and J. S. Famiglietti (2009), Satellite-based estimates of groundwater depletion in India, *Nature*, *460*, 999–1002, doi:10.1038/nature08238.

Sahagian, D. L. (2000), Global physical effects of anthropogenic hydrological alterations: Sea level and water redistribution, *Global Planet. Change*, *25*, 39–48, doi:10.1016/S0921-8181(00)00020-5.

Sahagian, D. L., F. W. Schwartz, and D. K. Jacobs (1994), Direct anthropogenic contributions to sea level rise in the twentieth century, *Nature*, *367*, 54–57, doi:10.1038/367054a0.

Schwartz, F. W., and M. Ibaraki (2011), Groundwater: A resource in decline, *Elements*, *7*, 175–179, doi:10.2113/gselements.7.3.175.

Theis, C. V. (1940), The source of water derived from wells, *Civ. Eng.*, *10*, 277–280.

Tiwari, V. M., J. Wahr, and S. Swenson (2009), Dwindling groundwater resources in northern India, from satellite gravity observations, *Geophys. Res. Lett.*, *36*, L18401, doi:10.1029/2009GL039401.

U.S. Geological Survey (2002), Concepts for national assessment of water availability and use, *U.S. Geol. Surv. Circ.*, *1223*, 34 pp.

Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and M. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

L. F. Konikow, U.S. Geological Survey, 431 National Cent., Reston, VA 20192, USA. (lkonikow@usgs.gov)