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Impact of Artificial Reservoir Water Impoundment on Global Sea Level

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By reconstructing the history of the water impoundment in world's artificial reservoirs, we show that a total of ~10,800 km^3 of water has been impounded on land to date, reducing the magnitude of global sea level (GSL) rise by –30.0 mm, by an average rate of –0.55 mm/yr during the past half century. This demands a significantly larger contribution to GSL rise from other (natural and anthropogenic) causes than otherwise required. The reconstructed GSL history accounting for the impact of reservoirs (by adding back the impounded water volume) shows an essentially constant rate of rise at +2.46 mm/yr over at least the last 80 years, contrary to the conventional view of apparently variable GSL rise based on face values of observation.

The various causes of the observed global sea level (GSL) rise have been under study, and debate, for years. The IPCC 2007 Climate Change report (*1*) concluded that "the budget (of GSL rise) has not yet been closed satisfactorily", primarily because the anthropogenic contribution from land water alterations is too poorly known. Among them, the negative contribution due to water impoundment in artificial reservoirs behind dams has long been recognized to be a major term (*1–7*), although one poorly quantified in want of compiled information. Based on only incomplete data, previous (and very crude) estimates of the total water impoundment have ranged from close to 15,000 km^3 (extrapolated to year 2000) (*2*), to ~10,000 km^3 (*3*), given the ~4,000 km^3 volume of the "top 100" (named) reservoirs only (*4*), to 5,000 – 6,000 km^3 (*5–7*) and much less (*8*).

Here we reconstruct the water impoundment history by assembling a comprehensive tally of the world's reservoirs constructed since ~1900, and study its impact on GSL rise. Our main source of data is the ICOLD (International Commission on Large Dams) World Register of Dams (*9*), but augmented and corrected for apparently erroneous or inconsistent entries by consulting with various ancillary data sources (*10–16*), yielding a list of 29,484 named reservoirs with nominal capacity and year of completion (*17*).

Let $V(t)$ be the (cumulative) total volume of water impoundment in world's reservoir at any given time t (in calendar year), V_i be the capacity of a given individual reservoir modeled as an addition to V in year t_i of its completion, causing an instantaneous GSL drop (recognizing the ocean as the ultimate source of the water). That is, $V(t) = \Sigma_i V_i H(t-t_i)$ and the corresponding GSL drop $d(t) = –V(t)/A$ (a negative value), where H is the Heaviside function and $A = 3.61 \times 10^8$ km^2 is the total ocean area. This 'nominal' time history for $V(t)$ is shown in Fig. 1 (dashed blue curve); the total nominal V to-date is 8,300 km^3, corresponding to a d of –23 mm. The inset shows the per-year number of reservoirs being completed, which soared since ~1950 but saw a distinct decease in the recent 3 decades, especially in North America and Europe, because of environmental concerns. The slowdown during the 1940s World War II is also well noted (see also Fig. 3). In addition, the continental break-down in Fig. 1 reflects the contrasting and changing societal behavior and economic activity of peoples on different continents.

Next, the following potentially significant modifications to the nominal history above should be considered.

First, while being essentially complete for the major and relatively large ones, our tally of reservoirs inevitably becomes less complete with decreasing reservoir size as those reservoirs become more numerous. We assess the untallied amount of water as follows. We plot in Fig. 2 the histogram of the number of tallied reservoirs n (in logarithm) versus a convenient reservoir "magnitude" $M = \log(C)$ where C is the reservoir capacity in m^3 of volume. The said drop-off of the tally of n is found to occur around $M \sim 6.5$ (corresponding to a moderate reservoir of, say, 1 km long, 150 m wide, 20 m deep). Over the main body of the histogram for $M > 6.5$ (numbering 16,600 reservoirs) up to $M = 10.5$ with binwidth of 0.1, the (log-log) relation conforms to a straight line, corresponding to an empirical power law: $n(C) = 10^{6.69} \times C^{-0.52}$ (*18*). Extrapolating to zero capacity, this relation yields the integrated water amount for all reservoirs smaller than $M = 6.5$, which amounts to only 0.73%, to be augmented to the total (*19*, *20*). This reassures us that our tally's incompleteness in small reservoirs is inconsequential as far as total water volume is concerned.

Second, accounting only for the "visible" part of the impounded water, the nominal V_i ignores the water that inevitably seeps underground to manifest as elevated water table. Typically comparable to the capacity, the volume of this invisible subsurface water varies greatly from case to case depending on the local geology and climate. Short of detailed information, here we make an average, conservative estimate: For all reservoirs we assume an annual subsurface seepage rate of 5% of the capacity volume for the first year of existence (*6*), while we consider for out years a dynamic fluid diffusion model which dictates the water seepage to decrease as $1/\sqrt{t}$, so that the total water seepage grows slowly as $\sqrt{t}$. We then integrate this seepage into the total volume accordingly.

Third, reservoirs are not always filled to 100% of V_i. Depending on the usage and the regional climatology and hydrology, actual reservoir storage can fluctuate significantly, especially seasonally and often interannually. Here, following (*6*), we adopt a long-term average percentage of 85% and thus an overall scale factor of 0.85. Incidentally, the inevitable silting of reservoirs need not be of concern here [contrary to (*5–7*)] because, just like water, the silt represents that much volume withheld on land, which would otherwise flow to the ocean raising GSL. Whether the volume withheld by the dam is water or silt has the same impact on GSL.

Combining the above, a modified water impoundment curve for $V(t)$ and $d(t)$ (the red solid curve in Fig. 1) emerges from the nominal curve. The total actual water impoundment to-date is $V = 10{,}800$ km^3, corresponding to a $d = 30.0$ mm (*21*). Figure 3 shows the per-year GSL drop [essentially the time derivative of $V(t)$]; in peak years during ~1960 – 1990 it reached as high as –0.4 ~ –0.9 mm/yr. The average GSL drop rate during the past half century is about –0.55 mm/yr.

Sea level varies on all temporal and spatial scales for a host of reasons. GSL has been found to rise at +1.7~1.8 mm/year during the 20th century from tide gauge data [(*1*) and references therein], while accelerating to +3.36 ± 0.4 mm/year during 1993-2007 according to satellite altimetry (*22*), although it is uncertain whether this is a long-term trend or decadal variability (*1*). A quarter to a half of the rise in the past half century is believed to have come from the thermal expansion of the top layers of global oceans (the steric effect). The rest, barring a relatively small but uncertain portion from the mantle glacial isostatic adjustment, is attributed to water mass addition occurring in two forms: (i) melting of mountain glaciers (estimated contribution to GSL rise: +0.50 ± 0.18 mm/yr during 1961-2003 and 0.77 ± 0.22 mm/yr during 1993-2003) plus that of the ice sheets on Antarctica (+0.14 ± 0.41 mm/yr and 0.21 ± 0.35 mm/yr, respectively) and Greenland (+0.05 ± 0.12 mm/yr and +0.21 ± 0.07 mm/yr, respectively), and (ii) climate-driven variations in soil water, inland seas and large lakes (+0.12 mm/yr during the last two decades although with large interannual and decadal fluctuations), plus various anthropogenic contributions including the impoundment under study here.

Thus our estimate of a –0.55 mm/yr difference due to artificial reservoirs represents a significant (negative) impact to the GSL rise budget for the past several decades, which has more than compensated for nearly all of the individual natural or anthropogenic (positive) contributions above (*23*). This creates an even larger gap in the GSL rise budget, demanding a larger contribution from the natural (and perhaps anthropogenic) causes than otherwise required.

Equally significant, the above has intriguing implications for the history of the GSL rise, a key indicator of global climatic change. In Fig. 4 we plot the observed GSL history (*1*, *24*) as the blue line, with a splice-on segment for the last decade using the altimetry result (*22*) (the purple segment) after adjusting a vertical offset to match the former. That curve implies that the observed GSL rise during the last century has been variable in a piece-wise manner: a slower section prior to ~1930 is followed by a faster section until ~1960, with a slower section again extending until ~1990 before becoming faster again. We suggest that this seeming variability in rate is “artificial”. If we add back the actual $V(t)$ in Fig. 1 to reconstruct a GSL curve giving the GSL variation that would have been free from the impact of artificial reservoirs, it becomes evident that, in contrast to the observed, the post-1930 GSL rose essentially at a constant rate all the way to the recent (barring any interspersed interannual fluctuations such as ENSO events or volcanic activities) -- at rate +2.46 mm/yr (compared to an average of +1.7~1.8 mm/year during the 20th century with recent acceleration). Whether this means that the global changes causing the GSL rise have been in operation in a rather steady fashion, or these changes fortuitously compensated one another over at last the past 80 years, remains to be examined. The above presents a different view than the conventional wisdom which holds an apparent variable GSL rise according to the face values of observation as stated above. This, of course, by no means precludes the most recent or possible future acceleration of GSL rise (*22*) due to natural causes compounded by the further slowdown of reservoir-building in the upcoming future (*25*).

References and Notes

1. N. L. Bindoff *et al*., 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* (Cambridge Univ. Press, New York, 2007), Chap. 5.
2. W. S. Newman, R. W. Fairbridge, *Nature* **320**, 319 (1986).
3. B. F. Chao, *Eos* **72**, 492 (1991).
4. B. F. Chao, *Geophys. Res. Lett.* **22**, 3533 (1995).
5. V. Gornitz, C. Rosenzweig, D. Hillel, *Global Planet. Change* **14**, 147 (1997).
6. V. Gornitz, in *Sea Level Rise*, B. Douglas, M. Kearney, S. Leatherman, Eds. (Academic Press, London, 2001).
7. D. L. Sahagian, *Global Planet. Change* **25**, 39 (2000).
8. D. L. Sahagian, F. W. Schwartz, D. K. Jacobs, *Nature* **367**, 54 (1994).
9. *World Register of Dams* (International Commission on Large Dams, Paris, 2007) (www.icold-cigb.net).
10. F. Ven der Leeden, *Water Resources of the World* (Water Information Center Inc., New York, 1975).
11. *World Water Balance and Water Resources of the Earth* (UNESCO Press, 1978).
12. U.S. Dept. of Interior, *Major Dams, Reservoirs, and Hydroelectric Plants* (Bureau of Reclamation, Denver, 1983).
13. *International Water Power & Dam Construction Handbook*, R. M. Taylor, Ed. (Reed Business Pub., Surrey, 1993).
14. *World Commission on Dams, Dams and Development* (Earthscan, London, 2000).
15. UNESCO, *World Water Resources at the Beginning of the 21st Century* (Cambridge Univ. Press, New York, 2003).
16. *World Water Storage in Man-Made Reservoirs* (Foundation for Water Research, UK, 2005).
17. A compilation of these reservoirs containing name, country, nominal capacity, and year of completion is given in the Supporting Online Material.
18. Different (least-squares) fit ranges and binwidths were tried; the results vary little.
19. The rapid convergence of the extrapolated integration, consistent with (*20*), down to small reservoir size is assured as follows. For a self-similar fractal “map” distribution of self-similar reservoirs w.r.t. the linear dimension L, the reservoir numbers decreases as L^{-2} while the corresponding volume increases as L^3. Hence the water impoundment for a given size increases as L, dominated by large reservoirs. The actual reservoir number increases with smaller size even slower than the above, only at $L^{-1.56}$ ($-1.56 = -0.52 \times 3$). The situation is analogous to the (Richter-Gutenberg) frequency-moment relationship for seismicity, where the “β value” (or the negative of the

power-law slope) is ⅔, hence the total seismic energy release is dominated by large earthquakes even though the smaller earthquakes are much more numerous.
20. M. I. L'vovich, G. F. White, in *The Earth as Transformed by Human Action*, B. L. Turner II *et al*., Eds. (Cambridge Univ. Press, Cambridge, 1990).
21. In comparison, in terms of GSL the total atmospheric water content is equivalent to ~35 mm, and the total biological water to a small ~3 mm.
22. B. D. Beckley, F. G. Lemoine, S. B. Luthcke, R. D. Ray, N. P. Zelensky, *Geophys. Res. Lett.* **34**, L14608 (2007).
23. Among other anthropogenic (positive) contributions to GSL, groundwater mining (mainly for irrigation) is potentially significant (*1*, *5*–*7*) which partially offsets the impact of the reservoir impoundment. Its amount is considerably smaller (*6*), albeit far less certain, than the reservoirs', and presumably grew over the decades with a different time signature. A separate assessment is needed.
24. J. A. Church, N. J. White, *Geophys. Res. Lett.* **33**, L01602 (2006).
25. The slowdown is already evident in Fig. 1 which includes the projection into the next few years according to our tally (for example $d = –30.6$ mm by 2010), although late reporting of reservoir-building may have also contributed to the apparent slowdown.
26. Discussions with and assistance from the following persons are acknowledged: J. Church, R. Ray, D. Sahagian, A. Cazenave, C.K. Shum, L.Y. Tsai, S.T. Li, and L. Lin. This study is partially sponsored by the TSMC Chair Professorship, and supported by the National Science Council of Taiwan under Grant #NSC96-2111-M-008-016-MY2.

Supporting Online Material
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Materials and Methods
Table S1

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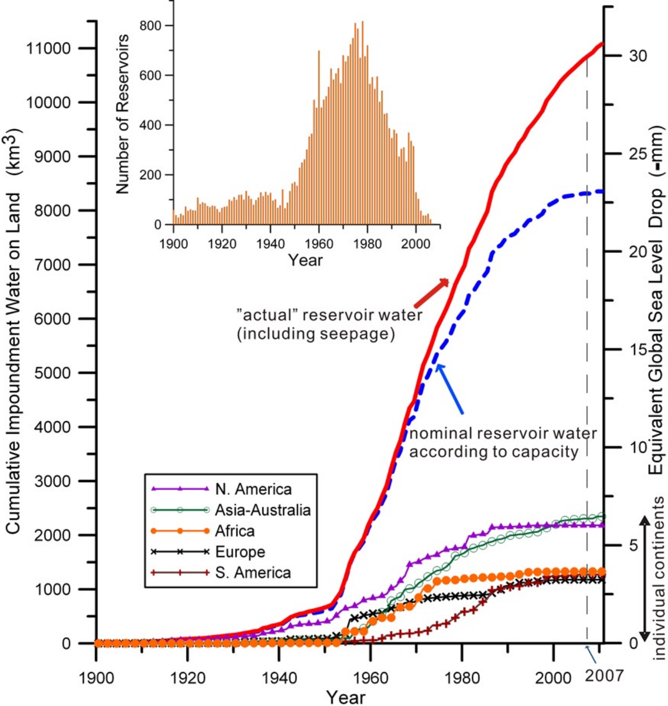
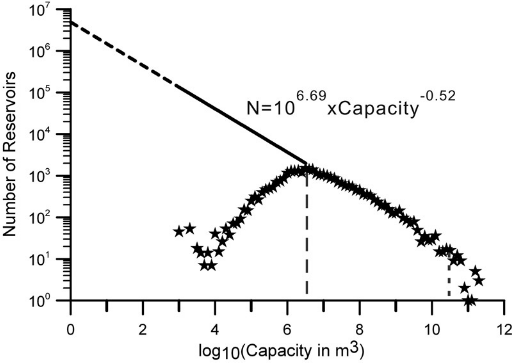
Fig. 1. The cumulative water impoundment [$V(t)$, the red solid curve] as a function of calendar year, based on the nominal water impoundment (the blue dash curve) according to our compiled tally of 29,484 reservoirs' capacity (*17*) but taking into account of realistic modifications (including subsurface seepage). The lower thin lines are the breakdowns for individual continents, showing continental contrasts. The left vertical scale is in units of km^3; the right scale in equivalent GSL drop. The inset shows the history of the per-year number of reservoirs completed.

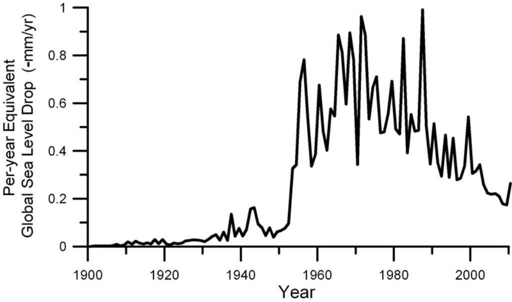
Fig. 2. Histogram of the number of tallied reservoirs (in logarithm) versus the reservoir magnitude $M = \log(C)$ where C is the reservoir capacity in m^3 of volume. Over the main body of the histogram for $M = 6.5 - 10.5$, the (log-log) relation conforms to a straight line with slope –0.52.

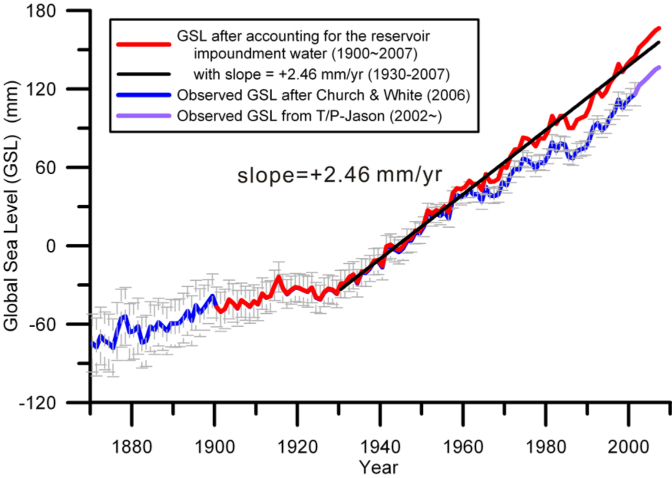
Fig. 3. The history of per-year GSL drop due to water impoundment in artificial reservoirs.

Fig. 4. The blue curve with error bar is the observed GSL history [(*1*, *24*); zero level is arbitrary], with a purple segment from altimetry data (*22*) spliced on for the last few years after adjusting a vertical offset. The red line is the GSL corrected for the impact of artificial reservoirs, reconstructed by adding back the reservoir impoundment contribution (in Fig. 1) to the blue curve. It exhibits an essentially constant slope of +2.46 mm/yr for the last 80 years.


Number of Reservoirs
800
600
400
200
0
1900
1920
1940
1960
1980
2000
Year
Cumulative Impoundment Water on Land (km3)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
"actual" reservoir water
(including seepage)
nominal reservoir water
according to capacity
N. America
Asia-Australia
Africa
Europe
S. America
1900
1920
1940
1960
1980
2000
2007
Year
Equivalent Global Sea Level Drop (-mm)
30
25
20
15
10
5
0
individual continents


10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Number of Reservoirs
$N=10^{6.69}\times Capacity^{-0.52}$
0
2
4
6
8
10
12
$\log_{10}$(Capacity in m^3)


Per-year Equivalent
Global Sea Level Drop (-mm/yr)
0
0.2
0.4
0.6
0.8
1
1900
1920
1940
1960
1980
2000
Year


GSL after accounting for the reservoir impoundment water (1900~2007)
with slope = +2.46 mm/yr (1930-2007)
Observed GSL after Church & White (2006)
Observed GSL from T/P-Jason (2002~)
slope=+2.46 mm/yr
Global Sea Level (GSL) (mm)
180
120
60
0
-60
-120
1880
1900
1920
1940
1960
1980
2000
Year