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Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs

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Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs

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[1] Water storage is an important way to cope with temporal variation in water supply and demand. The storage capacity and the lifetime of water storage reservoirs can be significantly reduced by the inflow of sediments. A global, spatially explicit assessment of reservoir storage loss in conjunction with vulnerability to storage loss has not been done. We estimated the loss in reservoir capacity for a global data set of large reservoirs from 1901 to 2010, using modeled sediment flux data. We use spatially explicit population data sets as a proxy for storage demand and calculate storage capacity for all river basins globally. Simulations suggest that the net reservoir capacity is declining as a result of sedimentation (~5% compared to the installed capacity). Combined with increasing need for storage, these losses challenge the sustainable management of reservoir operation and water resources management in many regions. River basins that are most vulnerable include those with a strong seasonal flow pattern and high population growth rates such as the major river basins in India and China. Decreasing storage capacity globally suggests that the role of reservoir water storage in offsetting sea-level rise is likely weakening and may be changing sign.

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1. Introduction

[2] Water storage in reservoirs is one of the primary mechanisms for coping with the variability of water supply and demand. Globally, water from reservoirs supplies an estimated 30–40% of irrigated areas [*World Commission on Dams*, 2000], contributes 20% of global electricity generation in the form of hydropower [*Demirbas*, 2009], and serves a number of other beneficial purposes including flood control, recreation, and navigation.

[3] During the last century, humans have constructed more than 45,000 dams (taller than 15 m) on earth, creating a combined installed storage capacity that is estimated between 6700 and 8000 km^3 [*World Commission on Dams*, 2000; *Chao et al.*, 2008; *ICOLD*, 2011], representing 17% of global annual runoff. Installation of large reservoirs peaked during the 1960s and 1970s, both by number and storage volume. With growing interest in water security and renewable energy, reservoir installation rates may increase again [*Lettenmaier and Milly*, 2009]; with the most suitable locations for large reservoirs already in use, future growth in hydropower production will likely come from smaller reservoirs [*Demirbas*, 2009]. Reservoirs are increasingly being considered an important adaptation option to climate induced changes in water availability [*Kundzewicz et al*., 2007]. However, a number of factors have called into question the sustainability of large dams and reservoirs [*World Commission on Dams*, 2000; *Moore et al*., 2010; *Richter and Postel*, 2010].

[4] Reservoirs retain a significant amount of global sediment flux [*Vörösmarty et al*., 2003] and this change in sediment dynamics has complex engineering and environmental effects. Besides the direct effect of a loss in reservoir storage capacity, sediment retention in reservoirs is a significant sink of carbon [*Mulholland et al*., 1982; *Stallard*, 1998]. The reduction of sediment flux has implications for coastal retreat and the export of minerals and nutrients from the continents to the oceans [*Syvitski et al*., 2005]. Sedimentation within reservoirs has many ecological and engineering effects [*Morris and Fan*, 1998], including accelerated eutrophication and loss of habitat [*Hargrove et al*., 2010], morphological changes [*De Araujo et al*., 2006], and interference with the outlet works or hydropower intakes [*Graf et al*., 2010].

[5] Sedimentation of reservoirs usually happens faster than the loss of integrity of the structure itself [*Morris and Fan*, 1998]; the lifetime and the sustainability of a reservoir is, therefore, controlled by the sedimentation. Dams are planned, designed, and operated for a finite life time

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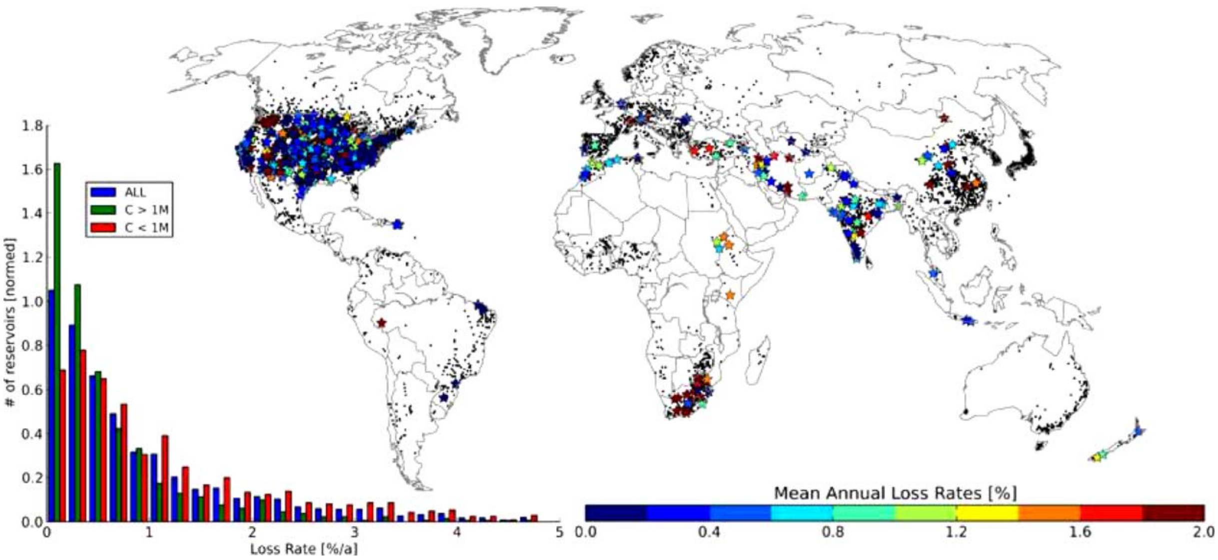

Figure 1. Location of 1215 case studies with observed reservoir sedimentation rates (colored stars, see scale bar), and location of 6399 GRanD reservoirs (small black dots). Inset: histogram of 1215 observed annual reservoir capacity loss rates, as percentage of installed capacity, grouped by capacity larger than 1 million m^3 and smaller than 1 million m^3.

[*Wang*, 2005], in some cases as short as 100 years [*Morris and Fan*, 1998]. Many of the large reservoirs in the US, designed for 150–200 years, have had their life time reduced by 50–100 years due to sedimentation [*Hargrove et al*., 2010] and a significant loss of storage is observed in many regions of the world. Globally, the annual loss rates relative to installed capacity are generally estimated to range between 0.5 and 1% [*Mahmood*, 1987; *White*, 2001; *Basson*, 2009; *Schleiss et al*., 2010].

[6] Loss rates for individual reservoirs are highly site specific and controlled by a number of local factors, resulting in large differences in local to regional sedimentation rates. For example, *Wang and Hu* [2009] recently estimated that sedimentation has decreased the total reservoir capacity in China by 66%, while *Minear and Kondolf* [2009] found a decrease in state wide reservoir capacity in California of only 4.5%.

[7] The total storage volume lost to sedimentation globally is, therefore, highly uncertain and the vulnerability of large river basins as a result of loss in storage has not been globally assessed. Here, we use a recently compiled global data set of large reservoirs in combination with output from a global sediment delivery model to estimate the evolution of storage capacity over time. Future water demand for all sectors will depend on population [*Vörösmarty et al*., 2000]; increasing climate variability will increase the need for water storage. We, therefore, use population numbers as a surrogate measure for the combined storage requirements for all uses of water. We compute total reservoir storage and storage per person to assess the ability of river basins to buffer changing conditions of water supply and demand with water storage.

2. Data and Methods

2.1. GRanD Reservoir Data

[8] We used the Global Reservoir and Dams database (GRanD, rev. 1) that contains attributes for 6862 georeferenced reservoirs globally [*Lehner et al*., 2011]. We selected 6399 reservoirs with complete information on year of construction (Figure 1); the total capacity of those reservoirs is 5990 km^3. The GRanD database contains an estimate of mean annual runoff (MAR) flowing into each reservoir, based on channeling runoff estimates from a global hydrological model driven with climate data for the period 1961–1990, routed through the HydroSHEDS river network [*Lehner et al*., 2008].

[9] According to reservoir data extracted from the GRanD database, the construction of reservoirs peaked in the 1960s and 1970s when about 150 km^3 of storage capacity in 130 reservoirs were added per year. The growth has since slowed down to about 15 km^3 per year in eight reservoirs for the last decade (2001–2010). The average age of reservoirs today is 50 years, with older reservoirs in North America (average age 60 years) and younger reservoirs in Asia and Africa (40 years). The majority of the installed capacity (64%) has hydropower as its main purpose. Reservoirs constructed primarily for irrigation represent 17% of the total capacity and the remainder is for flood control (8.5%), water supply (2.7%), recreation (0.8%), and others (7%). The majority of reservoirs are hydrologically small with residence times (installed capacity, *C*, divided by (modeled) MAR) less than 1 year (median 0.91 years). The reservoirs intercept runoff on 53 million km^2, 40% of the total global land mass (excluding Antarctica and Greenland).

2.2. Population Numbers and River Basins

[10] Reservoir locations were geolocated to the 5 min (~9 km at the equator) version of the Dominant River Tracing (DRT) network (hereafter DRT) [*Wu et al*., 2012] to introduce the upstream/downstream topology. To estimate population in each DRT river basin, we used the 0.5 degree version of the Gridded Population of the World, Version 3 (GPWv3) [*CIESIN*, 2012] and aggregated the

gridded population data to these basins. Gridded population data are available in 5 year intervals for the period 1990 through 2010; we compute changes in basin population for the period 1990/2010. For each river basin, we calculated per capita reservoir storage in 1990 and 2010. We also aggregated these by continent.

2.3. Reservoir Sedimentation Model With Sediment Flux

[11] To calculate sediment flux into the reservoirs, we used output from a recently developed global sediment discharge and delivery ratio model [*Pelletier*, 2012], which explicitly models long-term suspended sediment discharge for pre-dam conditions. The model includes major controls on sediment discharge (slope, precipitation, temperature, vegetation, and soil texture), operates at a spatial resolution of 5 min and is capable of reproducing the long-term sediment yield of 128 global river basins with an R value of 0.79. Because of a spatial mismatch between the drainage river network used in *Pelletier* [2012] and the DRT river network to which the reservoirs were referenced, we regridded basin average values of sediment flux to the DRT river basins.

[12] For the period 1901–2010, each GRanD reservoir was added in its year of installation and the amount of sediment trapped in each reservoir was calculated as the sediment flux (assumed constant over the entire period) entering the reservoir (taking into account the sediments that were already trapped upstream) and the trapping efficiency (*TE*). *TE* is the fraction of incoming sediment that is deposited in a reservoir related to the inflow of sediments. *TE* of an individual reservoir depends on a number of factors such as reservoir and sediment properties and can be directly measured by observing changes in the reservoir volume [*Kummu et al*., 2010]. Empirical relationships were developed to estimate *TE* as a function of reservoir and catchment properties. We used the method of *Brune* [1953] to estimate *TE* for each reservoir as a function of local water residence time, τ (a):

$$TE = 1 - \frac{0.05}{\sqrt{\tau}}; \tau = \frac{C}{MAR} \qquad (1)$$

where C (m^3) is the capacity of the reservoir and MAR ($m^3\ a^{-1}$) is the mean annual river flow volume entering the reservoir, taken from the GRanD database.

[13] With increasing sedimentation in a reservoir and therefore decreasing capacity over time, the trapping efficiency computed with equation (1) decreases with time. *TE* values for all reservoirs for their initial capacity C_0 vary between 0.01 and 0.999, with a median value of 0.94.

[14] For each reservoir, a sediment budget is kept to compute sediment release (i.e., the untrapped fraction), and trapped sediment volume. We used a density of 1200 $kg m^{-3}$ to estimate sediment volumes.

2.4. Reservoir Sedimentation Model With Uniform Loss Rates

[15] The sedimentation of reservoirs is commonly described by a loss rate LR (% a^{-1}) relating the annual loss of storage to the initial capacity so that the expected life time T (a) of the reservoir is $T = 100/LR$. For comparison, we also compute the aggregated loss in reservoir storage if all reservoirs would lose storage at a constant, uniform loss rate LR (% a^{-1}), based on reported data (see section 2.5). In this case, the reservoir capacity C_t (m^3) after t years is:

$$C_t = \max\left(0, C_0 - \frac{LR}{100} C_0 t\right) \qquad (2)$$

where C_0 is the initial reservoir capacity (m^3). For the period 1901–2010, each GRanD reservoir was added in its year of installation. On installation, each reservoir was assigned a constant LR.

2.5. Observed Reservoir Sedimentation Rates

[16] A global data set with consistently measured sediment volumes trapped in reservoirs over time is not available, and, in fact there has been a decline in the collection of sedimentation data [*Syvitski*, 2003; *Vanmaercke et al*., 2011b]. For the US, the Reservoir Sedimentation Database (RESSED) [*Ackermann et al*., 2009] provides statistics on reservoir volumes derived from bathymetric surveys for more than 1800 reservoirs from which sedimentation loss rates can be calculated (using successive surveys). We calculated sedimentation rates of 1024 reservoirs with at least two complete surveys (using the most recent surveys) and supplemented this data set with observed loss rates from an additional 191 reservoirs globally from a variety of sources (Figure 1) to get a global sample of observed loss rates.

[17] This data set covers a wide range of physical conditions in the catchment (e.g., slope, climate, soil type, and land use) and local reservoir conditions (size, area, bathymetry, purpose, and management practices). Observed loss rates vary between 0.0017% a^{-1} and 36% a^{-1} and are 1.35% a^{-1} on average (median = 0.55% a^{-1}). Loss rates for reservoirs with a capacity larger than the minimum capacity in the GRanD database (1 million m^3) have lower loss rates (mean = 0.76% a^{-1}, median 0.35% a^{-1}; Table 1). Weighted by initial capacity, the mean loss rate is 0.66%.

3. Results

[18] The contemporary (year 2010) aggregated net storage capacity (installed capacity minus sedimentation losses) for all GRanD reservoirs is 5720 km^3, nearly 5% lower than the installed capacity of 5990 km^3. The peak in net reservoir storage was reached in 2006 (Figure 2).

[19] In the sediment flux model of reservoir sedimentation, the loss rates, LR, for individual reservoirs tend to be higher for reservoirs with smaller capacity (Figure 3); LR values are 0.64% on average with a median of 0.08%, and a capacity weighted average of 0.13%. Although net storage capacity is decreasing in almost all river basins globally, contemporary storage losses vary regionally (Table 2),

Table 1. Statistics of Observed Reservoir Sedimentation Loss Rates (% a^{-1})

	N	Min	Max	Average	Median	C-Weighted Mean
All	1215	0.0017	36	1.35	0.55	0.66
$C < 1M\ m^3$	733	0.0017	36	1.73	0.70	0.89
$C > 1M\ m^3$	482	0.0041	15	0.76	0.35	0.66

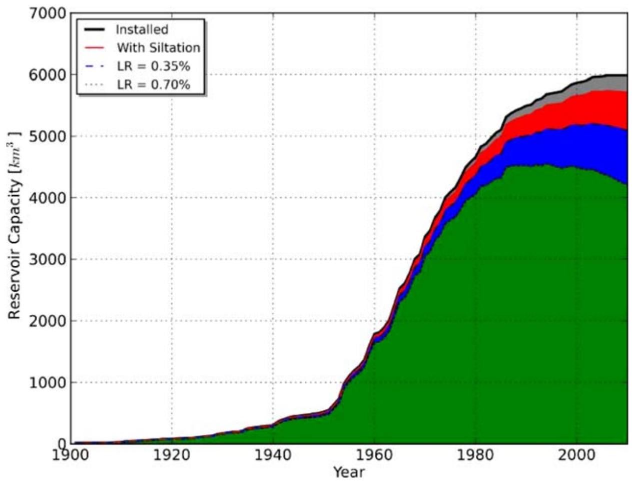

Figure 2. Time series of annual installed and net (with modeled siltation) GRanD reservoir capacity (km^3), aggregated for 6399 GRanD reservoirs. For comparison, net reservoir capacity assuming uniform and constant loss rates (median values of observations in Table 1) are also shown.

with the highest losses occurring in Asia (6.5%), Europe (7.5%), Australia/Oceania (4.3%), and the lowest in South America (2.5%), North America (3.2%) and Africa (3.4%). These regional differences reflect the differences in sediment delivery and reservoir age across regions. Compared to 1990, the global reservoir capacity in 2010 had increased by about 7%, with large variations across regions depending on the balance of reservoir construction and reservoir sedimentation. The largest reductions in net capacity over the last 20 years are seen in Australia where net capacity decreased by 1.9%. Capacity in North America, Africa, and Europe increased slightly by 0.7, 0.6, and 1.3%. There are considerable increases in the net capacity in Asia (12.4%) and South America (24.1%).

[20] In Africa, all river basins have had nearly constant or declining net storage during the last 20 years, with the exception of the Lake Chad basin (35% increase) and the Orange River basin (12% increase). In Asia, most river basins show decreasing storage capacity. River basins with increasing net storage include the Yangtze (53%, mostly due to the construction of the Three Gorges Project), Yellow (32%), Shat el Arab (54%), and the Mekong river basin (9%). The Paraná and Tocantins river basins in South America experienced a considerable growth in net storage (113% and 35%). All other large river basins have declining net storage capacity.

[21] The impressive growth in installed reservoir capacity during the last century was outpaced late in the century by the growth in population. From 1990 to 2010 global population increased by about 30%, while the installed reservoir capacity grew from 5497 to 5990 km^3, an increase of about 9%.

[22] Not taking into account sedimentation losses, reservoir capacity available per person peaked in 1987 (1073 m^3) and decreased by 19% in 2010 (868 m^3). When sedimentation is considered, the highest per capita net storage capacity (1047 m^3) was available in 1987 and has since then declined by 21% to 828 m^3 today (Figure 4).

[23] Related to population, the largest net storage is available in Australia, North America, and South America. Despite an increase in net reservoir capacity in Asia, many basins have dramatically decreased the available storage per person as a result of rapid population growth (Figure 5). The highly populated river basins in East and South Asia (Indus, Ganges, Yellow, and Yangtze) have relatively

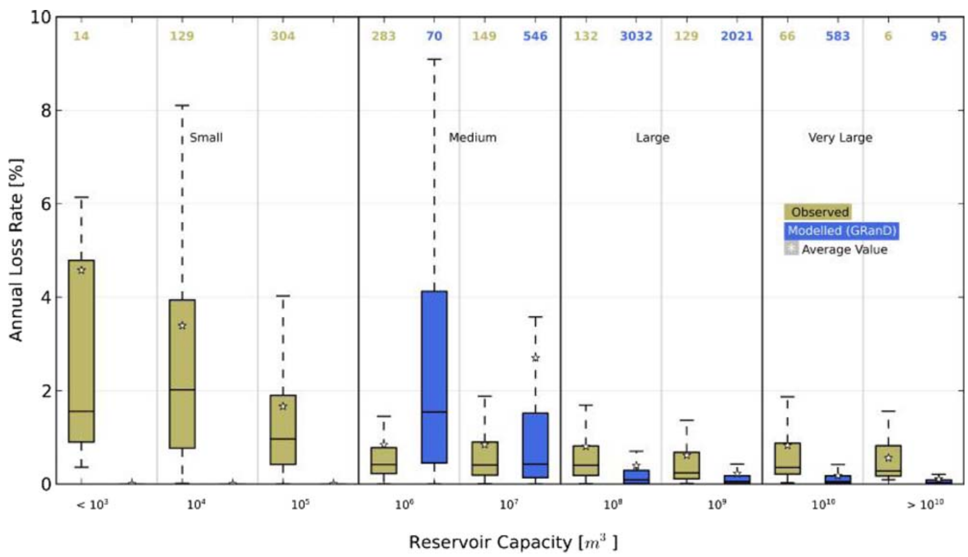

Figure 3. Observed (brown) and modeled (blue) annual loss rates for individual reservoirs (% a^{-1}), grouped by reservoir size classes (upper class limits labeled). Size definitions (small, medium, large, very large) indicate size definitions for American dams [*Graf*, 2005]. Numbers on top indicate number of reservoirs in each size class. Boxes show median and upper and quartiles, whiskers show most extreme values in the 1.5 times interquartile range, star shows average values. Note that observed and modeled reservoir represent independent samples of the total global population of reservoirs (see Figure 1); no GRanD reservoirs fall into the "small" size class.

Table 2. Reservoir Installed and Net Capacity and Population in 1990 and 2010, and Percent Change in Capacity and Population 1990–2010, by Continent

	Installed Grand Reservoirs		Net Capacity (km^3)		Population[a] (Billion People)		Change in Capacity (%)		Change in Population (%)
Continent	Number	Capacity (km^3)	1990	2010	1990	2010	Inst/2010[b]	1990/2010	1990/2010
Asia	1774	1810	1500	1690	2.994	3.906	−6.5	12.4	30.5
North America	2213	1710	1640	1650	0.389	0.493	−3.2	0.7	26.8
Australia/Oceania	239	95	92	91	0.018	0.022	−4.3	−1.9	24.4
South America	292	851	669	830	0.27	0.362	−2.5	24.1	34.0
Europe	1241	548	500	507	0.629	0.624	−7.5	1.3	−0.8
Africa	640	981	942	948	0.588	0.948	−3.4	0.6	61.2
Total	6399	5990	5350	5720	4.889	6.356	−4.5	6.9	30.0

[a]Note that the total population is ~7% lower than in the original CIESN data due to a spatial mismatch between landmasks in DRT and CIESN data.
[b]Change in contemporary storage capacity compared to installed capacity.

low storage; per person storage in those basins decreased during the last 20 years as a result of population growth.

4. Discussion

4.1. Comparison With Other Studies

[24] Our mean estimated storage loss of 270 km^3 or 5% of the installed reservoir capacity reduces the net reservoir capacity to 5720 km^3. This estimated loss is lower than the 2000 km^3 previously estimated by *Basson* [2009], using a global sedimentation rate of 0.8% per year. Applying the 0.8% a^{-1} rate to all reservoirs, the GRanD data set results in a net storage of 3890 km^3. If loss rates are taken as the median value from the entire data set of observed sedimentation rates and for reservoirs larger than 1 million m^3 (0.70% and 0.35%; Table 1), the simulated net storage in 2010 is 4160 and 5070 km^3, translating to a loss of reservoir storage of 27% and 15% compared to the installed capacity. Our estimated loss represents about half of the 567 km^3 estimated for the year 2000 reported by *White* [2001] using data from the 1998 global register of dams [*ICOLD*, 1998].

[25] For reservoirs with capacity greater than 10^5 m^3, we can compare our modeled siltation rates with the observed values. The observed sedimentation rates are fairly uniform for all medium, large, and very larger reservoirs, while the modeled rates decline with size across this range, and match the observed only for $10^6 < C \leq 10^7$ m^3 (Figure 3). Our results and the observed loss rates in 1215 reservoirs (Table 1 and Figure 3) suggest that the loss rates are generally higher for smaller reservoirs. Larger reservoirs may have more upstream reservoirs trapping sediments lowering their inputs and a higher fraction of catchment area that has low slope, a major factor controlling sediment yield.

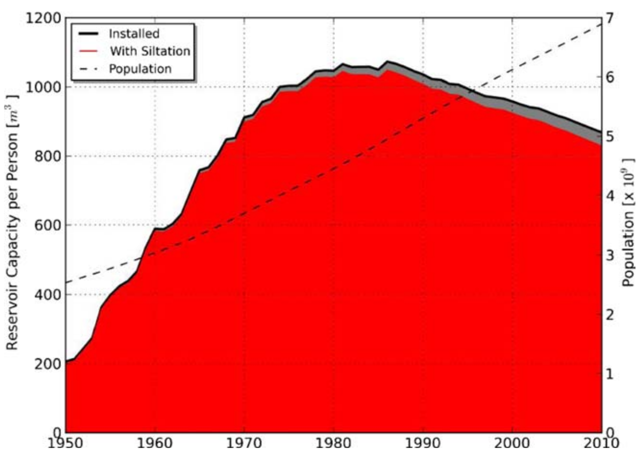

Figure 4. Simulated mean reservoir GRanD capacity per person based on installed and net (with modeled siltation) reservoir capacity from 1950 to 2010, along with global population (black dashed line).

[26] This relationship has important implications for the sediment loss of all reservoirs. GRanD represents an estimated 75% of the total storage, and it is estimated that 16.7 million smaller reservoirs exist globally with an additional storage capacity of 1873 km^3 [*Lehner et al*., 2011]. The actual loss in those reservoirs depends on the age structure of the reservoirs and their location with regard to the spatial distribution of sediment yield. Had those smaller reservoirs had their storage reduced at the same rate as the reservoirs in GRanD (5%), the loss in those smaller reservoirs would be 94 km^3 but the relationship in Figure 3 implies that the loss is likely to be much higher. Assuming a constant loss rate from the median of observed values, the loss in the storage capacity in smaller reservoirs would be as high as 27%, representing an accumulated loss of 490 km^3. On the other hand, we do not consider remediation efforts (this is discussed in more detail below).

[27] Assuming a sediment density of 1200 kgm^{-3}, this implies that 326 Gt of sediments are currently trapped behind large reservoirs. The mean annual loss in reservoir capacity for the last two decades is about 6.2 km^3 a^{-1} (7.44 Gt a^{-1}) and is comparable to the results of *Vörösmarty et al*. [2003] who estimated the interception of all registered dams to be 4 and 5 Gt a^{-1}.

4.2. Implications for Sea-Level Rise

[28] The sequestration of water in constructed reservoirs reduced the rate of sea-level rise by around 0.5 mm a^{-1} at the time of peak reservoir construction near the middle of the 20th century [*Chao et al*., 2008; *Lettenmaier and Milly*, 2009]. The decline of reservoir storage capacity as a result of sedimentation and decreased reservoir construction rates in the most recent decades suggest that role of large reservoirs could change from suppressing sea-level rise to making a small positive contribution to sea-level rise due to sediment displacement of reservoir water.

4.3. Uncertainties

[29] It is important to understand the uncertainty associated with these estimates. The uncertainties in the sediment

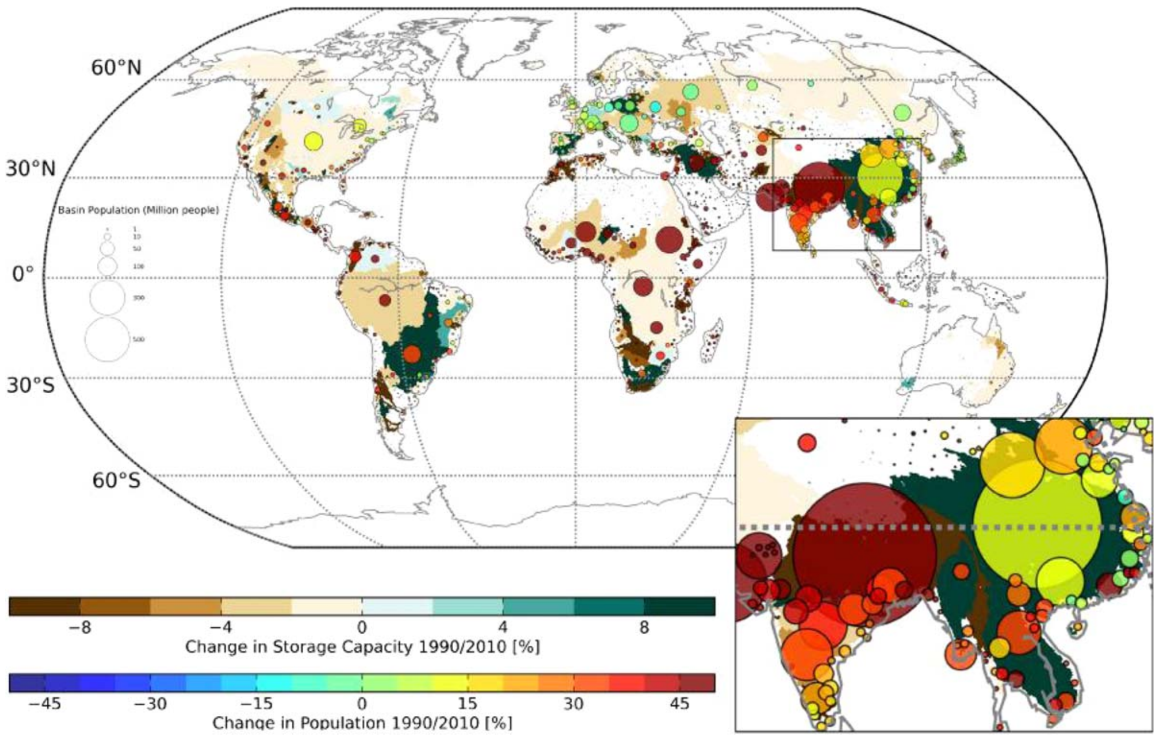

Figure 5. Percent change in basin-wide values of net reservoir capacity (shaded basins) and population (filled circles) between 1990 and 2010 for the largest 2000 basins based on the DRT river network. Unshaded regions represent basins with no reservoir in the GRanD database.

flux data set are discussed in *Pelletier* [2012]; they are mainly related to the lack of an explicit modeling of the episodicity of sediment discharge (for example, as a result of landslides [*Koi et al*., 2008]). Sediment yield also depends on other disturbances such as land use changes [*Vanmaercke et al*., 2011b]; these are not considered when using long-term sediment yield data for the entire simulation period.

[30] The sediment flux data set considers only the suspended sediment flux; this represents the vast majority of total sediment flux; not including sediments that move close to the river bed (bed flux) might lead to additional uncertainties in certain regions. In addition, our estimates of reservoir sedimentation do not consider measures to minimize the effects of siltation and to partly restore reservoir capacity. Reservoir operation policies that try to achieve a balance between sediment inflow and outflow can greatly reduce the accumulation of sediments in the reservoir [*Wang*, 2005]. Conservation practices that trap sediments upstream of the reservoir have proven to be economically viable for individual reservoirs [*Kawashima*, 2007] but dredging to recover the capacity of large reservoirs is mostly prohibitive by cost [*Minear and Kondolf*, 2009]. Costs for sediment removal through flushing are related to the loss of water yield [*Kawashima*, 2007] and flushing success depends on a number of site-specific characteristics and is generally more successful for reservoirs with residence times <0.3 a [*White*, 2001]. It is generally not considered to be economically feasible. *Palimeri et al*. [2003] estimated the cost to replace the lost storage (adding 45 km^3 per year) to be US$13 billion, not counting the social and environmental cost associated with the construction of new reservoirs; however, many silted reservoirs cannot simply be replaced by other reservoirs because of site characteristics [*Morris and Fan*, 1998]. There are also costs and environmental problems associated with decommissioning dams [*Palmieri et al*., 2001]. Note that, since the scope of efforts to reverse sedimentation losses in reservoirs globally is unknown and not included in our analysis, our estimates of storage loss may be biased high.

[31] Although the GRanD database is the most comprehensive spatial data set of large reservoirs, the database might be biased toward older reservoirs. It is likely that the decrease in reservoir growth depicted in the GRanD database for the last decade may partly be the result of recently built reservoirs not appearing in data repositories that were used to compile the GRanD data set.

[32] Uncertainties are not only related to the model results but also to the observed sedimentation rates. The compiled values are typically computed from bathymetric surveys assuming a constant loss between the surveys. Sedimentation rates for individual reservoirs are very likely to change over time, both as a result of lower trapping efficiency with decreased capacity, and as a result of varying sediment influx, for example, as a result of landslides. Due to the large number of observed sedimentation rates coming from the RESSED database, the values used to simulate reservoir capacity have a geographical bias toward North America and might not be representative for other regions. The median value of observed sedimentation for all reservoirs rates (0.55% a^{-1}) is similar to the 0.48% a^{-1} reported by *White* [2001] who compiled data for 2300 reservoirs in 31 countries and summarized storage losses with a considerable range between countries and regions

(China: 2.3% a^{-1}, Northern Africa: 0.08% a^{-1}). In a similar exercise, *Basson* [2009] reported reservoir capacity loss rates by continent and region with a much smaller range (0.68% a^{-1} for North America to 1.02% a^{-1} for the Middle East), and with a mean value of 0.8% a^{-1}. The mean reported values for Europe, for example, are much lower than data for 161 Mediterranean reservoirs that have an average annual loss rate of 2.5% a^{-1} and span four orders of magnitude [*Vanmaercke et al*., 2011a].

[33] Despite the uncertainty in these estimates, sedimentation is an acknowledged problem in reservoir management, one that is typically not given enough attention when designing reservoirs [*Schleiss et al*., 2010], and might be a larger problem for some river basins than originally thought.

[34] The loss in storage in many river basins as a result of sedimentation in reservoirs, in combination with higher demand for water with growing population, poses a significant challenge from a water resources management point of view. Storage is one of the primary mechanisms used to balance water supply and demand, and a loss of storage will decrease the capability of a river basin or region to cope with increased hydroclimatic variability. Declining storage will, therefore, increase the vulnerability of a region to climate change [*Kundzewicz et al*., 2007]. This problem is particularly relevant in river basins with a pronounced seasonal (e.g., nival, glacial, and monsoonal) flow regime, which might change with changing climate or climate variability.

[35] Reservoir storage can buffer changes in the flow regime arising from changes in the timing of snowmelt in snow-dominated river basins [*Barnett et al*., 2005] when critical demand occurs during the snowmelt season. Where storage is not available, additional river water flowing outside the crop growing season is not available for irrigation [*Gornall et al*., 2010]. For example, the declining absolute storage in the Indus River basin limits the ability to transfer surplus summer flow to sustain winter wheat irrigation in the basin [*Laghari et al*., 2012]. The impact of reservoir capacity reduction on reservoir yield depends on local characteristics of the reservoir, the operations policy, and the hydrological regime of the inflow [*De Araujo et al*., 2006].

[36] Erosion and sediment dynamics will change with changing climate and land use. *Yang et al*.[2003] estimated a 17% increase in soil erosion related to the development of croplands over the last century. Climate is a strong control on sediment flux through changes in the overall water balance [*Syvitski*, 2003]. How these changes in soil erosion will translate into sediment yield is, however, unclear because of the complex interactions between erosion and deposition in a river basin. On average, 90% of eroded material is stored in the river basin and not exported from the watershed [*Stallard*, 1998; *Syvitski*, 2003]; estimating how changes in erosion dynamics translate into varying sediment export from watersheds will, therefore, require a more complete understanding of the complex dynamics of buffering and storage within the watershed [*Walling*, 2009].

5. Conclusions

[37] Based on an analysis of the best available geospatially explicit data on large reservoirs and outputs from a recently developed global sediment discharge model, we have estimated the total available capacity of large reservoirs over time. Net reservoir storage most likely peaked around 2006 and has been decreasing since then. Neglecting spatial variations in sediment delivery and the capacity dependence of loss rates by applying a uniform loss rate to all reservoirs globally might result in an overestimation of capacity losses.

[38] Using population data as a simple surrogate for demand in storage, we demonstrate that reservoir storage capacity per person has been declining in most river basins globally since the 1980s.

[39] These losses, in combination with changes in the spatial and temporal dynamics of water demand, exert rising challenges on balancing water supply and demand in many river basins in the face of population growth and climate change. Given the potential environmental and social impacts of large reservoirs and the limited number of suitable locations available for large reservoirs, efforts to address these challenges should include improved reservoir management to minimize sedimentation storage losses, enhanced or restored groundwater storage through managed aquifer recharge, the construction of small reservoirs (reservoirs not on main stem rivers), as well as measures that focus on improving the productivity of water (the "soft path" for water [*Gleick*, 2003]).

[40] Changing climate variability and land use are likely to change erosion rates and potentially sediment yield in the future. To better understand these dynamics over large scales and in time, a more consistent monitoring of sediment transport and reservoir sedimentation rates is needed.

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