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Anthropogenic impact on global geodynamics due to reservoir water impoundment

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Abstract. Water impounded in artificial reservoirs since ~1950 is by far the largest anthropogenic hydrological change in terms of the mass involved. This mass redistribution contributes to geodynamic changes in the Earth's rotation and gravitational field that have been closely monitored by modern space geodetic techniques. We compute the effect of 88 major reservoirs on length-of-day, polar motion, and low-degree gravitational coefficients. On an individual basis much smaller than geophysical signals in scale and magnitude, these anthropogenic effects prove to be non-negligible cumulatively, especially when considering the fact that our results represent underestimates of the reality. In particular, reservoir water has contributed a significant fraction in the total observed polar drift over the last 40 years.

Introduction

Human activities have greatly altered the living environment throughout history. One of the most significant alterations is water management that has been administered on land. Among various types of water management projects, the artificial reservoirs are by far the largest in terms of the amount of water involved [e.g., *Chao*, 1991].

Ever since the early 1950s, the world has seen intensive construction of artificial reservoirs. In a study of the anthropogenic impact on sea level, *Chao* [1991] estimated that, growing essentially linearly, the amount of water impounded in these reservoirs by the early 1990s have reached as much as 10,000 km^3, or 10^{16} kg. This is as much water as there is total atmospheric moisture or equivalent to 10 times the Earth's biological water, and greatly exceed the 1,900 km^3 compiled by *Sahagian et al.* [1994] which has been considered as a gross underestimate [*Chao*, 1994; *Rodenburg*, 1994]. Ultimately removed from the ocean, it has lowered the sea level by about 3 cm, equivalent to an average rate of sea level drop of 0.7 mm per year over the past 40 years.

The water mass redistribution due to the artificial reservoirs also has impact on global geodynamics in two distinct effects: It changes the moment of inertia, and hence the rotation of the Earth under the conservation of angular momentum. It also changes the external gravitational field according to Newton's gravitational law. The Earth rotational change is conveniently expressed in terms of its magnitude, or the length-of-day (LOD) variation, and its orientation in the terrestrial reference frame, or the polar motion excitation. The gravitational changes are expressed in terms of the variation of the harmonic coefficients of the gravitational potential field. These are the specific geodynamic quantities we will compute.

Chao [1988] has computed the polar motion excitation produced by a host of major hydrological changes including those due to major artificial reservoirs in the world completed before 1986. Building upon the latter, we will in this paper compute and discuss not only the polar motion excitation but also LOD and low-degree gravitational changes due to a more complete and up-to-date list of major reservoirs.

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Data and Computation

We have compiled a tally of 88 major reservoirs that exceed 10 km^3 in capacity from four different sources. Two of them, *Van der Leeden* [1975] and *U.S. Department of the Interior* [1983], led to 53 major reservoirs previously listed and employed by *Chao* [1988]. Two additional sources, *U.S. Department of the Interior* [1988] and *International Water Power & Dam Construction Handbook* [1993], provide supplementary as well as more up-to-date tally. Figure 1 shows their geographical distribution and relative sizes in logarithmic scale. The corresponding cumulative water impoundment is shown in Figure 2. The growth of the amount of water over time is virtually linear since 1950, showing no sign of slowing down.

The computations conducted below in this paper pertain to these major reservoirs. The water mass redistribution is modeled as an instantaneous addition of a point mass equal to the full capacity at the reservoir location in the year of its completion, minus an accompanying eustatic drop in the sea level to conserve the total water mass (see the inside scale of Figure 2). The formulae for computing changes of the geodynamic quantities due to the addition of a point mass m at location (latitude θ, longitude λ) are of the general form:

$$\Delta Q = q(\theta,\lambda)\ m \,/\, (\text{mass of Earth}) + [\text{ocean correction}]. \quad (1)$$

The function $q(\theta,\lambda)$ is the geographical weighting function depending on the parameter in question.

For the change in the normalized harmonic coefficients of the gravitational field, or the (complex) Stokes coefficients $C_{lm} + iS_{lm}$ of degree l and order m, $q = [(1+k_l')/(2l+1)]P_{lm}(\theta)\exp(im\lambda)$ [e.g., *Chao and O'Connor*, 1988], where P_{lm} is the 4π-normalized Legendre function, and the factor $1+k_l'$ (where k_l' is the load Love number, e.g., $k_2' = -0.31$, $k_3' = -0.20$, $k_4' = -0.13$, etc.) accounts for the elastic yielding effect of the Earth under loading. In particular, the un-normalized zonal "J" coefficients are given by $J_l = -(2l+1)^{1/2}\, C_{l0}$.

The LOD change in units of μs can be directly evaluated by multiplying 1.96×10^{11} to the change in J_2. This is because the two changes are proportional to each other as long as the mass

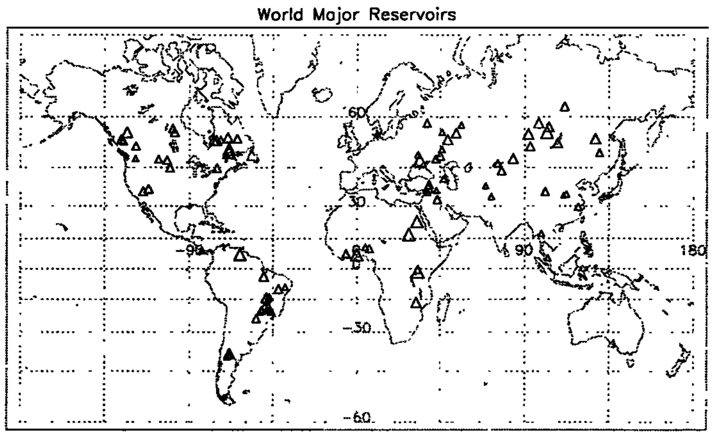

Figure 1. The geographical distribution of 88 major reservoirs and their relative sizes in logarithmic scale.

redistribution occurs on the surface of the Earth which can be well approximated by a spherical shell (so that the change in the trace of the inertia tensor vanishes subject to the conservation of mass, see *Chao and O'Connor* [1988]). Here it is assumed that the fluid core is decoupled from the mantle in the excitation process that is rapid compared to the characteristic time for the Earth's visco-elastic responses.

The polar motion excitation is often expressed in the complex quantity $\Psi = \Psi_x + i\Psi_y$ where x and y axes point to the Greenwich Meridian and the 90°E longitude in the terrestrial coordinate system. Its geographical weighting function is $q = -1.12 \sin\theta \cos\theta \exp(i\lambda) / J_2$, proportional to the change in the Stokes coefficients of degree 2 and order 1. The point-mass excitation is most effective at the 45° latitudes and zero at the poles and the Equator, whereas two equal masses located on the same latitude but 180° apart in longitude, such as Canada and Siberia (cf. Figure 1), will cancel each other. The factor 1.12 takes into account the elastic yielding effect and the decoupling of the core. The polar motion excitation enjoys the magnification by the factor $1/J_2$ (where $J_2 = 1.083 \times 10^{-3}$ is the Earth's dynamic oblateness), because the system "inertia" that it needs to overcome is only the difference between the axial and equatorial moments of inertia of the Earth (as opposed to the axial moment of inertia itself in the case of the LOD).

An ocean correction term is invoked in Equation (1) to conserve water mass. It is assumed that the water impounded in reservoirs ultimately comes from the ocean (by way of the atmosphere), resulting in an instantaneous, uniform eustatic drop of sea level. This term is computed according to *Chao and O'Connor* [1988] (an extra factor of 1.12 is introduced to LOD and polar motion excitations to account for the decoupling of the core). The ocean correction is typically no more than a tenth of the point-mass contribution, because the water distribution involved is wide spread and hence less effective than point masses. In addition, the actual motion of the (water) mass transport also excites Earth rotational variations. However, this contribution in our present case is negligible as the motion (from ocean to the reservoirs) is a relatively slow process.

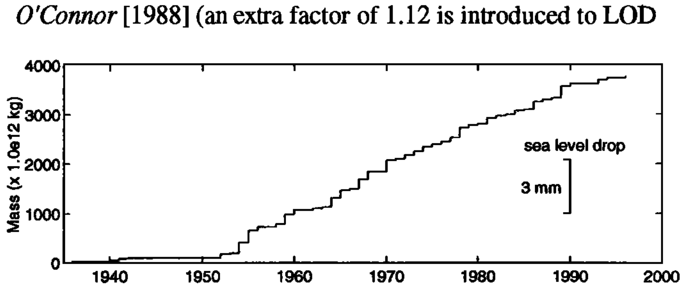

Figure 2. The cumulative impoundment of reservoir water over time. The inside scale gives the equivalent eustatic sea-level drop.

As a rule of thumb from Equation (1), a point mass equivalent to 100 km^3 of water (as with the very largest reservoirs) will only produce a LOD change on the order of 1 μs, a polar motion excitation on the order of 1 milliarcsecond (mas), and a J_2 change on the order of 10^{-11}. We shall examine the *cumulative* effects computed simply by sequentially summing up the 88 individual contributions over time: $\Delta Q(t) = \Sigma_i \Delta Q_i H(t-t_i)$, where H indicates the Heaviside function and t_i is the completion time (in nominal year) of the ith reservoir.

Results and Discussion

We compute the changes induced by the 88 reservoirs in the three degree-1 Stokes coefficients (C_{10}, C_{11}, S_{11}), the five degree-2 Stokes coefficients (J_2, C_{21}, S_{21}, C_{22}, S_{22}), and the zonal coefficients of degree 3 and 4 (J_3, J_4). As stated, the change in LOD is proportional to that of J_2, and the polar motion excitation is proportional to the change in $C_{21} + iS_{21}$. Higher harmonic changes, which tend to be smaller in magnitude because of geographical cancellations, are of less interest as they are not subject to direct observations.

Figure 3 shows the reservoir-induced, cumulative changes in C_{10}, C_{11}, and S_{11}, converted to distance (in mm) by multiplying the Earth's mean radius and inverting the sign. Respectively they represent the z, x, and y components of the shift of the "geocenter" location. The center of mass of the total system of [solid Earth + reservoirs] remains unchanged as the reservoirs are filled, of course. Therefore, the center of mass of the solid Earth, or geocenter, shifts in the opposite direction to the net water mass shift (which is toward the northern hemisphere and the positive x direction). The geocenter shift can be detected by space geodetic measurements made at geodetic stations, which

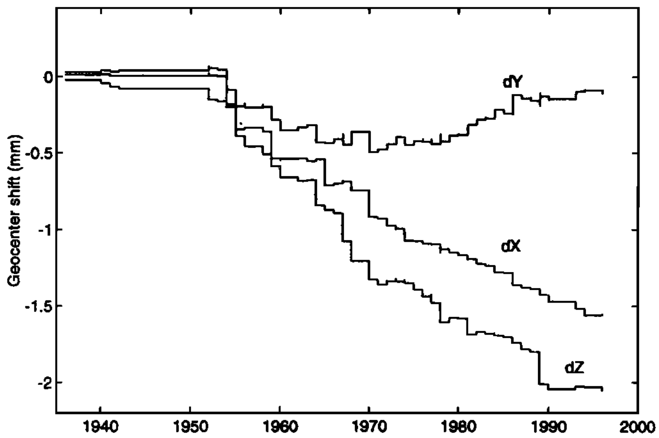

Figure 3. Geocenter shift due to world's major reservoirs.

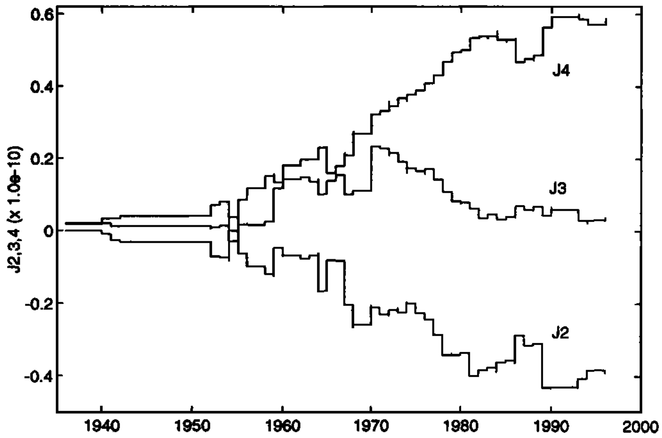

Figure 4. Changes in the Earth's zonal gravitational coefficients J_2, J_3, and J_4 due to world's major reservoirs.

are fixed w.r.t the solid Earth. The total reservoir-induced shift of about 3 mm is comparable in magnitude to the rms center-of-mass fluctuations caused by the seasonal atmospheric mass redistribution [R. S. Nerem, personal communication, 1995].

Figure 4 shows the cumulative changes in the zonal J_2, J_3, and J_4. In particular, the reservoirs caused the Earth's dynamic oblateness J_2 to decrease at the rate of about -1.0×10^{-12} per year since ~1950. This quasi-secular rate is an order of magnitude larger than the earthquake-induced counterpart at about -0.2×10^{-12} per year averaged over 1977-1993 [*Chao et al.*, 1995]. In comparison, the observed secular rate of J_2 determined from laser ranging to Lageos satellite is about -26×10^{-12} per year, whereas the rms seasonal fluctuation of J_2 is even larger at about 200×10^{-12} [e.g., *Nerem et al.*, 1993]. The former has been attributed to the post-glacial rebound and polar ice sheet variations, and the latter is primarily a consequence of atmospheric mass redistributions. Similarly, the overall reservoir-induced variation in J_3 is two orders of magnitude smaller than that observed by Lageos.

Figure 5 gives the cumulative changes in J_{22} and ϕ_{22}, defined by $J_{22} \exp(i2\phi_{22}) = C_{22} + iS_{22}$. As shown by *Liu and Chao* [1991], J_{22} is a normalized positive difference between the two equatorial principal moments of inertia, while ϕ_{22} is the longitude of the (equatorial) principal axis of the least moment of inertia. Their changes can be easily evaluated from the Earth's existing C_{22} and S_{22} and changes thereof. The reservoir-induced J_{22} shows a decreasing trend at the rate of about -0.6×10^{-12} per year for the last 40 years. Like J_2, this rate is an order of magnitude larger than the earthquake-induced counterpart during 1977-1993. The reservoir-induced change in the angle ϕ_{22} has, to date, reverted to its original value after peaked at some 1.4 arcseconds in the 1970s.

The reservoir-induced LOD change is proportional to that of J_2. The cumulative change is shown in Figure 6, displaying an average rate of about -0.2 μs (in each day) per year for the past 40 years. Although hardly noticeable even in modern measurements, this rate is about twice that due to earthquakes during 1977-1993 [*Chao and Gross*, 1995]. It is interesting to examine the physics of the process. The net water transport has been toward high latitudes (cf. Figure 1); J_2 reduces as a result and so does the Earth's axial moment of inertia. Like a spinning skaters drawing her arms toward her body, the Earth spins faster under the conservation of angular momentum (hence shorter LOD), and the kinetic energy of the spin increases in the process. The ultimate source of this energy is the solar energy transferred by way of the meteorological heat engine. It is easy to show [*Chao and Gross*, 1995] that the average rate of this spin energy increase is $+10^{18}$ joul per year, or about 30 gigawatt, equivalent to about 3% of the total human power consumption. In comparison, the average rate of seismic wave energy release during 1977-1993 is about 5 gigawatt.

Figure 7 shows the polar motion excitation function Ψ. Despite a considerable geographical cancellation, both x and y components show a quasi-secular trend. Thus, the filling of major reservoirs over the past 40 years has caused the mean rotational pole to drift some 20 mas, amounting to an average of 0.5 mas per year, toward ~130°W. The observed polar drift over the same period is estimated to be 3.2 mas per year in the direction of 81°W [R. S. Gross, personal communication, 1994]. The reservoirs have thus contributed a significant fraction in the observed polar drift, in roughly the same general direction. This should be taken into consideration in studies with respect to the geophysical causes of the polar drift.

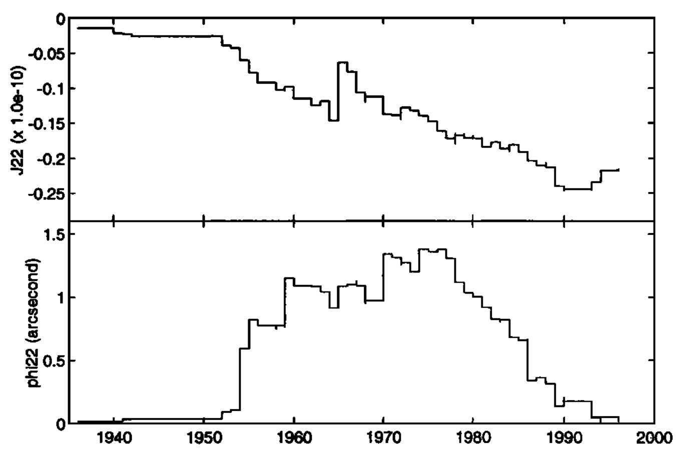

Figure 5. Changes in the Earth's equatorial moments of inertia due to world's major reservoirs.

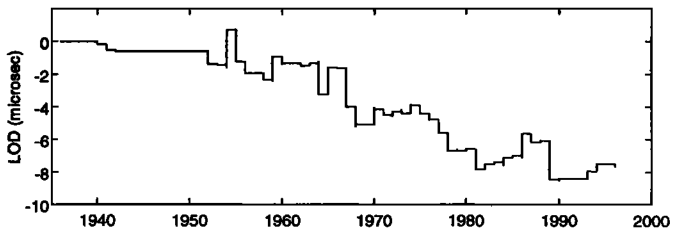

Figure 6. Changes in the length-of-day due to world's major reservoirs.

Discussions and Summary

The water impounded in artificial reservoirs is by far the largest anthropogenic hydrological change in terms of total water mass involved. It not only represents a significant element in the global hydrological and sea level budget, but also contributes to geodynamic changes in the Earth's rotation and gravitational field that have been closely monitored by modern space geodetic techniques. We have compiled a list of 88 major reservoirs that exceed 10 km^3 in capacity, and computed the effect of the associated water mass redistribution on length-of-day, polar motion, and low-degree gravitational coefficients. The mass redistribution is modeled as an instantaneous addition of a point mass minus an accompanying eustatic drop in the sea level to conserve the total mass. In terms of magnitude, these anthropogenic geodynamic signals from individual reservoirs are barely detectable. However, the *cumulative* effects show non-negligible, quasi-secular behavior (as opposed to characteristics of a random walk process) due to non-randomness in the reservoirs' geographical distribution. In particular, the reservoirs account for a significant fraction in the observed polar drift.

Finally, we should point out that our computed results only represent underestimates of the reality, for two reasons. First, the major reservoirs under consideration account for about 40% of the total water impoundment in the world to date [cf. *Chao*, 1994]. Smaller reservoirs are more numerous; individually they are indeed entirely negligible. But their collective contribution may not be negligible. This omission is presumably more severe for LOD and the zonal gravitational harmonics considering the zonal nature of human activities, than for the polar motion excitation because of the east-west cancellation mentioned above. The second, and potentially more important, reason is that we have only considered the "visible" part of the water impoundment and ignored the water that is stored underground in an artificially elevated water table [*Chao*, 1991]. The amount of this "invisible" water can often be comparable if not significantly larger than the visible part [D. Sahagian, personal communication, 1995], although the effect is often partially offset by the fact that the reservoirs are not always filled to the design capacity. A more realistic account for this effect is pending better knowledge about the local geology and reservoir history.

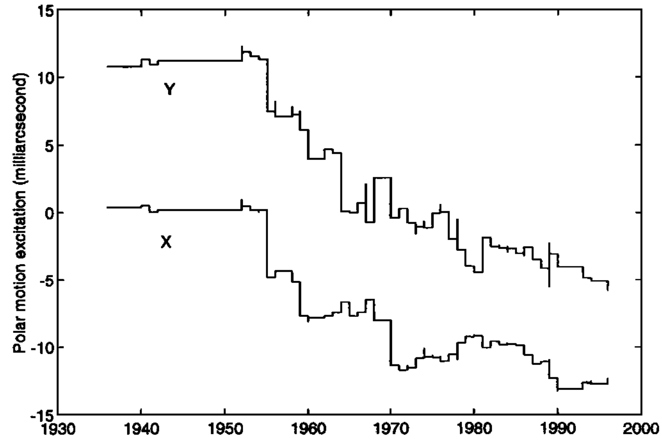

Figure 7. Polar motion excitation by world's major reservoirs (the *y* component offset vertically by an arbitrary amount).

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