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Effects of anthropogenic intervention in the land hydrologic cycle on global sea level rise

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Abstract

Recent studies suggest that anthropogenic modification of land hydrology (e.g. through groundwater mining, dam building, irrigation, deforestation, wetlands drainage, and urbanization) could significantly impact sea-level rise, although the magnitude and sign of this effect have been widely debated. This paper attempts a comprehensive overview of the effects of human activities on land hydrology. Estimates are provided for the volumes of water associated with each of the major anthropogenic processes and the corresponding equivalent in sea level.

Groundwater mining and runoff from paved and built-up areas are two major sources of water added to the ocean. In contrast, storage of water behind dams, losses through percolation, and evapotranspiration from irrigated fields withhold water that would otherwise flow to the sea. The net effect of these processes holds back the equivalent of 0.8 ± 0.4 mm/yr from sea-level rise. This is a magnitude comparable to, but in the opposite direction from the currently observed sea-level rise of 1–2 mm/yr. These estimates are still preliminary, awaiting better documentation. Coupling of improved land hydrology models with GCMs will help in analysis of feedbacks, especially the partitioning of water among runoff, infiltration, and evaporation.

Keywords: deforestation; groundwater; human activities; hydrology; irrigation; reservoirs; sea-level change; water storage

1. Introduction

Global mean sea level has apparently been rising at rates ranging between 1 and 2 mm/yr over the last 100–150 years (Warrick and Oerlemans, 1990; Gornitz, 1995). Studies that are based on longer records and that correct for post-glacial rebound report values closer to 2 mm/yr (i.e., 20 cm total for the last century; Peltier and Tushingham, 1991; Douglas, 1991). Within the next 100 years, projected global greenhouse warming may increase the rates of sea level rise (SLR) 2–5 times over present rates, posing a threat to low-lying coastal regions (Warrick et al., 1996).

Approximately 10 out of the estimated 20 cm of the SLR of the last 100–150 years can be attributed to thermal expansion of the upper ocean layers and to melting of mountain glaciers, related to rising global mean surface surface air temperature (Warrick et al., 1996; Gornitz, 1995; Douglas, 1995). The

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present contribution to SLR from melting of the Greenland and Antarctic ice sheets is much less certain, however, and may be close to zero (Warrick et al., 1996). Some 10 cm remain to be accounted for by other processes, including human intervention in the hydrologic cycle.

The possible effects of anthropogenic modification of land hydrology on sea level have long been debated. Kalinin (1968) suggested that filling of reservoirs and seepage from impoundments and from irrigation could lower mean sea level by several tenths of a millimeter per year. Gornitz and Lebedeff (1987) argued that the drop in sea level due to the volume of water withheld from the sea in reservoirs and lost through deep seepage was nearly balanced by the seaward drainage due to groundwater mining. On the other hand, Newman and Fairbridge (1986) claimed that a volume equivalent to an average of 0.75 mm/yr SLR had been stored by reservoirs and used in irrigation projects between 1932–1982, and that the extent of groundwater mining had been vastly overestimated by at least an order of magnitude. Chao (1991) calculated a lowering of SLR of 0.7 mm/yr resulting from dam impoundment alone.

More recently, Sahagian et al. (1994) estimated that groundwater mining, surface water diversion, and deforestation would actually *add* 0.54 mm/yr to SLR. However, their figure of 1900 km^3 for water storage in reservoirs is too low (Rodenburg, 1994; Chao, 1994), and they overlooked other possible land sinks (e.g., deep percolation beneath reservoirs and irrigated fields; increased atmospheric moisture retention), which could instead withhold up to 1.6 mm/yr of potential SLR (Gornitz et al., 1994).

Furthermore, in the calculations by Sahagian et al. almost 40% of the SLR attributed to direct anthropogenic activities came from the Caspian and Aral Seas. The level of the Caspian Sea exhibits marked fluctuations, showing a sharp rise in the period since 1978, following a long period of fall between 1880 and 1977 (Ignatov et al., 1993). These fluctuations largely reflect adjustments of the water budget to natural climatic variations (D. Aubrey, pers. comm., 1996), although man-made modifications of the drainage basins may also have contributed. Recent damming of the Kara-Bogaz-Gol has aggravated the flooding situation along the shores of the Caspian (Rich, 1991).

In contrast, the Aral Sea has been falling precipitously over the last 30 years, largely due to upstream diversion for irrigation (Perera, 1993). Ironically, water losses from irrigation canals and beneath irri-

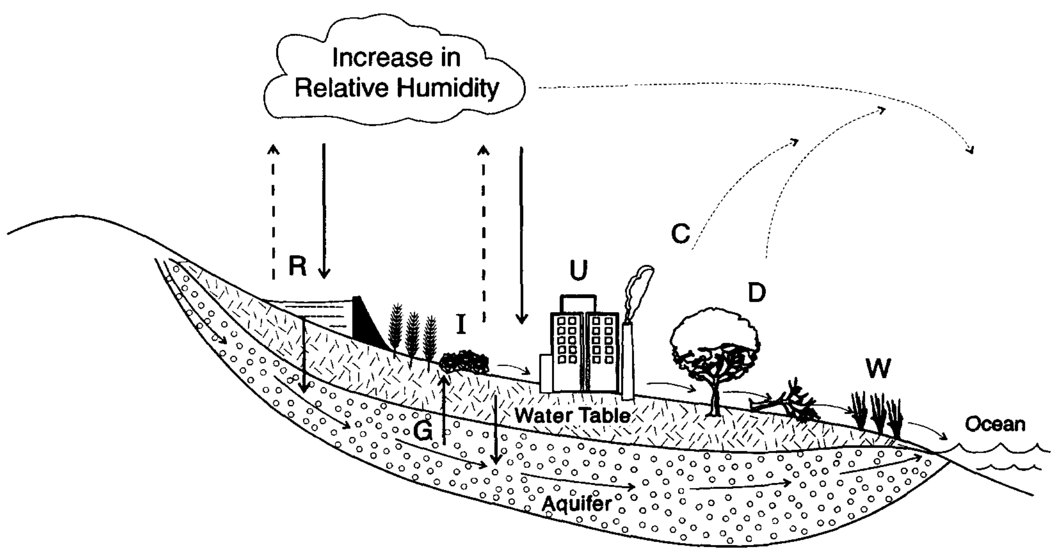

Fig. 1. Schematic diagram illustrating the effects on sea level of anthropogenic intervention in the hydrologic cycle. $R =$ reservoir impoundment; $G =$ groundwater mining; $I =$ irrigation; $U =$ runoff from urbanization; $C =$ water released by carbon emissions; $D =$ runoff due to deforestation; and $W =$ wetland drainage.

Table 1
Estimated contribution of groundwater mining to sea-level rise

Country or region	V_{gm} (km^3/yr)	V_{ww} (km^3/yr)	V_{gw}/V_{ww}	V_{gw} (km^3/yr)	V_{gm}/V_{gw}
High Plains	4.9				
SW USA	10.0				
California	13.0				
USA	27.9	467.0	0.235	109.7	0.25
Sahara	10.0				
Sahel	3.4				
Morocco	0.03				
Africa	13.4	144.0	0.345	49.7	0.27
Greece	1.7	7.0	0.275	1.9	0.89
Italy	0.4	56.2	0.275	15.5	0.03
Spain	0.7	45.9	0.275	12.6	0.06
Europe	2.8	109.1	0.275	30.0	0.09
India	20.3	380.0	0.275	104.5	0.19
Saudi Arabia	5.2 *	12.0 *	0.75 *	9.0	0.58
Iran	0.2	45.4	0.275	12.5	0.02
Asia	25.7	437.4		126.0	0.20
Australia	0.04	17.8	0.149	2.7	0.02
Total	69.8	1175	0.306	318.0	0.22

Sources of data:
Column 2: Dugan et al., 1994; Sahagian et al., 1994; UN, 1983; Marinos and Diamandis, 1992; Beretta et al., 1992; Singh, 1992; Jellali et al., 1992; Lopen-Camacho and Sanchez-Gonzalez, 1992; Al-Ibrahim, 1991; Hosseinipour and Ghobadian, 1990.
Column 3: WRI, 1994 (late 1980s).
Column 4: Solley et al., 1993 (USA); Zektser and Loaiciga, 1993. (elsewhere).
Column 5: col. 3 x col. 4; Column 6: col. 1 ÷ col. 5.
* From Al-Ibrahim, 1991.

gated cotton and rice fields are raising groundwater levels and waterlogging the soil. Although these landlocked lakes are highly sensitive to natural variations in precipitation and evaporation, as well as to reductions of inflow produced by hydrologic diversions, the net effect of these interior lake changes on global sea level is probably small and indirect.

The Intergovermental Panel on Climate Change estimates that anthropogenic changes [1] could contribute between −0.4 to +0.75 mm/yr to sea level (Warrick et al., 1996). These estimates show considerable spread; thus, considerable uncertainty exists over the magnitude and even the sign of the effects on SLR of anthropogenic changes in land hydrology. In this paper, we present a comprehensive literature review of data pertaining to human modification of the land's hydrologic system since the beginning of this century. A more accurate budget awaits analysis with improved global hydrology and land-surface models (currently under development) linked to global climate models (e.g. Abramopoulos et al., 1994; Dickinson and Henderson-Sellers, 1988; Henderson-Sellers et al., 1993).

2. Land hydrology changes

The contribution to sea level-rise over a specified time period (SLR_a) of anthropogenic interventions in the land hydrologic cycle can be expressed as:

$$SLR_a = (G + U + C + D + W) - (R + I) \quad (1)$$

[1] These include: groundwater depletion, surface water storage, deforestation, wetlands loss, thawing of permafrost, infiltration from reservoirs, infiltration from irrigation, evaporation from reservoirs, evaporation from irrigation.

where: G = SLR due to groundwater mining; U = SLR due to increased runoff from urbanization; C = SLR due to water release from combustion of fossil fuels and decomposition of biomass and soil organic matter; D = SLR due to increased runoff from deforestation; W = SLR due to drainage of wetlands; R = SLR reduction due to impoundment in reservoirs; I = SLR reduction due to irrigation.

The major anthropogenic processes are illustrated schematically in Fig. 1. The terms in Eq. (1), as used in this paper, represent potential annual changes in SLR attributed to these various processes in the late 1980s to ~ 1990. Strictly speaking, these terms are not entirely independent; for example, much of mined groundwater is used in irrigation, a large fraction of which water is lost to evaporation and to seepage, as discussed below. These feedbacks and transient changes in atmospheric humidity and groundwater will be more fully modelled in future work. We now estimate separate values for each of the terms in Eq. (1).

2.1. Groundwater mining

Groundwater mining or overdraft (G) is defined as the withdrawal or removal of groundwater in excess of natural recharge from infiltration and from underground inflow. Global water balance inventories (e.g., Shiklomanov, 1993; L'vovich and White, 1990) indicate the total amount of water withdrawn (both surface and underground), and the fraction used consumptively (i.e., evaporated, transpired, or otherwise consumed by humans, animals, or plants, and not returned to streamflow). The proportion of water resources distributed between surface and groundwater flow has also been estimated by continent (Zektser and Loaiciga, 1993). However, no global compilation of groundwater *mining* exists.

A global extrapolation of groundwater mining is made from the partial sampling of Table 1, in the following manner. Column 2 (Table 1) gives the volume of groundwater mined (V_{gm}) in each of the countries or regions listed in column 1. Column 3 presents the total volume of water (both surface and underground) withdrawn (V_{ww}) in the corresponding countries or regions. To find the volume of groundwater withdrawn (V_{gw}, col. 5) in each of these areas, the total volume of water withdrawn (V_{ww}, col. 3) is multiplied by the regional or continental fraction of the total water withdrawn that comes from groundwater (V_{gw}/V_{ww}, col. 4). Column 6 lists the ratio (V_{gm}/V_{gw}) of the volume of groundwater mined (col. 1) to the volume of groundwater withdrawn (col. 5) in each region.

The global volume of groundwater withdrawn (V_{GW}) circa 1990 is 3240 km^3/yr ×0.306 (WRI, 1994) (i.e., the global value of V_{gw}/V_{ww}; Zektser and Loaiciga, 1993) = 991.4 km^3/yr. An alternative value for V_{GW} is 4130 km^3/yr ×0.306 = 1264 km^3 (Shiklomanov, 1993).

The global volume of groundwater mined (V_{GM}) can be extrapolated:

$$V_{GM} = V_{GW}(\Sigma V_{gm}/\Sigma V_{gw}) \quad (2)$$

where ($\Sigma V_{gm}/\Sigma V_{gw}$) is the ratio of the sum of the volumes of groundwater mined in the countries or regions (col. 2) to the sum of the volumes of groundwater withdrawn in these regions (col. 5), or 69.8/318.0 = 0.22 (Table 1). Then, V_{GM} becomes 0.22 × 991.4 = 218.1 km^3 or 0.22 × 1264 = 278.1 km^3, equivalent to 0.61 or 0.8 mm/yr SLR, respectively.

However, given the large variation in country or regional ratios of V_{gm}/V_{gw} (Table 1), due to major differences in groundwater extraction practices, a better measure to use is the mean of the regional mean ratios of V_{gm}/V_{gw}, or 0.17 ± 0.11. Using the resulting range of values for V_{gm}/V_{gw} in Eq. (2), V_{GM} ranges between 59.5 and 277.6 km^3/yr, equivalent to 0.17–0.77 mm/yr SLR [2] (after WRI), or 75.8–353.9 km^3/yr, equivalent to 0.21–0.98 mm/yr (after Shiklomanov, 1993).

A substantial fraction [ranging from 57% (Shiklomanov, 1993), to as much as 71% (L'vovich and White, 1990)] of the annual water withdrawn globally in 1990 has been used consumptively (i.e., evaporated, transpired, or consumed). Therefore, the amount of mined groundwater that runs off may only contribute between 0.1 and 0.4 mm/yr to SLR, if all of this water were to flow into the ocean (Table 5).

[2] 360 km^3 is equivalent to 1 mm of sea level rise.

2.2. Urbanization

Hydrologic changes associated with urbanization (U) may counteract, to some extent, the effects of groundwater mining. Although excessive groundwater extraction in many urban areas has lowered water tables, causing land subsidence (Chi and Reilinger, 1984), in other cities, water tables have risen due to reductions in pumping for public or industrial water supply, or to leakage of sewers or pipes (Wilkinson and Brassington, 1991). However, quantitative data on the volume of groundwater involved in these processes is incomplete.

A more significant consequence of urbanization is the net increase in total runoff due to the expansion of area of impermeable pavements, buildings, and other covered surfaces, all of which impede the replenishment of groundwater. The increase in runoff due to urban growth amounted to some 137 km^3/yr (or 0.38 mm/yr SLR) in the 1980s (L'vovich and White, 1990). The uncertainty associated with estimating growth of urban impermeable surfaces (as well as wastewater discharge through sewers and drains) suggests a plausible sea-level change in the range of 0.35–0.41 mm/yr.

2.3. Water released by oxidation of fossil fuels and vegetation

Water is released into the atmosphere together with carbon dioxide by fossil fuel combustion and tropical deforestation (Table 2). Conversely, water and carbon dioxide are removed from the atmosphere as inorganic bicarbonate and carbonate ions in the ocean, and as new organic matter (reduced carbon) in forest regrowth (CO_2 assimilation) and soil carbon storage. Water exchanges associated with the carbon cycle (C) are now reviewed, in order to estimate their net effect on sea level.

2.3.1. Fossil fuel emissions

Combustion or oxidation of fossil fuels (natural gas, petroleum and coal) yields carbon dioxide and water. In the case of methane, the following reaction occurs:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (3)$$

More generally:

$$C_xH_y + (x + y/4)O_2 \rightarrow xCO_2 + y/2H_2O \quad (4)$$

The relative proportions of CO_2 emissions by the three dominant fossil fuel types (average of 1980–

Table 2
Water associated with CO_2 emissions for two estimates of the carbon cycle

	Average annual CO_2 budget (GT C/yr)		Water released, in SLR equivalent (mm/yr)
CO_2 sources	D [a]	S [b]	
Fossil fuel combustion and cement production	5.4	5.5	0.021
Tropical deforestation	1.6	1.6	0.034
Total sources	7.0	7.1	
CO_2 sinks			
Atmosphere	3.2	3.2	-
Ocean uptake	2.0	2.0	−0.008
Northern Hemisphere forest regrowth	0.7	0.5	−0.015– −0.011
"Additional sinks" (CO_2 fertilization, nitrogen fertilization, soil storage)	1.1	1.4	−0.023– −0.029
Total sinks	7.0	7.1	
Total sea level rise			0.009–0.007

[a] Dixon et al., 1994.
[b] Schimel et al., 1995.

1989 CO_2 emissions, after Marland and Boden (1993); their Table 1) are: 0.16 (gas), 0.43 (liquid), and 0.41 (solid fuels). Corresponding CO_2 emissions are 0.81, 2.28, and 2.14 GT C/yr, respectively. These values can be used to estimate the volumes of water produced.

2.3.2. Gas

Oxidation of natural gas (predominantly CH_4) is given by Eq. (3). The mass of CO_2 released is 2.97 GT CO_2/yr (3.667 [the stoichiometric factor] × 0.81 GT/yr). (1 GT = 10^{15} g). This is equivalent to 2.43 km^3/yr H_2O or *0.0068 mm/yr* SLR (2.97 GT × (36/44) ÷ 1.0 g/cm^3 ÷ 10^{15} cm^3/km^3 ÷ 360 km^3/1 mm SLR).

2.3.3. Liquid (petroleum)

The average mass composition of liquified natural gas and world crude oil is close to 85% C and 15% H (Marland and Rotty, 1983). The atomic proportions are roughly $CH_{2.12}$. Thus, combustion yields:

$$CH_{2.12} + 1.53O_2 \rightarrow CO_2 + 1.06H_2O \quad (5)$$

or, roughly one molecule of H_2O for each molecule of CO_2 produced.

The mass of CO_2 given off by liquid fuel combustion is then 8.36 × GT CO_2/yr, equivalent to 3.63 km^3/yr H_2O or *0.01 mm/yr* SLR.

2.3.4. Solid fuel (coal)

Coal has an average carbon content of around 77.7% (Speight, 1994), and a C:H ratio of approximately 1:0.81 (neglecting O and other minor constituents). Burning coal yields:

$$CH_{0.81} + 1.2O_2 \rightarrow CO_2 + 0.405H_2O \quad (6)$$

The mass of CO_2 generated by burning coal is 7.8 GT CO_2/yr, equivalent to 1.3 km^3/yr H_2O or *0.004 mm/yr* SLR.

The total water released by fossil fuel combustion is therefore equivalent to a SLR of *0.021* mm/yr (Table 2).

2.3.5. Deforestation

The net atmospheric carbon release from global land-use change is around 0.9–1.1 GT C/yr, representing the difference between tropical deforestation (1.6 GT C/yr) and temperate-boreal forest regrowth (O.7 GT C/yr, Dixon et al., 1994; 0.5 GT C/yr, Schimel et al., 1995; Table 2). Oxidation of dry vegetative biomass (through direct combustion and bacterial decomposition) produces CO_2 and H_2O, according to:

$$O_2 + CH_2O \rightarrow CO_2 + H_2O \quad (7)$$

where (CH_2O) represents the average composition of plant matter.

Thus, the mass of carbon released from dry vegetation each year is equivalent to 1.35–1.65 km^3 H_2O, or 0.004–0.005 mm/yr SLR.

The net annual water released by vegetation clearance each year is found using a dry-to-wet biomass ratio of 0.25 (Rohrig, 1991). This water volume ranges between 6.75–8.25 km^3 H_2O [3], equivalent to *0.019–0.023 mm/yr* SLR (Table 2).

2.3.6. Ocean uptake

The world's oceans absorb around 2.0 GT C/yr of CO_2 released by fossil fuel emissions and deforestation (Table 2). The oceanic uptake of carbon dioxide can be expressed by Eq. (8):

$$CO_2 + H_2O \rightarrow 2H^+ + CO_3^{2-} \quad (8)$$

This chemical reaction consumes the equivalent of 3.0 km^3/yr H_2O, corresponding to about *−0.008 mm/yr* SLR.

2.3.7. Additional sinks

Terrestrial sinks for atmospheric carbon dioxide include enhanced plant assimilation under elevated CO_2 and enhanced plant growth due to nitrogen from fertilizers and fossil fuel burning. These processes are represented schematically in (9):

$$CO_2 + H_2O \rightarrow CH_2O + O_2 \quad (9)$$

The uptake of 1.1 GT C (after Dixon et al., 1994) corresponds to 1.65 km^3 of *dry* biomass. Using a dry-to-wet biomass ratio of 0.25 (Rohrig, 1991) gives the water taken up by new vegetation as 8.25 km^3 or *−0.023 mm/yr* SLR equivalent. This compares to the sea level change estimated from an uptake of 1.4 GT C (after Schimel et al., 1995), namely *−0.029 mm/yr* (Table 2).

[3] This figure includes oxidation of above and below-ground tree biomass, soil organic matter to 1 m depth, woody debris, and long-term decay of wood products.

The net contribution of water from all of these processes is then (in terms of SLR equivalent) *0.009 mm/yr* (after Dixon et al., 1994) or *0.007 mm/yr* (after Schimel et al., 1995; Tables 2 and 5).

2.4. Changes in runoff due to deforestation

Widespread tropical forest clearing generally increases total streamflow by as much as 125–820 mm/yr during the first three years (Bruijnzeel, 1993; Fritsch, 1993; Pereira, 1973). An average value for the increase in runoff in newly cleared humid tropical forest (D) is around 300 mm/yr (Bruijnzeel, 1993). Using this figure together with an average deforestation rate of 15.4×10^{10} m^2/yr (FAO, 1993) gives an increase in runoff of approximately 46.2 km^3/yr, or *0.13 mm/yr* SLR. This estimate does not take into account possible climate feedbacks leading to decreased runoff, as suggested by several modeling studies (e.g., Dickinson and Henderson-Sellers, 1988; Zeng et al., 1996).

2.5. Wetlands

Wetlands are vegetation communities adapted to the presence of a perennial near-surface water table, which creates standing bodies of water or saturated (waterlogged) soils. The lack of a universally agreed-upon definition of wetlands, due to the wide diversity of wetland types and soil conditions, has introduced an element of uncertainty in the location and areal extent of wetlands (Williams, 1990). For example, Matthews and Fung (1987) calculate a global wetland area of 5.26 million km^2, by integrating three databases; Williams (1990) gives a worldwide area of 8.558 million km^2.

The accumulation of organic-rich sediments in undisturbed wetlands constitutes a significant carbon sink. On the other hand, draining of swamps, bogs, or marshlands leads to oxidation of soil organic matter. Burning of vegetation, including peat for fuel, as well as agricultural conversion also release CO_2 from wetlands.

Prior to major clearance of forests for agriculture (c. 1795), temperate wetlands stored carbon at rates of 56.9–82.6 million t C/yr (Armentano and Menges, 1986). By 1980, annual carbon accumulation rates had decreased to −6.5 million t C/yr (i.e., a source of carbon) to 19.1 million t C/yr, representing a net reduction of 63.4 t C/yr in carbon storage from temperate wetlands (Armentano and Menges, 1986). (A separate study, cited by Armentano and Menges, gives a figure of 85 million t C/yr). In addition, wetland losses due to peat combustion and industrial usage bring the total change in temperate annual carbon storage (from pre-clearance values) to 97–126 million t C/yr. Extensive clearance of tropical wetlands has occurred during the 20th century. For example, southern Asia has lost ~ 45% of its tropical mangroves and associated wetlands since 1900 (Table 3). Adding in tropical wetland conversion c. 1980 brings the overall global reduction in annual carbon storage rates, relative to pre-clearance values, to around 150–184 million t C/yr (Armentano and Menges, 1986). Assuming that the ratio of the annual carbon emission rate in temperate regions to that of the world (c. 1980) is proportional to the temperate to global ratio of the difference between present carbon storage rates and pre-clearance rates, then the annual global emissions of carbon from wetland drainage and conversion could range between 22 and 101 million t C/yr.

Water associated with drainage and burning of wetlands is calculated similarly to that of deforestation (see above). This yields 0.03–0.15 km^3 H_20 released per year, equivalent to 0.0001–0.0004 mm/yr SLR. Using a dry-to-wet biomass ratio of 0.25, and adding in the dry biomass brings the total SLR due to wetland drainage and oxidation to *0.001–0.002 mm/yr*. Possible changes in runoff

Table 3
Wetland losses in selected Asian countries

Country	Area (km^2)			
	1900	1940	1980	Δ1980–1900
Bangladesh	1001	889	722	−279
Brunei	1464	1074	692	−772
Malaysia	46,620	39,070	21,710	−24,910
Myanmar (Burma)	23,140	16,500	12,050	−11,090
North India (60% of total area)	51,990	46,580	32,590	−19,400
Pakistan	2850	2640	2130	−720
Total	127,065	106,753	69,894	−57,171

(after Gleick, 1993; table F.6).

resulting from wetland clearance have not been included, because of lack of relevant data.

2.6. Reservoirs

A major reduction in potential SLR results from sequestration of river flow behind dams (R). Sahagian et al. (1994) estimate of 1900 km^3 of water impounded by dams is much too low (Chao, 1994, Chao, 1995; Rodenburg, 1994). The world's largest reservoirs (> 3 million m^3) have a total storage capacity of 3991 km^3 (Mermel, 1992). Other types of dams with > 0.5 million m^3 capacity (e.g., concrete dams and concrete-faced rockfill dams) add another 23.5 km^3 and 13.4 km^3, respectively (1992 Water Power and Dam Construction Handbook), giving a total storage capacity of 4028 km^3. (The latter types of dams were checked against Mermel's compilation to eliminate redundancies). Several recent estimates are higher: > 5000 km^3 (Shiklomanov, 1993), and 5525 km^3 for reservoirs over 100 million m^3 capacity in 1985 (L'vovich and White, 1990). Small impoundments (< 100 million m^3) could add another 4.5% (L'vovich and White, 1990; p. 239), making a total global reservoir storage capacity of 5773.6 km^3. A reasonable assumption is that reservoirs are filled to 85% of capacity, on average. Then the total global volume in reservoirs is around 4908 km^3, corresponding to a potential decrease of 13.6 mm in SLR. Since 90% of the total reservoir capacity has been created since the 1950s, and since reservoir capacity has grown at a linear rate (Chao, 1995; L'vovich and White, 1990), this respresents a potential average reduction in SLR of 0.34 mm/yr.

This potential reduction in sea-level rise could be counterbalanced to some extent by sediment accumulation. Although sedimentation rates vary widely, the overall effect is comparatively small. The extent of sediment settling depends on the sediment load of the river, the size and settling velocity of the sediments, and the trapping efficiency, which in turn is related to the reservoir capacity and annual volume of inflow. Around 0.2% of U.S. reservoir storage capacity is lost annually to sedimentation (Gleick, 1992; Dendy et al., 1973). Lake Mead, for example, lost 0.3%/yr of capacity to siltation in the 1940s (Smith et al., 1960). Lake Bhaka, on the Sutlej River in northern India, has been filling at an average rate of 0.5%/yr (Rao and Palta, 1973). Annual reservoir filling rates for several Asian and African reservoirs range between 0.8–2.4% of capacity (Douglas, 1990). North African reservoirs are filling up annually at rates corresponding, on average, to ~ 1% of their initial capacity (Shahin, 1993). Several reservoirs reported to be filling at annual rates of 2–7%/yr of storage capacity (James and Kiersch, 1988) represent exceptionally high sedimentation rates. Such locally high reservoir sedimentation rates could seriously shorten the useful lifetime of the reservoirs and reduce their hydroelectric generation and flood control capability. If the global mean annual loss of reservoir capacity is under 1%, total global reservoir storage capacity would be reduced to 4860 km^3, and the change in the impact on SLR from that estimated above would be negligible.

This storage capacity represents a lower bound of SLR reduction from reservoirs. Additional withholding of water comes from seepage losses beneath reservoirs, which strongly depend on rock permeabilities, geologic structures, and position of the water table (James and Kiersch, 1988). Seepage losses are associated with geological features such as fractures, faults, solution cavities or sinkholes in carbonate rocks (Moneymaker, 1969), unconsolidated and/or permeable sedimentary rocks (Gardner, 1969), and lava tunnels (Monahan, 1969).

Very little data exist on seepage losses. Maximal seepage losses at Lake Nasser have been estimated at ~ 0.6% of capacity per year (Wafa and Labib, 1973). However, storage of water in dry rock pore volume may ultimately reach up to 29% of maximum reservoir capacity at Lake Nasser. Lake Mead lost ~ 1.7% of its initial capacity per year in the 1940s (Smith et al., 1960). Annual seepage losses for several small mid-Western reservoirs range from 0.1 to 39% of capacity (Gardner, 1969). In some extreme cases, disregard of geologic conditions has led to severe reservoir leakage, resulting in abandonment of the reservoir and even dam failure (Kiersch, 1958).

This limited sampling suggests a potentially wide range of losses due to reservoir seepage. An annual average figure has been estimated at ~ 5% of reservoir volume (Gleick, 1992). In the absence of additional data, we assume an average annual loss of $5 \pm 0.5\%$ of reservoir volume for reservoirs built up to 1990. This amounts to 245 km^3/yr, or 0.68

mm/yr withheld from SLR, with an estimated range between 0.61 and 0.75 mm/yr (Table 5).

Percolation beneath reservoirs recharges aquifers, ultimately increasing groundwater discharge to the sea. However, since the global residence time for groundwater in aquifers has been estimated at around 330 years (L'vovich, 1979) and possibly even thousands of years or more (Hay and Leslie, 1990), this effect is probably relatively small over short (< 100 year) periods, and is neglected here.

Evaporation from reservoirs may also withold some water from the sea. Evaporative losses from reservoirs are calculated as the difference in mean evaporation from the lake surface and that of dry land, using mean evaporation data for each climate zone. These losses, amounting to around 6.5 km^3/yr in 1950 (Shiklomanov, 1993), have increased to between 130 km^3/yr (L'vovich and White, 1990) and 170 km^3/yr (Shiklomanov, 1993), by 1985–1990. Although the bulk of this evaporated water may reprecipitate regionally, a small fraction may be retained as vapor in the atmosphere, particularly in drier regions, a portion of which then eventually reaches the sea after long-range transport. Although the fraction of the evaporated water that is stored in the atmosphere is uncertain, a plausible upper bound lies between 1–3% (see below). This could reduce SLR by 0.005–0.014 mm/yr.

2.7. Irrigation

Losses of irrigation water (I) to deep seepage and evaporation also lessen the anthropogenic input to SLR. In 1992, 249.6 million ha were under irrigation, with 64% of the total in Asia and 11.6% in North and Central America (FAO, 1994). The average annual per hectare water use varies widely from around 12,000 to 15,000 m^3/ha in North Africa to less than 4000 m^3/ha in several western European countries (Table 4; after Framji et al., 1981). The global average water use weighted by percent area under irrigation is approximately 9800 m^3. This figure multiplied by the world area under irrigation gives a volume of 2446 km^3. Multiplying this volume by 1.3 to account for conveyance losses (Postel, 1989) brings the total to 3180 km^3.

Irrigation efficiency is a measure of the fraction of applied water that is used consumptively, i.e., that is taken up and evapotranspired by crops. The consumptive use of water in irrigation has variously been estimated to total 86.3% (L'vovich and White, 1990) and 76.5% (Shiklomanov, 1993) of the water withdrawn. Using an efficiency of 76.5% combined with the above estimate gives 2432.7 km^3/yr. If, as in the case of evaporation from reservoirs, up to 2 percent remains in the atmosphere as added vapor, then the amount of SLR withheld through evapotranspiration would be 0.14 mm/yr, in the 1990s. An irrigation efficiency of 86.3% leads to the equivalent of 0.15 mm/yr SLR withheld.

Table 4
Irrigation area and average per hectare water usage

Continent	Area irrigated ($\times 10^6$ ha)	Percent of area irrigated	Average water usage (m^3/ha)
Africa	11.50	4.61	11,000
North/Central America	28.99	11.62	8000
South America	8.90	3.56	11,400 *
Asia	160.86	64.44	10,000
Europe	16.51	6.61	5500
Oceania	2.36	0.94	11,400 *
former USSR	20.49	8.21	12,500
World	249.62	99.99	wt. av. 9784

Notes: areas under irrigation are from FAO, 1993 Production Yearbook; average water usage in irrigation is adapted from Framji et al. (1981); * default value for areas lacking more specific data (after Postel, 1989).

The evaporation of 76.5–86.3% of irrigation water leaves 13.7–23.5%, or 435.7–747.3 km^3, which can infiltrate into the soil. If we assume that, as in the case of reservoirs, around $5 \pm 0.5\%$ of this water ends up in deep percolation, this yields 19.6–41.1 km^3. In addition, up to 98% of the irrigation water lost through evapotranspiration (e.g. $0.765 \times 3180 \times 0.98 = 2384$ km^3) is ultimately re-precipitated. If again $5 \pm 0.5\%$ of this water infiltrates at depth, this removes another 107.3–147.9 km^3. A total of 140.9–172.2 km^3 could therefore be sequestered at depth, corresponding to 0.39–0.48 mm/yr withheld from SLR.

The *saturation specific humidity*, or saturation concentration of water vapor for the annual mean temperature and pressure at a given atmospheric level, can indicate an upper limit to the amount of water sequestered by evaporation from reservoirs and irrigated fields. A substantial portion of the earth's precipitation originates in lower levels of the atmosphere. The global mean value of the saturation specific humidity of atmospheric level 1 (984–934 mb) in the GISS GCM Model II (Hansen et al., 1983) is 12.13 g/kg (Ken Lo, 1995, pers. comm.). Taking the product of the saturation specific humidity, the specific volume of liquid water, the total mass of the atmosphere, the fraction of the atmosphere in level 1, and the land area, one can calculate the volume of water at saturation, in km^3, over land. This volume is: 12.13 g/kg $\times$ 1.0 cm^3/g $\times$ 9928 kg/m^2 $\times$ 0.0513 $\times$ 1.497 $\times$ 10^{14} m^2 = 9.248 $\times$ 10^{17} cm^3 or 925 km^3.

The land area-weighted global mean relative humidity is 66.0% (Ken Lo, pers. comm.). Thus the

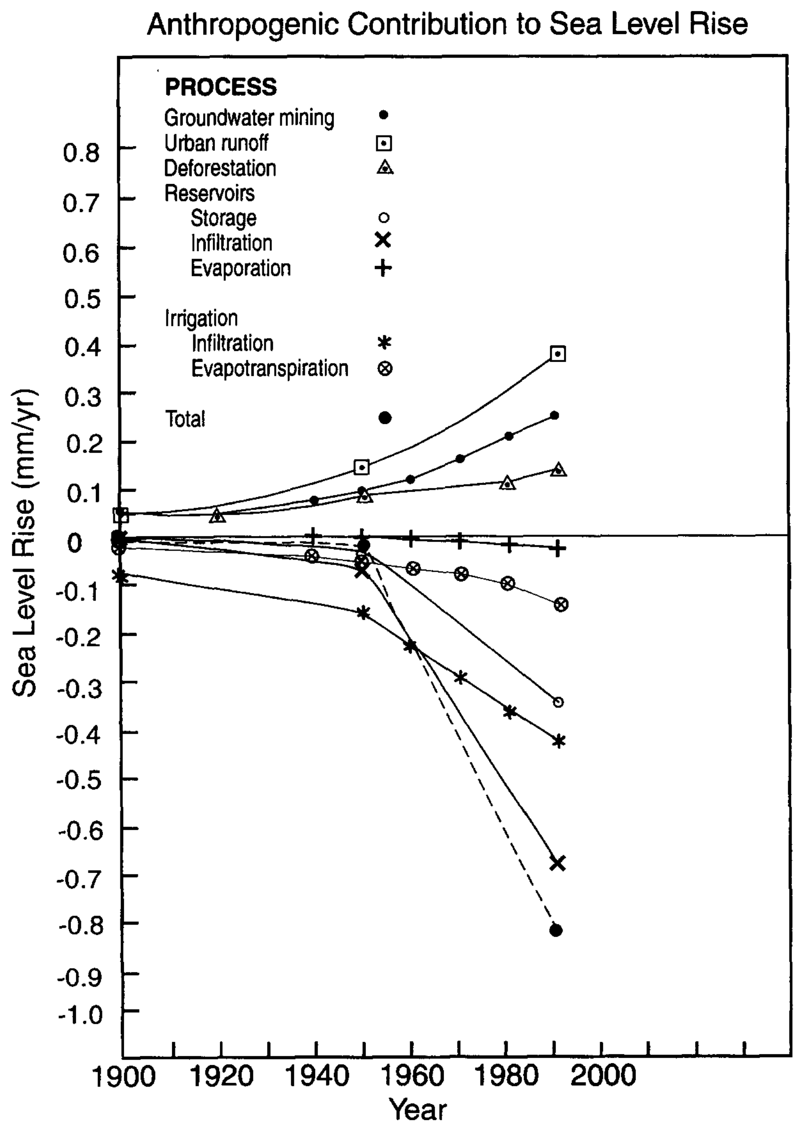

Fig. 2. Time history of estimated contributions to sea level rise from various anthropogenic processes, using mid-range estimates of Table 5. Historical data on urban runoff and reservoirs, after L'vovich and White (1990); global groundwater withdrawn, irrigation water consumption, after Shiklomanov (1993), Gleick (1993); deforestation (FAO, 1994). See text for details.

Table 5
Anthropogenic contributions to sea level rise

Process	Sea level rise (mm/yr)		
	Low	Mid	High
Groundwater mining (G)	0.10	0.30	0.40
Urban runoff (U)	0.35	0.38	0.41
Water released by oxidation of fossil fuels, vegetation, and other sinks (C)	0.007	0.008	0.009
Deforestation-induced runoff (D)	0.12	0.13	0.14
Wetlands loss (W)	0.001	0.0015	0.002
Reservoirs and dams (R) storage	−0.38	−0.34	−0.30
Infiltration	−0.75	−0.68	−0.61
Evaporation	−0.014	−0.01	−0.005
Irrigation (I)			
Infiltration	−0.48	−0.44	−0.40
Evapotranspiration	−0.15	−0.15	−0.14
Total	−1.20	−0.80	−0.49

volume of water in atmospheric level 1 is 611 km^3. If the atmosphere retained as little as 1–3% of the water evaporated from reservoirs and irrigated fields each year, this corresponds to volumes of 26.0–78.1 km^3, respectively. These figures would lead to increases of 4.3–12.8% in the mean relative humidity over land. While such increases in mean relative humidity could occur in the vicinity of reservoirs and irrigated fields, they are probably too high when averaged over the entire land area. Thus, assumed atmospheric water retentions of 1–3% provide upper bounds to the corresponding changes in SLR.

3. Discussion

Table 5 summarizes the estimated contributions to SLR from the various anthropogenic activities. Processes such as groundwater mining, increased runoff due to land-cover changes, and combustion of fossil fuel and vegetation could elevate SLR by 0.8 ± 0.2 mm/yr. On the other hand, storage of water in reservoirs and losses due to infiltration and evapotranspiration associated with man-made lakes and irrigation could prevent the equivalent of 1.6 ± 0.2 mm/yr from reaching the sea. The net effect of these processes taken together is to withhold around 0.8 ± 0.4 mm/yr from sea level rise.

The time trajectories of estimated historical changes in sea level resulting from various anthropogenic activities since 1900, based on mid-range estimates (Table 5) is presented in Fig. 2. The effects on sea level become significant only since the 1940s, i.e. within the last 50 years. The increased magnitude of these effects is closely linked to the overall human transformation of the earth's surface, driven, in general, by the rapid 20th century growth in population and in economic development (e.g., see Turner et al., 1990). Among the processes considered, groundwater mining and urban runoff are potentially the major sources adding water to the sea, whereas dam storage and infiltration withhold most of the water, if these estimates are at all realistic.

The above estimates of sea-level changes associated with anthropogenic modifications of the hydrologic cycle, though still preliminary, imply a net negative effect, comparable in magnitude to the observed recent sea-level rise. However, data on the global extent of many important processes, such as groundwater mining, urban runoff, deep percolation losses beneath reservoirs and irrigated fields, and atmospheric storage are still fragmentary and probably represent upper bounds. Nonetheless, overestimates in the rates of groundwater mining and urban runoff, which tend to increase sea level, could be counterbalanced by similarly overestimated rates of atmospheric moisture increase and losses to deep percolation, going in the opposite direction. Thus, the net effect could still be roughly comparable to that suggested here. More importantly, while the historical approach, as used here, gives a broad overview of the scope of the processes, a unified systems approach is required to trace the path of water more accurately through the various sub-systems, allowing for recycling and redistribution.

Biogeophysical feedbacks on climate from land-cover changes have been investigated in a number of studies. Effects of deforestation on the partitioning of water between evapotranspiration, precipitation, and soil moisture have been modeled (Zeng et al., 1996; Polcher and Laval, 1994; Henderson-Sellers et al., 1993; Shukla et al., 1990). While, in general, deforestation leads to increased surface temperatures, a number of models (e.g. Zeng et al., 1996; Henderson-Sellers et al., 1993; Shukla et al., 1990) also found a decrease in runoff in Amazonia, because the calculated decrease in precipitation exceeded the decrease in evapotranspiration. On the other hand, Polcher and Laval (1994) noted substantial increases in simulated runoff for both Amazonia and Africa. In their model, an increase in precipitation accompanied the predicted decrease in evapotranspiration. However, their model may have overestimated evapotranspiration by its use of the leaf-area-index rather than an effective evaporating surface.

"Tracer" studies have been undertaken to track sources of precipitation (Salati et al., 1979; Koster et al., 1986; Druyan and Koster, 1989). Such techniques could eventually be adapted to address the specific questions posed here, such as: the extent to which excess moisture from irrigated soils or large reservoirs will (1) increase evaporation or evapotranspiration, (2) increase local precipitation, and/or (3) advect moisture to adjoining regions. The net balance among these three factors will help establish any increase in relative humidity (especially in arid regions), thus reducing contibutions to sea level rise. On the other hand, if enhanced evaporation/evapotranspiration results in greater local precipitation, then runoff may also increase, hence elevating sea level. Answers to these questions await analysis with improved land-surface hydrology models currently embedded within GCMs, to calculate feedbacks such as the partitioning of water from groundwater mining among runoff, infiltration, and evaporation; how much of the recharge by irrigation and reservoirs is retained by the aquifer or added to underground flow, amd how much of the additional evaporation from reservoirs and irrigated land is retained in the atmosphere or precipitated and eventually conveyed seaward.

4. Conclusions

Plausible ranges in sea level changes associated with major human transformations of the land hydrologic system have been examined. Increased runoff from groundwater mining and impermeable urbanized surfaces are potentially important anthropogenic sources contributing to sea-level rise. Runoff from tropical deforestation and water released by oxidation of fossil fuel and biomass, including wetlands clearance, provide a smaller share of the total. Taken together, these processes could augment sea level by some 0.6–1.0 mm/yr (Table 5).

On the other hand, storage of water behind dams, and losses of water due to infiltration beneath reservoirs and irrigated fields, along with evaporation from these surfaces could prevent the equivalent of 1.5–1.8 mm/yr from reaching the ocean. The net effect of all of these anthropogenic processes is to withhold the equivalent of 0.8 ± 0.4 mm/yr from the sea. This rate represents a significant fraction of the observed recent sea-level rise of 1–2 mm/yr, but opposite in sign.

These estimated impacts on sea-level rise represent upper bounds. An important limitation is the incomplete documentation of the historic trends and global coverage for many of these processes. Furthermore, the increased volume of moisture stored in the atmosphere due to evaporation from reservoirs or irrigated fields provides only an upper bound, inasmuch as the atmospheric effects are probably localized and thus are unlikely to represent large-scale averages. Finally, a number of the processes are interrelated, so that a unified systems approach, using coupled land-surface hydrology and climate models, is needed to trace the path of water through the various sub-systems, allowing for recycling and redistribution.

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