**Title**

GROUND WATER FLOW IN THE GLOBAL HYDROLOGIC CYCLE - PAST, PRESENT, AND FUTURE

**Authors**

ZEKTSER, IS
LOAICIGA, HA

**Publication Date**

1993

*Journal of Hydrology*, 144 (1993) 405–427
Elsevier Science Publishers B.V., Amsterdam

[2]

# Groundwater fluxes in the global hydrologic cycle: past, present and future

I.S. Zektser[a] and Hugo A. Loaiciga[b]

[a]*Hydrogeology Department, Institute of Water Problems, Russian Academy of Sciences, 13/3 Sadovaya-Chernogryazskaya St., 103064 Moscow, Russia*
[b]*Department of Geography and Environmental Studies Program, University of California, Santa Barbara, CA 93106-4060, USA*

(Received 16 November 1991; revision accepted 16 February 1992)

## ABSTRACT

Zektser, I.S. and Loaiciga, H.G., 1993. Groundwater fluxes in the global hydrologic cycle: past, present and future. J. Hydrol., 144: 405–427.

A quantification of groundwater fluxes in the hydrologic cycle for large river basins and on a global scale is reported in this paper. Groundwater contributions to river runoff (i.e. baseflow), direct submarine groundwater discharge to the ocean floor, and salt throughput to oceans and seas are analyzed. The baseflow/precipitation and baseflow/river runoff ratios are found to be approximately 10% and 30% on a world-wide basis, showing great geographical variability across the major continents of the Earth. Direct groundwater discharge to the ocean floor is only 6% of the total water influx to oceans and seas, yet, it contributes a salt load to oceans and seas that is approximately 50% of the salt loading by rivers. Factors and uncertainties germane to global groundwater balancing, recent anthropogenic modifications of groundwater contributions to runoff, and the likely role of potential global warming in groundwater circulation are discussed. Over the last 300 years baseflow contribution to river runoff has slightly increased, whereas the river runoff has declined as a result of anthropogenic modifications to the natural environment. Assuming a 10% increase in global annual precipitation from potential greenhouse warming, the associated increases in baseflow contribution to river runoff and direct groundwater discharge to oceans would amount to 1200 $km^3$ $year^{-1}$ and 260 $km^3$ $year^{-1}$, respectively. The additional salt load to oceans and seas by direct groundwater flow is estimated at 140 000 000 t $year^{-1}$. Salinity of oceans and seas could rise if their water volumes do not increase enough to offset the larger salt load.

## INTRODUCTION

Global hydrology is emerging as one of the key disciplines of the Earth Sciences (Nace, 1978; Eagleson, 1986, 1991; Barron, 1991). This can be attributed in part to the realization that human-induced changes in the Earth's environment, most prominently the build-up of greenhouse gases in the

---

Correspondence to: H.A. Loaiciga, Department of Geography and Environmental Studies Program, University of California, Santa Barbara, CA 93106–4060, USA.

atmosphere, are likely to be felt first — and most severely — in hydrologic cycle modifications of profound consequences (Budyko et al., 1966; Budyko, 1977; Ramanathan, 1988; Gleick, 1989; Mitchell, 1989; Rosenberg, 1990). The impact that global climatic change might have on key hydrologic variables, such as precipitation, runoff, and evapotranspiration, is rather poorly understood at this time. The limited predictive capability of existing general circulation models (Tsonis, 1991), and the complexity of land–ocean–atmosphere interactions (Wolman, 1991; Giorgi and Mearns, 1991) prevent reliable assessments of hydrologic cycle modifications as a result of large-scale environmental stresses such as potential greenhouse warming. Among the components of the global hydrologic cycle, groundwater circulation is perhaps the most difficult to quantify, with and without climatic change scenarios. The reasons are obvious: monitoring of groundwater fluxes is difficult and expensive to implement (Loaiciga, 1989), and ground water exhibits great variability in its rates of flux, depth, and storage in the subsurface environment, which extends from the ground surface to several kilometers deep in the Earth's crust (Keller and Loaiciga, 1991).

Early work on global water balances and the hydrologic cycle was carried out as part of studies of the Earth's climate (Budyko and Drozdov, 1953; Budyko et al., 1962; Manabe et al., 1965) or in surveys of the water resources of the world (Nace, 1964). Many of the early studies of the global water cycle (Budyko et al., 1962; Nace, 1967, 1970) emphasized the disposition of annual precipitation on a world-wide scale, without fully addressing the geographic distribution of the various water fluxes throughout continents and oceans, and, in particular, excluding the analysis of groundwater fluxes throughout continental land masses. Currently, however, fueled by the scientific interest in possible disruptions of the hydrologic cycle by potential greenhouse warming and associated precipitation/runoff variations, studies of the global hydrologic cycle and its geographic and seasonal fluctuations in general, and the quantification of groundwater flow throughout continents and coastal areas, in particular, are receiving renewed attention from the hydrologic community.

In this work we examine global-scale calculations of groundwater flow to effluent streams (baseflow) and direct groundwater flow to the ocean floors, with a breakdown of groundwater fluxes over major land masses of the Earth. Most of the data examined in this paper have been developed by the senior author and other Russian hydrogeologists over the last three decades, and are not yet well disseminated within the Western hydrologic community.

A brief review of possible impacts of greenhouse warming on the status of ground water completes this paper.

## FACTORS CONTROLLING GROUNDWATER FLOW

Ground water is an important element of the water balance of river basins, seas, oceans, and lakes. It participates in the hydrologic cycle as the subsurface component of river runoff, or baseflow, and as direct, submarine, groundwater flow from land to seas (or large lakes) and oceans, bypassing the river network. Zektser (1977) has classified the factors that govern groundwater recharge and baseflow contributions to river runoff into seven groups.

The first group is comprised of meteorological factors. These govern the potential for infiltration recharge of ground water, and include patterns of atmospheric circulation and moisture transfer, types and forms of precipitation, and evapotranspiration. In some arid and karst regions, where streams are highly influent, streamflow should be considered as a factor of groundwater flow generation. In such a case, the first group of factors might be better classified as hydrometeorological.

The second group of factors include geological and hydrogeological factors, such as the hydraulic characteristics of soils in the vadose zone and the thicknesses and composition of the rocks overlying the aquifers, i.e. groundwater recharge conditions. The hydraulic conductivity and hydraulic gradient of aquifers are also part of this second group of factors and exert a direct control on groundwater movement.

The third group comprises geomorphological factors. These include the general nature of topography, erosional dissection of the area of interest, drainage density (i.e. factors determining the distance from areas of recharge to areas of discharge), and the degree of hydraulic connection between ground and surface waters. The factors of the second and third group change on the scale of geologic time and, typically, remain constant over the periods of hydrogeologic studies.

The fourth group includes cosmogenic factors that account for the gravitational effects of celestial bodies, solar activity, geomagnetic disturbances of the Earth's hydrosphere, in general, and of groundwater flow in particular.

The fifth group of factors comprises anthropogenic modification of groundwater regimes and balance. Biogenic factors (also part of the biosphere) — for the most part vegetation cover in the form of forests and other living organisms— constitute the sixth group of factors.

Cryogenic (permafrost) factors may be classified as a separate, and seventh, group because of the nature, thickness, and continuity of occurrence of perennially frozen ground, which control soil/ aquifer permeability and groundwater flow in very temperate zones.

Through the analysis of the factors that govern groundwater 0flow and pertinent hydroclimatic and hydrogeologic data, it is possible to estimate groundwater and dissolved solid fluxes in continental land masses and along their land–water interfaces. Recent estimates of groundwater and salt fluxes will be examined in this work.

## INTRODUCTION TO GLOBAL WATER BALANCES

There is a fair amount of Soviet literature on studies of global water balances (e.g. Budyko et al., 1962; Lvovich, 1974). Table 1 (Lvovich, 1974) provides one of the very few available calculations of water balance over the land masses of the world (excluding the ice-capped territories of Antarctica, Greenland, and the Canadian archipelago). The estimates of Table 1 were derived from laborious analyses of precipitation, latent heat (or direct evaporation), and runoff data from all the continents. The disposition of precipitation as runoff and evapotranspiration is the first step in carrying out a water-balance closure. The groundwater contribution to runoff, or baseflow, can be calculated by runoff hydrograph separation into baseflow and direct runoff, or from groundwater elevation maps combined with hydrographic information (Lvovich, 1974; Zektser and Dzhamalov, 1988).

Table 1 shows that the baseflow varies from 15 to 35% of river runoff (where river runoff equals the sum of baseflow and direct surface runoff) in different continents, excluding the polar areas cited above, where baseflow and runoff are negligible. Considering all the continents, baseflow is approximately 31% of river runoff. The 294 mm year$^{-1}$ of river runoff in Table 1 is distributed over the land surface of the Earth, which totals $128 \times 10^6$ km$^2$, and excludes ice caps and glaciers. Therefore, the river runoff is equal to 38 000 km$^3$ year$^{-1}$. (The area of the planet comprised of ice caps and glaciers

TABLE 1

Water balance of the continents (mm year$^{-1}$)[a]

| Water-balance components | Eurasia | Africa | North America | South America | Australia (without islands) | Earth's land surface[b] |
|---|---|---|---|---|---|---|
| Precipitation | 728 | 686 | 670 | 1650 | 440 | 834 |
| Evapotranspiration | 430 | 547 | 383 | 1065 | 393 | 540 |
| Total river runoff | 298 | 139 | 287 | 585 | 47 | 294 |
| Surface flow | 216 | 91 | 203 | 375 | 40 | 204 |
| Groundwater contribution | 82 | 48 | 84 | 210 | 7 | 90 |

[a] After Lvovich (1974).

[b] Excluding ice caps and glaciers the land surface is approximately 128 000 000 km$^2$.

is approximately $18 \times 10^6$ km$^2$ and the area of the oceans is $364 \times 10^6$ km$^2$, adding up to a total area of the globe of $510 \times 10^6$ km$^2$.)

It follows from Table 1, also, that, world-wide, the baseflow contribution to river runoff is 11% of the land precipitation (excluding ice caps and glaciers). The baseflow/precipitation ratio is important, since it quantifies the proportion of gross precipitation that becomes groundwater contribution to runoff. Areas with relatively high baseflow/precipitation ratios tend to have more (temporally) stable river runoff regimes. The baseflow/precipitation ratio varies from 1.6 (in Australia) to 13% (in North and South America). Africa is unusual in that its baseflow/precipitation ratio is one of the lowest among all the continents (7%); yet, it has the second largest baseflow/river runoff ratio, or 34%. This is due to large evapotranspiration losses (80% of precipitation), and relatively effective groundwater recharge mechanisms, overall, in the African continent. On the other hand, Australia has the lowest baseflow/precipitation ratio (1.6%), as well as the lowest baseflow/river runoff ratio (15%). Like Africa, Australia has large evapotranspiration losses (89% of total precipitation, the largest of all the continents), but, unlike the African continent, it has extensive low-permeability surficial rocks (sandstones and granite, for example), which result in a low average groundwater recharge rate throughout the continent.

If one considers the precipitation over the entire globe (100 cm year$^{-1}$), about 9% of it becomes baseflow. (As will be seen later, it is advantageous to express baseflow as a percentage of global precipitation, since scenarios for impacts of potential global warming on the hydrologic cycle are commonly constructed in terms of global precipitation increases.) The Table 1 estimates imply that the totality of groundwater discharge ultimately reaches the ocean, seas, and lakes via the river network. In truth, there are deeper groundwater flow systems that discharge directly (e.g. as submarine flow) to the floor of large water bodies, bypassing the river network. (It will be shown below that this direct groundwater component amounts to about 19 mm year$^{-1}$, distributed over the land surface, meaning that approximately 2% of the global precipitation becomes direct groundwater discharge to the ocean and sea floors.) This direct (or submarine) component of ground water introduces complications in establishing annual water balances, for the residence time of deep ground water in the Earth's crust is typically much longer than 1 year (ranging from tens of years to tens of thousands of years, or more). It is, therefore, worth noticing that a fraction of annual precipitation enters deep groundwater systems in any one year and discharges directly into large water bodies, bypassing the river network, many years laters. Although this fraction is globally small, it can become significant in regional water balances. In constructing annual global water balances it is, therefore, necessary to take annual averages of the various water fluxes over sufficiently long periods of time to better approximate equilibrium conditions for all water fluxes.

Precipitation, evapotranspiration, and runoff are the major water fluxes in the hydrologic cycle, as seen in Table 1. These fluxes govern the average residence time of water in the atmosphere, which is on the order of $10^1$ days, and on land (rivers, lakes, wetlands and the surficial soil layer), which is on the order of $10^2$ days. These short residence times explain why global water balances are commonly based on annual average values of the major water fluxes. These averages are often taken over the length of hydrologic and climatic records (as in Table 1), which may be relatively short in some cases when compared with the residence time of ground water in the Earth's crust. Consequently, an element of uncertainty is introduced in the calculation of annual water balances by the long, multiyear, residence time of water in the Earth's crust. It is assumed, therefore, that the hydrologic cycle is in a steady-state condition, and water fluxes are in equilibrium, when calculating global water balances based on annual average water fluxes.

The estimates in Table 1 attest to the volumetric importance of ground water in establishing water balances of land masses. The importance of quantifying groundwater fluxes in the hydrologic cycle is accentuated by the critical role of ground water in biogeochemical cycles, geologic processes, and human activities. Without a full quantification of groundwater fluxes, either contributing to total river runoff or bypassing the river network, the world's water balance would remain unclosed. Over the last three decades hydrogeologists from several countries, including Canada, France, the former Soviet Union, and the USA, have carried out successful studies on the quantification of groundwater flow in large regions (Kudelin, 1960; Walton, 1970; Freeze, 1972a,b; Toth, 1972; Zektser, 1977; Bodelle and Margot, 1980; Vsevolozhskii, 1983; Zektser and Dzhamalov, 1988). These efforts have resulted in an improved quantitative assessment of groundwater fluxes on a global scale.

## STUDIES OF GROUNDWATER FLOW IN LARGE RIVER BASINS

The role of ground water in a region can be characterized by means of two parameters: the baseflow/precipitation ratio and the baseflow/river runoff ratio, where both ratios are expressed in percent. The first ratio represents the fraction of precipitation that becomes baseflow contribution to river runoff. This ratio varies from 0% in impermeable subsurface conditions (e.g. permafrost) to, theoretically, over 100% in some exceptional cases. Values of this ratio exceeding 100% indicate sources of groundwater discharge in addition to percolation from precipitation. The second ratio measures the relative contribution of ground water to river runoff. By definition, this ratio ranges from 0 (e.g. in permafrost conditions) to 100% (when runoff originates from ground water exclusively).

### *Baseflow to precipitation ratio*

Baseflow to precipitation ratios average 9% within the Soviet Union. Their magnitude is governed by a complex of natural factors among which are the precipitation /evaporation ratio, and the composition and thickness of the vadose zone. In low-relief areas of the former Soviet Union, there is a latitudinal variation of average values of the baseflow/ precipitation ratio. Baseflow decreases from northwest to southeast, ranging from 10 to 20% in zones of excessive moisture to 1% or less in steppe and semidesert regions. In some mountainous areas of the former Soviet Union, baseflow/precipitation ratios increase as precipitation and recharge are enhanced with altitude (i.e. orographic effects increase precipitation in mountainous areas, some of which are extensively folded and profusely fractured, with high recharge rates). For instance, the orographic effect in the Carpathians, raises the baseflow/ precipitation ratios from 5 to 10–15%; in the Urals from 10 to 20–40%; in the Altai area from 5–10 to 15–20% (Zektser, 1977; Konoplyantsev, 1982).

Local hydrogeological conditions of river basins and the presence of permafrost strata exert a substantial effect on the distribution of baseflow/ precipitation ratios. In karstic areas (Silurian Plateau, Onega–Northern Dvina interfluve, Kuloi Plateau, and Timan), groundwater discharge/precipitation ratios amount to 40–50%, or more. In permafrost regions of Siberia and the USSR's northeast, these ratios are insignificant.

Baseflow/precipitation ratios range broadly for the vast area of Central and Eastern Europe, illustrating the diverse climatic, orographical, geomorphological, geological, and hydrogeological conditions. The largest baseflow/ precipitation ratios are typically found in mountain-fold regions. Large ratios are observed within the Crimea–Caucasus groundwater discharge province where they are over 50% in some areas. In karstic regions of the Mountain Crimea the ratios are as high as 70%. The smallest observed ratios are found in moisture-deficient regions.

Early studies in the USA quantified the effect of the vadose zone composition on the portion of precipitation that becomes baseflow. As an example, Newport (1959) reported that groundwater recharge varied from 25 mm year$^{-1}$ to 130 mm year$^{-1}$ in areas underlain by impermeable rocks and loess deposits, respectively, in parts of Nebraska. Harder and Drescher (1954) reported a baseflow/ precipitation ratio of at least 18% in glacial outwash deposits in Wisconsin. Data suitable for the estimation of the groundwater flow/ precipitation ratio in the USA, can, for the most part, be found in

United States Geological Survey water supply papers dealing with reconnaissance hydroclimatic and hydrogeologic surveys of rivers or physiographic basins of that country (e.g. Sun, 1986). For Canada and the USA as a whole, baseflow/precipitation ratios in general increase from northern to southern latitudes, with values in northern latitudes averaging about 5%, and approximately 30–40% or more in the humid subtropical regions of the southeastern USA.

Data on baseflow/precipitation ratios exist for other parts of the world. For example, in Ireland, baseflow is over 30% (360 mm year$^{-1}$) of average precipitation (1130 mm year$^{-1}$). According to Indian specialists, the value of baseflow in various areas of India exceeds 50% of total precipitation during the monsoon period. It is estimated that the extensive network of irrigation canals in India could raise total groundwater recharge up to 760 km$^3$ year$^{-1}$ by the year 2000 (Chatuverdi, 1981).

### *Baseflow/total river runoff ratio*

In Central and Eastern Europe, the distribution of baseflow/ river runoff ratios is strongly correlated with altitudinal and latitudinal zonality. Three latitudinal zones (northern, central, and southern) have been identified to represent the most distinctive features of baseflow generation in Central and Eastern Europe.

Baseflow/river runoff ratios range from 10 to 30% in the northern zone of Central and Eastern Europe (the Karelian–Kola region, Pechora River Basin, basins of the Barents and White seas, and the northern portion of the USSR area adjacent to the Baltic Sea). Highly beneficial conditions for generation of river runoff and overland flow exist here due to relatively rugged topography and shallow groundwater occurrence. A local contribution of baseflow to river runoff of up to 35–40% has been observed in karst areas (the Onega–Severnaya Dvina drainage divide and Kuloi Plateau).

Moving to the midlatitudinal zone of Eastern Europe, baseflow/river runoff ratios are as great as 40–50% in the middle portion of the Eastern Middle European groundwater province (Central Russian Platform for the most part). Favorable conditions for the occurrence of highly effluent streams in this region are explained by the presence of a thick upper hydrodynamic zone that is actively drained by rivers.

In the southern zone of Eastern and Central Europe, the baseflow contribution to river runoff drops sharply to 10–15% and even as low as zero in arid zones where evaporation is the predominant groundwater balance component (Konoplyantsev, 1982).

Considering altitudinal effects on baseflow contributions within Eastern

TABLE 2

Annual average long-term water balances of Central and Eastern European countries

| Country | Area ($km^2$) | Precipitation (mm) | Evaporation (mm) | Total river runoff (mm) | Groundwater discharge to rivers (mm) |
|---|---|---|---|---|---|
| Bulgaria | 110988 | 690 | 514 | 176 | 63 |
| Hungary | 93030 | 689 | 630 | 59 | 29 |
| East Germany | 108300 | 719 | 556 | 163 | 97 |
| Poland | 312677 | 715 | 550 | 165 | 91 |
| Romania | 237500 | 738 | 590 | 148 | 42 |
| Czechoslovakia | 127829 | 831 | 615 | 216 | 89 |

and Central Europe, mountainous regions are characterized by higher baseflow/river runoff ratios when compared with areas of lower relief within this part of Europe. The ratios are as great as 70–80% (sometimes 100%) within the mountain-fold areas of Central and Eastern Europe. These high ratios are due to greater precipitation and favorable infiltration conditions created by extensive rock fracturing and the occurrence of detrital sediments and karst. Overall, baseflow in the majority of the rivers in these mountainous areas ranges from 40 to 60%, although extreme variability is observed within the Greater Caucasus Region where values range from 2–5 to 70–75%.

Baseflow/river runoff ratios provide a breakdown of the proportionate magnitudes of groundwater and surface-water resources. Their analysis is of practical importance when solving problems of conjunctive water use and in calculating water resources balances. For the totality of the USSR this ratio has an average value of about 24%, ranging from a low of 5–10% in regions with small thicknesses of the upper hydrodynamic zone (where ground water is in hydraulic contact with river streamflow), a poorly dissected topography, and favorable conditions for runoff generation, to at least 40–50% in regions underlain by water-saturated soils and rocks intensely drained by rivers (Konoplyantsev, 1982).

Data on baseflow for several central and eastern European countries are shown in Table 2 (Water Balance Maps for the Territory of Central and Eastern Europe, 1984). It can be calculated from Table 2 that the areally weighted averages of the baseflow/precipitation and baseflow/river runoff ratios are approximately 10% and 45%, respectively, for the seven Eastern and Central European countries listed in it. These ratios compare with 11% and 31% for the baseflow/precipitation and baseflow/river runoff, respectively, derived from Table 1 for major continental land masses on Earth. Evidently, a relatively large fraction of river runoff originates from ground water in the area of Central and Eastern Europe relative to the overall contribution world-wide. This is not surprising considering the extensive karst terrain (in the Crimea–Caucasus groundwater province and the mountain-fold areas of Central and Eastern Europe), and the permeable deep sedimentary basins in the Central Russian Platform.

Baseflow/river runoff ratios for other parts of the world are also available. Generic values for the USA and Canada average approximately 30% (Ground Water in the Western Hemisphere, 1976), which is slightly less than the world average. For the majority of the river basins of Ireland the percentage of baseflow to river runoff typically exceeds 50% (Aldwell and Burdon, 1979). In France the average annual baseflow is over one half of river runoff (Bodelle and Margat, 1980). According to these same authors, in regions with wide karst development the baseflow/river runoff ratio amounts to 90%; in basins underlain by semipermeable glacial deposits the ratio diminishes to 10–20%.

The previous survey of baseflow/precipitation and baseflow/river runoff ratios indicates that data on these important hydrologic parameters are available for several regions of the world. There are presently, however, information gaps on these basic ratios which prevent a complete understanding of the regional variability of groundwater fluxes in some parts of the world (equatorial areas with a relatively intense hydrologic cycle, i.e. areas with large precipitation, evapotranspiration, and runoff fluxes are of particular interest in the closure of global water balances).

## GROUNDWATER CONTRIBUTION TO THE WATER BALANCE OF OCEANS AND SEAS

### *Direct groundwater discharge to oceans and seas*

The subsurface exchange between land and oceans is another of the hydrologic cycle components. This water exchange takes place in two ways: as groundwater discharge from land to the ocean floor or as seawater intrusion into coastal areas. Direct groundwater discharge to oceans occurs constantly and everywhere along coastlines, except for some Arctic and Antarctic regions composed of permafrost. Seawater intrusion into coastal areas, on the other hand, is of local character under natural conditions. Under artificially disturbed conditions, however, seawater intrusion is appreciably intensified, as in the case of seawater encroachment into coastal areas caused by freshwater withdrawals. Good quantification and numerical/theoretical studies of groundwater intrusion are available for many parts of the world, most notably, Israel, Japan, Netherlands, and the USA (Fetter, 1988).

The water exchange between land and oceans that we study in this section bypasses the river network. Considering this subsurface water flux, the long-term (i.e. multiyear given the long residence time of ground water in the Earth's crust) world water balance is characterized by the equations below.

For the peripheral part of land discharging subsurface flow to the ocean:

$$E_p = P_p - R_p - U_o \tag{1}$$

where $E$ is evapotranspiration, $P$ is precipitation, $R$ is river runoff that includes surface or direct runoff and baseflow, $U$ is groundwater discharge from land to oceans bypassing the river network, and the subscripts p and o denote peripheral area and ocean, respectively.

For closed (drainless areas):

$$E_c = P_c \tag{2}$$

where the subscript c denotes closed area.

For oceans:

$$E_o = P_o + R_p + U_o \tag{3}$$

For the world:

$$E = E_p + E_c + E_o = P_p + P_c + P_o = P \tag{4}$$

The introduction of the groundwater discharge $U_o$ as a separate component of the water balance in eqn. (1) (and eqn. (3)) is due to Zektser and Dzhamalov (1981). With accurate estimates of precipitation, evapotranspiration and runoff in peripheral areas, $U_o$ is readily calculated from eqn. (1). Alternatively, if precipitation and evapotranspiration over the ocean, and runoff to it, are available, the deep ocean floor discharge $U_o$ can be obtained from eqn. (3). The appearance of both runoff $R_p$ and groundwater discharge $U_o$ in eqns. (1) and (3), can be used as a check of consistency for the calculation of $U_o$ from these equations (i.e. by solving for $U_o + R_p$ from one of these equations and then comparing the result with the one that can be obtained from the other equation). Equation (4) (follows by adding the left-hand sides of eqns. (1) through (3) and equating the resulting sum to the sum of the right-hand sides of the same equations) states that, over sufficiently long periods of time, global precipitation equals global evapotranspiration, because runoff and groundwater discharge losses to land areas represent gains to the oceans.

Zektser and Dzhamalov (1981) discuss the applicability of eqns. (1) through (4) in developing global groundwater balances. They state that the order of accuracy of groundwater estimates is ± 20% on average. The difference in residence times of water in the Earth's crust and oceans from those in the atmosphere and over land requires that the average water fluxes in eqns. (1) through (4) be taken over sufficiently long periods of time. Steady-state conditions and equilibrium of water fluxes in the hydrologic cycle are then better approximated.

Only a few works have addressed the quantification of direct groundwater discharge ($U_0$) to the oceans. Garrels and Mackenzie (1971) estimated global direct groundwater discharge to the oceans at approximately 10% of river runoff (note that river runoff is composed of baseflow and direct surface runoff, and does not include the direct groundwater discharge). The first estimates of groundwater discharge to the oceans based on hydrogeologic analysis were made by Nace (1967, 1970). These estimates were very preliminary, since, at that time, factual data were scarce. Soviet scientists have also made approximate estimates of direct groundwater discharge to the oceans (Zektser and Dzhamalov, 1981). According to their estimates the world-wide contribution of direct (or submarine) groundwater discharge to the oceans is approximately 2382 km$^3$ year$^{-1}$ (which we round up to 2400 km$^3$), and includes 1300 km$^3$ year$^{-1}$ to the Pacific Ocean, 762 km$^3$ year$^{-1}$ to the Atlantic Ocean, 219 km$^3$ year$^{-1}$ to the Indian Ocean, 48 km$^3$ year$^{-1}$ to the Arctic Ocean, and 53 km$^3$ year$^{-1}$ to the Mediterranean Sea.

The approximate breakdown of direct groundwater discharge from continents to adjacent oceans and seas is as follows: Europe 153 km$^3$ year$^{-1}$, Asia 328 km$^3$ year$^{-1}$, North/Central/South America 729 km$^3$ year$^{-1}$, Africa 236 km$^3$ year$^{-1}$, Australia 24 km$^3$ year$^{-1}$, and major islands 914 km$^3$ year$^{-1}$ (see Table 3). The very low contribution of the Australian continent to direct groundwater flow in spite of its relatively large territory is striking. This can be attributed to the widespread presence of low-permeability surficial rocks in that continent. At the other extreme, the major islands of the world contribute over a third of the world's direct groundwater flow. The overall proximity of recharge areas to discharge areas is an obvious factor for the large contribution of islands to direct groundwater discharge. Considering river runoff and direct groundwater flow, the oceans and seas gain about 40 400 km$^3$ year$^{-1}$, of which 38 000 km$^3$ come from rivers and 2400 km$^3$ are direct groundwater flow. The latter flux represents, therefore, approximately 6% of the total annual global water gain by oceans and seas.

The world's distribution of direct groundwater discharge is highly variable, as seen in Table 3, and depends on a variety of factors cited earlier in this paper. In spite of the regional variability of direct groundwater discharge, some patterns are identifiable in relation to conspicuous regional hydroclimatic characteristics. For example, the largest (direct) groundwater discharge values are found in mountainous coastal areas of tropical and humid zones where they can be as high as 10–15 l $s^{-1}$ $km^{-2}$, while, measured along the coastline, the direct groundwater discharge can be on the order of tens of thousands of cubic meters per day per kilometer of coastline. The smallest direct groundwater discharge values (0.2–0.5 l $s^{-1}$ $km^{-2}$), occur in arid and arctic regions of unfavorable recharge and permeability conditions.

### *Salt loading to oceans and seas by direct ground water*

It can be concluded from the above discussion that direct groundwater discharge represents a relatively low percentage of the total water flux to oceans and seas (about 6% world-wide). The relative amount of dissolved salts output with direct groundwater discharge, however, is significant. For example, the direct groundwater discharge to the Caspian Sea is equivalent to about 1% of river inflow, while the outflow of dissolved solids in direct ground water amounts to about 27% of the salt load transported to the sea by rivers. On a global basis the transport of salts via direct ground water to oceans amounts to approximately 1300 000 000 t $year^{-1}$, as shown in Table 3. (Given the direct groundwater flow volume of 2400 $km^3$ $year^{-1}$ its average dissolved solids concentration is close to 540 mg $l^{-1}$). This amount is roughly equivalent to 52% of the salts input to oceans and seas by rivers. The high content of dissolved solids in direct ground water is due to its long residence time in the Earth's crust, where it is concentrated by minerals that dissolve in it. The figures of Table 3 are the first world-wide estimates of direct groundwater flow and salts discharge with reference to the different continental masses and islands on Earth.

## ANTHROPOGENIC IMPACTS ON GLOBAL GROUNDWATER FLUXES

### *Past anthropogenic impacts*

The previous estimates of groundwater fluxes in the global hydrologic cycle presume stable climatic and hydrogeologic regimes, where the water fluxes and water storage in the major reservoirs of the Earth (atmosphere, oceans, cryosphere, land, and the Earth's crust) are in a steady state. On the other hand, the past climate on Earth shows significant fluctuations, most recent and prominent of which are Late Pleistocene glaciations, which have had profound effects on the global water cycle (drastic sea-level changes, major changes in the volume of ice in the planet, variations of atmospheric temperature and global precipitation rates). For shorter times scales, human influence has been felt in the hydrologic cycle also, although not at the levels of intensity brought about by natural climatic changes of the recent past.

TABLE 3

Groundwater and subsurface dissolved solids discharge to oceans from continents and major islands[a]

| Oceans, continents and major islands | Groundwater discharge | | | Subsurface dissolved solids discharge | | |
|---|---|---|---|---|---|---|
| | Areal values ($l\,s^{-1}\,km^{-2}$) | Linear values ($10^3\,m^3\,day^{-1}\,km^{-1}$) | Total values ($km^3\,year^{-1}$) | Areal values ($t\,year^{-1}\,km^{-1}$) | Linear values ($10^3\,t\,year^{-1}\,km^{-1}$) | Total values ($10^6\,t\,year^{-1}$) |
| Pacific Ocean | | | | | | |
| Australia | 1.1 | 4.6 | 7.1 | 24.9 | 1.2 | 5.0 |
| Asia | 4.8 | 27.2 | 254.3 | 98.2 | 6.5 | 165.2 |
| North America | 5.4 | 21.9 | 124.6 | 50.1 | 2.4 | 36.7 |
| South America | 11.5 | 58.7 | 199.6 | 64.1 | 3.8 | 35.5 |
| Major islands | 13.0 | 51.0 | 714.7 | 159.8 | 7.3 | 278.1 |
| Total | | | 1300.3 | | | 520.5 |
| Atlantic Ocean | | | | | | |
| Africa | 3.9 | 40.4 | 208.7 | 99.9 | 12.0 | 169.2 |
| Europe | 4.2 | 15.4 | 71.2 | 47.8 | 2.0 | 25.8 |
| North America | 4.6 | 31.9 | 219.4 | 74.6 | 6.0 | 112.2 |
| South America | 3.0 | 28.2 | 185.3 | 40.2 | 4.3 | 77.7 |
| Major islands | 4.4 | 12.0 | 77.7 | 76.0 | 2.4 | 42.9 |
| Total | | | 762.3 | | | 427.8 |
| Mediterranean Sea | | | | | | |
| Africa | 0.4 | 3.1 | 5.1 | 24.4 | 2.2 | 9.9 |
| Asia | 2.4 | 7.0 | 8.3 | 110.3 | 3.6 | 11.9 |
| Europe | 4.0 | 10.9 | 33.9 | 68.4 | 2.1 | 18.4 |
| Major islands | 2.8 | 8.1 | 5.7 | 34.9 | 1.2 | 2.3 |
| Total | | | 53.0 | | | 42.5 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Indian Ocean | | | | | | |
| Australia | 0.2 | 3.7 | 16.4 | 28.4 | 5.5 | 66.7 |
| Africa | 0.6 | 5.1 | 22.1 | 38.7 | 4.1 | 49.0 |
| Asia | 1.7 | 10.7 | 65.3 | 97.2 | 7.1 | 119.2 |
| Major islands | 5.1 | 27.7 | 115.6 | 84.7 | 5.3 | 60.6 |
| Total | | | 219.4 | | | 295.5 |
| Arctic Ocean | | | | | | |
| Europe | 5.6 | 17.8 | 47.5 | 26.6 | 1.0 | 7.2 |
| World's total | | | 2382.5 | | | 1293.5 |

[a] After Zektser and Dzhamalov (1988).

TABLE 4

Man-induced changes in major water fluxes

| Year | Total runoff ($10^3 km^3$) | Baseflow ($10^3 km^3$) | Surface runoff ($10^3 km^3$) |
|---|---|---|---|
| 1680 | 40.8 | 11.2 | 29.6 |
| 1980 | 38.3 | 13.4 | 24.9 |
| Change | −2.50 | +2.20 | −4.70 |

[a] The results of M.I. Lvovich transmitted via personal communication by M.G. Wolman (1991).

Table 4 shows estimates of human-induced changes in the global water cycle between 1680 and 1980. (These figures were produced by the soviet hydrologist M.I. Lvovich (M.G. Wolman, personal communication, 1991)). It can be seen in Table 4 that the annual river runoff (surface runoff plus baseflow) has had a net loss of $2.5 \times 10^3$ km$^3$ in the last 300 years. In that same time period baseflow has increased by $2.2 \times 10^3$ km$^3$ and surface runoff has decreased by $4.7 \times 10^3$ km$^3$. The decline in surface runoff is due to evaporative losses in large water reservoirs and to enhanced infiltration in irrigated agricultural lands around the world. In turn, agricultural infiltration and seepage in large reservoirs have augmented baseflow. Over the last 300 years the combined effect of increases in baseflow and reductions in surface runoff is a net decrease in global annual river runoff. Evidently, the decreases in surface runoff due to the damming of rivers and to infiltration from irrigated agricultural lands have outweighed the increase in surface runoff typically associated with vegetation clearing (Hewlett, 1982), which has been pervasive in recent times.

### *Potential effects of greenhouse warming of the Earth on ground water*

Considering future human impacts on the hydrologic cycle the great uncertainties center around the implications of possible greenhouse warming of the Earth. Although general circulation models (GCM) predict a long-term 1–5°C increase of global mean surface temperature as a result of doubling $CO_2$ concentrations over the current mean level (which is about 345 ppm), there is substantial uncertainty in predictions concerning disturbances on the hydrosphere as a result of greenhouse warming. This uncertainty stems from GCM's limitations in representing the complex climate of the Earth (Mitchell, 1989; Giorgi and Mearns, 1991). Chief among the processes that complicate predictions of climatic effects of global warming are the feedback that water vapor, clouds, ice-albedo, and ocean–atmosphere interactions have on greenhouse warming (Ramanathan, 1988; Ramanathan et al., 1989). Some of the limitations of numerical climate simulations in predicting modifications of regional and global hydrologic regimes as a result of global warming have been studied by Dooge (1989), Gleick (1987b, 1989), and Mitchell (1989).

Given the larger atmospheric concentrations of water vapor that would result from warmer temperatures, a potential impact scenario for global warming could be an increase in precipitation rates for a warmer Earth. (Some GCM results indicate increments in global precipitation ranging from 5 to 15% of world-wide precipitation — which is about 100 cm year$^{-1}$ — according to Washington and Meehl (1984), Hansen et al. (1984), Wetherald and Manabe (1986), Schlesinger and Zhao (1987), and Wilson and Mitchell (1987)). Larger global precipitation would imply more runoff, water percolation, and groundwater flow. The major fluxes of the hydrologic cycle would be intensified. In coastal areas, potentially higher sea-levels, of a purportedly warmer Earth, would increase the landward encroachment of ocean water, partly upsetting the potential gain in direct groundwater flow that would otherwise result from larger groundwater recharge rates.

The analysis of hydrologic cycle disturbances (due to climatic change) based on global changes in precipitation is overly simplistic, however, because it does not yield specific information on the regional and seasonal climatic disturbances that can be expected throughout the planet as a result of global warming. That is, at the watershed or river basin scales, the resolution of GCM does not permit predictions of water-balance modifications. The most the GCM simulations can tell us at this point is that there seems to be general agreement that there would be increased precipitation over the high latitudes of the planet as a result of enhanced moisture transport from low to high latitudes on a warmer planet. With regard to available moisture at the Earth's surface, it would be enhanced over most of the northern extratropical continents in winter due to increased precipitation there. During the summer, however, there is no general agreement as to the status of surface moisture in these northern (important grain-producing) lands (Mitchell, 1989). Some authors, however, consider it probable that summer soil moisture would decrease in these midlatitude continental interiors due to shorter winter precipitation periods and earlier snowmelt there (Dickinson, 1990).

In view of the limitations of GCM in predicting regional climatic impact of potential greenhouse warming, climate modelers have devised the so-called limited-area-meteorological (LAM) models. These fine-mesh models are imbedded in a coarse-resolution GCM over an area of interest. The GCM provides initial and boundary conditions for the LAM, which, in turn, produces high-resolution hydroclimatic predictions. Hydrologists have used a similar nesting approach, whereby GCM outputs, such as average temperature and precipitation over the area of interest drive a numerical model of the regional hydrologic cycle (Gleick, 1986, 1987a; Lettenmaier and Sheer, 1991; Mimikou et al., 1991). Typically, precipitation is assigned a range of values, say, from −25 to 25% increments over current levels in the area of interest, and the associated impact on runoff, soil moisture, and evapotranspiration is calculated by simulation of a regional hydrologic model. Invariably, the baseflow and the direct groundwater flow are not isolated in these simulations. Therefore, there is virtually no information on the possible effects of greenhouse warming on regional groundwater systems. This is due to the uncertainties in modeling groundwater systems under such transient climatic conditions and to the relatively long residence times of water in the Earth's crust (compared with over-land and atmospheric water residence times), which hinder their incorporation in short-term hydrologic simulations.

### *A plausible scenario for climate change impact on groundwater fluxes*

In spite of the difficulties of predicting disturbances of ground water in a potentially warmer planet resulting from $CO_2$ doubling, earlier results on global water balances (see Tables 1 and 3) are useful in assessing the expected relative impacts on global groundwater fluxes under specified scenarios. Suppose, for the sake of argument, that global precipitation increases 10% over current levels. It was previously calculated that the baseflow is about 9% of global precipitation (total global precipitation is approximately 100 cm year$^{-1}$). Therefore, assuming that the baseflow/precipitation ratio remains constant, the increase in baseflow corresponding to a 10% rise in global precipitation would be 0.9% of current precipitation levels, or about 9 mm year$^{-1}$ distributed over the Earth's land surface. Considering that the land area of the world — excluding ice caps and glaciers — is $128 \times 10^6$ km$^2$, this 9 mm year$^{-1}$ flux is equivalent to, approximately, an additional 1200 km$^3$ year$^{-1}$ of the baseflow contribution to runoff. This represents a gain of baseflow approximately equal to 3% of current river runoff (current river runoff is approximately 38 000 km$^3$ year$^{-1}$).

With respect to direct groundwater flow (that bypasses the river network) the data in Table 3 provide a global estimate of direct groundwater flow of approximately 2400 km$^3$ year$^{-1}$. This is equivalent to 19 mm year$^{-1}$ over the Earth's land surface. Based on an average global precipitation of 100 cm year$^{-1}$, the direct groundwater flow is then approximately 2% of precipitation. Therefore, the increase in direct groundwater contribution to oceans and seas associated with a 10% increment of precipitation would amount to approximately 0.2% of global precipitation, or 2 mm year$^{-1}$. This is equivalent to an additional flux of direct ground water to oceans and seas of approximately 260 km$^3$ year$^{-1}$, which represents about 0.6% of the annual total water input to oceans and seas (i.e. including river runoff and direct groundwater flow of 40 400 $km^3$ $year^{-1}$). Although this additional flux of direct runoff is unequivocally small, the salt load in direct ground water is approximately 540 000 t $km^{-3}$ $year^{-1}$ (i.e. 2400 $km^3$ $year^{-1}$ of ground water carry 1300 000 000 t of salts annually, which is equivalent to a dissolved solids concentration of 540 mg $l^{-1}$). Therefore, an additional 260 $km^3$ $year^{-1}$ of direct ground water would mean about 140 000 000 t $year^{-1}$ of additional salts being added to the oceans and seas. Whether this additional salt load would increase the salinity of the oceans and seas is unclear. In an intensified hydrologic cycle there would be a larger water input to the oceans and higher rates of evaporation. If the water fluxes to and from the oceans eventually became equalized and the salt load increased at the rates previously calculated, then the salinity of the receiving water bodies would increase only if their total water volumes increased at a rate insufficient to dilute the salt content to at least present levels. At this point in time, it is not clear how much, or if at all, the volume of the oceans will increase as a result of thermal expansion and ice melting of a warmer planet (Chao, 1991).

The above are estimates of global groundwater disturbances arising from the hypothetical scenario for greenhouse warming (i.e. 10 % increase of global precipitation), and assuming that the hydrologic cycle has reached a steady state. Whereas the baseflow contribution to river runoff might take from tens to hundreds of years to reach its new equilibrium, direct groundwater flow might stabilize over time scales one or two orders of magnitude longer.

## SUMMARY AND CONCLUSIONS

A summary of the hydrogeologic quantification of global groundwater fluxes, and their relationship to runoff and precipitation, has been presented in this paper. The analysis of these data leads to the following conclusions:

(1)The world-wide ratios of baseflow/precipitation and baseflow/river runoff are approximately 10% and 30%, respectively. These ratios show a high geographical variability, which is controlled by prevailing regional climatic and hydrogeologic factors. The baseflow/precipitation ratio can vary from 0% in areas with impermeable ground (e.g. permafrost) to, theoretically, over 100%. In practice, the largest observed ratios are on the order of 70% (they have been documented to occur in karstic terrain of the Crimean region in eastern Europe). The range of observed values of the baseflow/river runoff is from 0%, in permafrost areas, up to 100%. The latter high values are known to occur in mountain-fold karst areas with favorable recharge conditions, such as those that prevail in central and Eastern Europe.

(2)Recent studies by the senior author and collaborators, indicate that, on a world-wide basis, the direct groundwater flow (this is the direct exchange of water between oceans/seas and the adjacent coastal aquifers, bypassing the river network) is approximately 2400 $km^3$ $year^{-1}$. This is equivalent to about 6% of the total annual water input to oceans and seas. In spite of its relatively low volume, direct groundwater recharge accounts for some 1300 000 000 t $year^{-1}$ of salts discharged to oceans and seas on a world-wide basis. This volume of salts is equal to 52% of the total dissolved solids annual output to oceans and seas by rivers.

(3)Baseflow has increased over approximately the last 300 years, as a result of infiltration from large-scale irrigation and seepage from man-made reservoirs. This gain in baseflow is approximately equal to 6% of the current river runoff (which equals 38 000 $km^3$ $year^{-1}$). Surface runoff (excluding baseflow), on the other hand, has decreased over the same period as a consequence of reservoir evaporation and infiltration losses (the loss amounts to about 12% of current total runoff). The combined effect of the gain in baseflow and the drop in surface runoff is a net decrease in global river runoff over the last 300 years of about 2500 $km^3$.

(4)Assuming a possible 10% increase of global precipitation as a result of potential greenhouse warming, the associated change in baseflow would be 9 mm $year^{-1}$, which is equivalent to 1200 $km^3$ $year^{-1}$. The change in direct groundwater discharge to oceans and seas would be approximately 2 mm $year^{-1}$, or, equivalently, 260 $km^3$ $year^{-1}$. Estabilishment of the baseflow and direct groundwater flow will take place over different time scales, with the latter flow taking a much longer time to reach equilibrium. The impact of the larger direct flow on the global water balance would be minimal from a volumetric point of view. The increment in salt discharge, however, is appreciable. The salinity of oceans and seas would increase if the increased salt load were maintained over long periods of time and the gain in the volume of receiving water bodies was not sufficient to offset the gain in salt content.

(5) There remain information gaps on groundwater fluxes for some parts of the world, some of which include large aquifers in regions with intense hydrologic cycles (e.g. equatorial areas in developing countries). The importance of ground water as a water source in the world points to the need for a greater understanding of the rates of groundwater and salt transport throughout the land masses of the Earth.

## ACKNOWLEDGMENTS

This work was supported by grants W-752 and W-761 from the California Water Resources Center, and by cooperative agreement US EPA CR-816969-01-0. This paper has not undergone review by either one of the funding agencies and it does not reflect their official positions nor their endorsement of any results or products cited in the paper. Comments by Kate Rees, Alexander Gershunov, and Rebecca Fawver helped in the preparation of the paper.

## REFERENCES

Aldwell, C.R. and Burdon, D.J., 1971. Ground Water Investigations in Eire: Hydrogeology in Ireland. Irish National Committee for International Hydrologic Programme, Dublin.

Barron, E.J., 1991. Addressing critical issues of climate and hydrology from space. EOS, Trans. Am. Geophys. Union, 72: 74.

Bodelle, J. and Margat, J., 1980. Ground Water in France. Masson, Paris (in French).

Budyko, N.I., 1977. Climatic Changes. American Geophysical Union, Washington, DC.

Budyko, N.I. and Drozdov, O.A., 1953. Characteristics of the moisture circulation in the atmosphere. Izv. Akad. Nauk. SSSR, Ser. Geogr. Geofiz., 4: 5–14.

Budyko, M.I., Efimova, Zubenok, L.I. and Strokina, L.A., 1962. The heat balance of the earth's surface. Izv. Akad. Nauk. SSSR, Ser.Geogr. Geofiz., 1: 6–16 (in Russian).

Budyko, M.I., Drozdov, O.A. and Yudin, M.I., 1966. The influence of man's economic activity on the climate. In: Contemporary Problems of Climatology. Gidrometeoizdat, Leningrad, pp. 435–448.

Chao, B.F., 1991. Man, water and global sea level. EOS, Trans. Am. Geophys. Union, 72: 492.

Chatuverdi, M.C., 1981. Water resources of India: overview. Proc. Indo-US Workshop on Flood Mitigation, Vol. 1, New Delhi, India. pp. 2.1–2.41.

Custodio, E., 1982. Elements of ground water flow balance (natural and as affected by man). Int. Symp. on Computation of Ground Water Balance, Varna, Bulgaria. 17pp.

Dickinson, R., 1990. Global warming. In: C.I. Silver and R.S. DeFries (Editors), One Earth, One Future. National Academy, Washington, DC, pp. 63–77.

Dooge, J.C.I., 1989. Effect of $CO_2$ increases in hydrology and water resources. In: R. Fantechi and A. Ghazi (Editors), Carbon Dioxide and other Greenhouse Gases: Climatic Associated Impacts. Kluwer, London, pp. 203–213.

Eagleson, P.S., 1986. The emergence of global scale hydrology. Water Resour. Res., 22: 6S–14S.

Eagleson, P.S., 1991. Hydrologic science, a distinct geoscience. Rev. Geophys., 29: 237–248.

Fetter, C.W., 1988. Applied Hydrogeology, 2nd edn. Merril, Columbus, OH.

Freeze, R.A., 1972a. Role of subsurface flow in generating surface runoff: 1, baseflow contributions to channel flow. Water Resour. Res., 8: 609–623.

Freeze, R.A., 1972b. Role of subsurface flow in generating surface runoff: 2, upstream source areas. Water Resour. Res., 8: 1272–1283.

Garrels, R.M. and Mackenzie, F.T., 1971. Evolution of Sedimentary Rocks. New York.

Giorgi, F. and Mearns, L.O., 1991. Approaches to the simulation of regional climate change: a review. Rev. Geophys., 29: 191–216.

Gleick, P.H., 1986. Methods for evaluating the regional hydrologic impacts of global climatic changes. J. Hydrol., 88: 97–116.

Gleick, P.H., 1987a. The development and testing of a water balance model for climate impacts assessment: modeling the Sacramento basin. Water Resour. Res., 23: 1049–1061.

Gleick, P.H., 1987b. Regional hydrologic consequences of increases in atmospheric $CO_2$ and other trace gases. Clim. Change, 10: 137–161.

Gleick, P.H., 1989. Climate change, hydrology, and water resources. Rev. Geophys., 27: 329–344.

Ground Water in the Western Hemisphere, 1976. United Nations, New York.

Hansen, J., Lacis, A., Rind, D., Stone, P., Fung, R., Ruedy, R. and Lerner, J.L., 1984. Climate sensitivity: analysis of feedback mechanisms. In: J. Hansen and T. Takahashi (Editors), Climate Processes and Climate Sensitivity, Geophys. Monogr. Ser., Vol. 29. American Geophysical Union, Washington, DC, pp. 130–163.

Harder, A.N. and Drescher, W.J., 1954. The great artesian basin, Australia. BMR J. Geol. Geogr., 5: 9–38.

Hewlett, J.D., 1982. Principles of Forest Hydrology. University of Georgia, Athens, GA.

Keller, E.A. and Loaiciga, H.A., 1991. Earthquakes, fluid pressure and mountain building: a model., Geol. Soc. Am. Abstr. Annu. Meet., 23: A84.

Konoplyantsev, A.A. (Editor), 1982. Ground Water Flow of Areas of Central and Eastern Europe. Vsegingeo, Leningrad (in Russian).

Kudelin, B.I., 1960. Principles of Regional Assessment of Natural Ground Water Resources. MGU, Moscow (in Russian).

Lettenmaier, D.P. and Sheer, D.P., 1991. Climatic sensitivity of California water resources. J. Water Resour. Plann. Manage., 117: 260–272.

Loaiciga, H.A., 1989. An optimization approach to ground water quality monitoring network design. Water Resour. Res., 25: 1771–1780.

Lvovich, M.I., 1974. World Water Resources and their Future. Mysl, Moscow (in Russian).

Manabe, S., Smagorinsky, J. and Strickler, R.F., 1965. Simulated climatology of a general circulation model with a hydrologic cycle. Mon. Weather Rev., 93: 769–798.

Mimikou, M., Kouvopoulos, Y., Cavadias, G. and Vayianos, N., 1991. Regional hydrological effects of climate change. J. Hydrol., 123: 119–146.

Mitchell, J.F.B., 1989. The greenhouse effect and climate change. Rev. Geophys., 27: 115–139.

Nace, R.L., 1964. Water of the world. Nat. Hist., 73.

Nace, R.L., 1967. Are we running out water. U.S. Surv., Circ. No. 586, Reston, VA.

Nace, R.L., 1970. World hydrology: status and prospectus. Proc. IASH-UNESCO-WHO Symp. on World Water Balance, Vol. 1, Reading, pp. 1–10.

Nace, R.L., 1978. Circulation and distribution of natural water.Water Resour. (Vodnye Resursy), 5: 635–646.

Newport, T.G., 1959. Ground water resources of the Lower Niobrara River and Ponca Creek Basins,.Nebraska and South Dakota. U.S. Geol. Surv., Water-Supply Pap. No. 1460-G, Reston, VA.

Ramanathan, V., 1988. The greenhouse theory of climate change: a test by an inadvertent global experiment. Science, 240: 293–299.

Ramanathan, V., Barkstrom, B.R. and Harrison, E.F., 1989. Climate and the earth's radiation budget. Phys. Today, May 1989, pp. 22–32.

Rosenberg, N., 1990. Food, water and changing climate. In: C.S. Silver and R.S. DeFries (Editors), One Earth, One Future. National Academy, Washington, DC, pp. 78–89.

Schlesinger, M.E. and Zhao, 1987. Seasonal climate changes induced by doubled $CO_2$ as simulated by the OSU atmospheric OCM/mixed layer model, I. Oregon State University Climate Institute Report No. 70, Corvallis, OR.

Sun, R.J. (Editor), 1986. Regional aquifer-system analysis program of the United States Geological Survey, summary of projects, 1978-1984. U.S., Geol. Surv., Circ. No. 1002, Reston, VA.

Toth, J., 1972. Properties and manifestations of regional ground water movement. Proc. 24th Int. Geological Congress, Section 2. pp. 153–163.

Tsonis, A.A., 1991. Sensitivity of the global climate system to initial conditions, I. EOS, Trans. Am. Geophys. Union, 72: 313–328.

Vsevolozhskii, V.A., 1983. Ground Water Runoff and Water Balance of Platform Structures. Nedra, Moscow.

Walton, W.C., 1970. Ground Water Resource Evaluation. McGraw-Hill, New York.

Washington, W.M. and Meehl, G.A., 1980. A seasonal cycle experiment on the climate sensitivity due to a doubling of $CO_2$ with an atmospheric circulation model coupled to a simple mixed layer ocean model, Int. J. Geophys. Res., 89: 9475–9503.

Water Balance Maps for the Territory of Central and Eastern Europe, 1984. Budapest.

Wetherald, R.T. and Manabe, S., 1986. An investigation of cloud cover change in response to thermal forcing. Clim. Change, 8: 5–24.

Wilson, C.A. and Mitchell, J.F.B., 1987. Simulated climate and $CO_2$-induced climate change over Western Europe. Clim. Change, 10: 11–42.

Wolman, M.G., 1991. Planet earth: part III, the impact of man. EOS, Trans. Am. Geophys. Union, 72: 884–886.

Zektser, I.S., 1977. Laws of Formation of Ground Water Runoff and Scientific and Methodological Principles of its Study. Nedra, Moscow (in Russian).

Zektser, I.S. and Dzhamalov, R.G., 1981. Ground water discharge to the world's oceans. Nat. Resour., 17: 18–20.

Zektser, I.S. and Dzhamalov, R.G., 1988. Role of Ground Water in the Hydrologic Cycle and in Continental Water Balance. UNESCO, Paris.