Water balance of Earth

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Abstract The paper presents a compact picture of the occurrence of water on Earth, including the temporal development of water resources of the planet, the current water balance, and the future of water on Earth. In examining numerous standard hydrological references and new developments in quantification of the water resources of planet Earth, several corrections are proposed to the hydrological water balance of Earth. Particular attention is drawn to the areas of open water surfaces on land, which according to current estimates are much larger than reported in standard hydrological references. The paper stresses the need for improvements in our understanding of the hydrological cycle and presents several conclusions on the ways to improve this understanding and future visualizations of the water balance of Earth.

Key words water; water balance; water balance of Earth; water cycle; planetary water cycle; hydrological cycle; hydrotectonics; Earth; Solar System

Bilan hydrologique de la Terre

Résumé L'article présente une image compacte de la présence de l'eau sur Terre, incluant le développement temporel des ressources en eau de la planète, le bilan hydrologique actuel, et le futur de l'eau sur Terre. A travers l'examen de plusieurs références hydrologiques standards et de nouveaux développements concernant la quantification des ressources en eau de la planète Terre, plusieurs corrections sont proposées au bilan hydrologique de la Terre. Une attention particulière est attirée sur les zones d'eau libre continentales, qui sont selon les estimations courantes bien supérieures à ce qu'indiquent les références hydrologiques standards. L'article insiste sur les nécessaires améliorations de notre compréhension du cycle hydrologique, et présente plusieurs conclusions sur les démarches à suivre pour améliorer cette compréhension et sur de futures visualisations du bilan hydrologique de la Terre.

Mots clefs eau; bilan hydrologique; bilan hydrologique de la Terre; cycle de l'eau; cycle planétaire de l'eau; cycle hydrologique; hydro-tectonique; Terre; Système Solaire

The basic business of hydrology is to solve the water balance equation.
J. C. I. Dooge

INTRODUCTION

The occurrence, quantity and circulation of water on Earth have been always of interest to humans; however, historically both the overall picture and the details were usually poorly understood. Our ancestors entertained a notion of Earth flowing on water, or the existence of an immense underground ocean, and in an allegoric or cosmological sense were actually not that far from the truth, taking into consideration the fact that the interior of the Earth, according to current thinking, contains an equivalent of several World Oceans. The first scientific reasoning on the water balance of Earth can be traced to Copernicus (1543), who, calculating mass balances of the Solar System and considering the revolutions of celestial bodies, came to the right conclusion that there is more land than water on Earth, although it possibly appears otherwise on the surface.

In recent times, the water balance of Earth gained immensely in importance due to increasing water scarcity, decreasing water resources *per capita*, and the overall need for much tighter water management practices. We also need to better accommodate water in global circulation models to evaluate the severity of the currently perceived water crisis situation, and predict the occurrence and consequences of much talked about climate change.

In this respect it is sobering to realize that while we can confidently state, for example, that the Sun is 333 332.4 more massive than the Earth, we have significant troubles to assign the third significant number to any term of the water balance of Earth, and for some of them even the second significant number is open to discussion. As will be demonstrated later, some of the traditionally accepted figures are, or have recently become, grossly incorrect.

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Certainly, there are many reasons for this state of affairs and hydrologists would routinely list a litany of causes, starting with the fact that the water is in a state of constant flux, with relationships changing in a mercurial fashion, and further elaborating that our measurement devices and methods are still sadly inadequate for the task at hand. On a positive note, in recent times hydrologists have received welcome help from a score of other scientific disciplines that include, but are not limited to, geologists, planetologists, mineralogists, seismologists, geochemists, meteorologists and climatologists.

There is little doubt now that the global warming will generally reduce our water supplies (Bates *et al.*, 2008) in times when both the global population and demand for water are increasing at an unprecedented pace. It is about time that we began to take a very detailed stock of our water.

The hydrological cycle forms the most dynamic part of the overall water circulation of planet Earth. While it is the most important water cycle in our daily life, other water cycles which operate on geological time scales are also important in visualizing a complete water perspective of our planet.

THE SHORT HISTORY OF WATER ON EARTH

The understanding of the history of Earth has improved dramatically over the last decade (Valley, 2006). Our existence can be traced to a molecular cloud of gas and dust, some 50 light years across, whose isotopic compositions (Nittler, 2003) point out to the stars that preceded our Sun, and include red giants, supernovae and novae. At some time, the cloud began to contract either under its own gravity, or more probably (Halliday, 2006) following a shock wave from a nearby supernova explosion, into a swirling disc in which the Sun and the planets accreted from the available material in a relatively short time of tens of million years. The Solar System is 4.567 billion years old (Valley, 2006). The Earth accreted most of its mass within 10 million years, and the Sun began to shine, entering the Main Sequence, within 50 million years (Zahnle, 2006), at about the time when the proto-Earth collided with a Mars-size object (Koeberl, 2006) code-named Theia, in an apocalyptic event that resulted in the creation of the double-planet system which the Earth now effectively forms with the Moon.

On a wider scale, while it is conceivable that the Sun may intercept some loose comets from interstellar space, so far, no hyperbolic comet has been observed and, therefore, the Solar System may be considered as a stand-alone entity when it comes to water.

The existence of water on Earth is an easily verifiable fact; however, as Halliday (2006) admits, we do not know where this water comes from. This leaves a wide field for reasoning and interpretation. As Zahnle (2006) explains, most water accreted by Earth was probably delivered in the form of hydrous silicates. There is general agreement that the Earth accreted "wet" and that the post-accretion influx of water to Earth from comets is limited to less than 20% (Dixon, 2003). Drake & Campins (2005) examine the efficacy of nebular gas adsorption as a mechanism by which the terrestrial planets accreted "wet" and postulate that some of the water in the terrestrial planets may have originated by adsorption of water by grains of dust in the accretion disk. A simple model suggests that grains accreted to Earth could have adsorbed 1–3 Earth oceans of water. Levison *et al.* (2001) reckon that the likelihood that any other known sources could have delivered an ocean of water to Earth after the Moon-forming impact is small. Torres & Winter (2008) calculate that the most likely contributions to Earth's water involve ~35% of absorbed water, 50–60% of asteroidal water and 5–15% of cometary water.

Ringwood (1975) presented a lucid interpretation of a possible Earth accretion scenario. A mass balance of the planet indicates that it consists of 90% of high-temperature condensates (see Table 1) and 10% of low-temperature condensates of the Solar nebula. Since mass balances show that we should have an ocean some 100 km deep, Ringwood (1975) and Kotwicki (1991) posed the question: where is the missing water? It appears that nearly all the water from a huge amount contained in low temperature condensates was lost early due to oxidization of iron by water vapour, and the subsequent escape of hydrogen into space.

Table 1 Percentage composition of solid phases condensing in the Solar nebula (Ringwood, 1975).

Solid phases of Solar nebula	Low-temperature condensate	High-temperature condensate
H_2O	19.2	-
Fe, +5% Ni	-	34.1
SiO_2	21.7	32.8
TiO_2	0.1	0.2
Al_2O_3	1.6	2.8
Cr_2O_3	0.35	0.2
MnO	0.2	0.1
FeO	22.9	-
NiO	1.2	-
MgO	15.2	27.7
CaO	1.2	2.3
Na_2O	0.7	-
K_2O	0.07	-
P_2O_5	0.3	-
S	5.7	-
Organic compounds	9.6	-
Total	**100**	**100**

The example of Venus, a twin planet of Earth, may illustrate this point. Venus accreted on an orbit which could have had less volatiles due to its proximity to the Sun. Nevertheless, whatever water it accreted, and any later cometary additions, were lost. Venus has no plate tectonics, and therefore, no plausible way to outgas its mantle.

It has been suggested that 10–50 Earth oceans of water existed in the primitive mantle (Abe *et al.*, 2000), although that amount has not yet been positively determined. Most of this water outgassed within 100 million years, and, in conditions prevailing on an early Earth, dissociated, with oxygen being absorbed by the lithosphere, and hydrogen escaping into outer space.

Oceans existed on our planet 4.2 billions years ago (Cavosie *et al.*, 2006) and maybe as early as 4.4 billion years ago (Nutman, 2006). Their volume may have been twice that of today's World Ocean (Russell & Arndt, 2005).

We do not know whether life originated on Earth or was seeded here from outer space, and if we do find any form of life elsewhere it will be powerful circumstantial evidence that life is abundant in the Universe. Schopf (2006) traces the evidence for life on Earth to sometime before 3.5 billion years ago, possibly around 4 billion years ago. Since its emergence, life has, to a large degree, shaped the atmosphere, hydrosphere and lithosphere of the planet.

The amount of water on the surface of Earth is not a constant figure. While we do not have a method yet to estimate the volume of the World Ocean at any desired point of the geological time scale, there are three points we can ponder on: the accretion water quantity of Earth, the present total water content of the planet, and the time when the Earth becomes dry. As we can see from a conceptual presentation of the incidence of water on Earth in Fig. 1, the occurrence of water on the surface of our planet is an episodic event that is related directly to the luminescence of the Sun.

Bounama *et al.* (2001) explains that the fate of the Earth's ocean is sealed by external forcing. In time, all water will disappear as a result of rising global temperature caused by increasing solar luminosity, with a catastrophic loss of water beginning 1.3 billion years from now, or even sooner.

When the Sun enters the red giant phase of its lifetime about five to seven billion years from now, its size will swell a hundred times, and its luminosity will increase thousands of times. The Earth will be reduced to cinders, but some water in the mantle may survive the fiery phase. Trillions of comets of both the Kuitper Belt and Oort Cloud will be vaporized and later possibly assemble into other molecular clouds, from which, in time, a new Sun and a new Earth will be born.

When the Sun becomes a white dwarf, and subsequently a black dwarf, in the last phase of its lifetime, the Earth will enter a deep-freeze period which may last for trillions of years, or infinity, depending on the cosmological leaning of the reader, unless by some cosmic collision it becomes incorporated into another celestial entity.

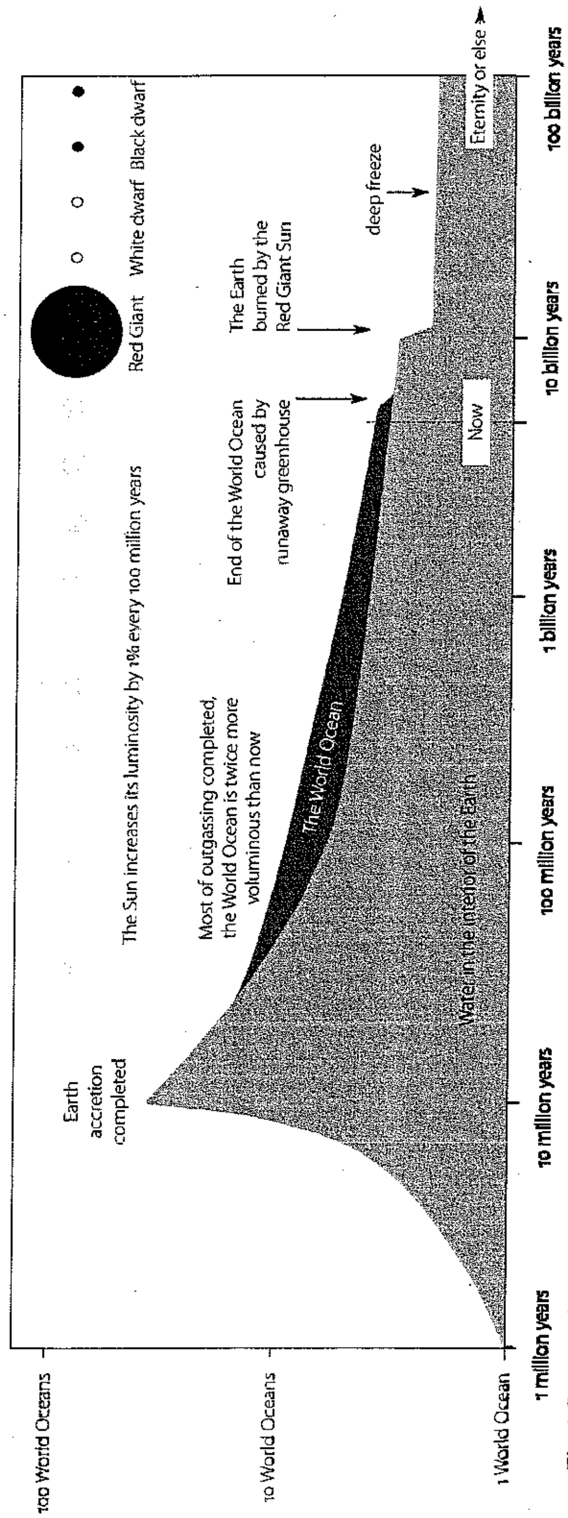

Fig. 1 Conceptual water balance of Earth over the lifetime of our planet (log-log scale).

Water exchange with outer space

While the Earth loses water to outer space, Kasting (1989) calculates that, at the present escape rate, it would take 7 billion years to lose the World Ocean, which corresponds to an escape rate of 0.2 km^3 $year^{-1}$. On the other hand, the Earth gains water from outer space, with volatile accretion rates estimated in a very wide range of between 0.0001 to 1 km^3 $year^{-1}$ (Bounama *et al.*, 2001).

Hydro-tectonic water cycle

The actual presence of water on the surface of Earth at any given time is an equilibrium between hydro-tectonic interactions of surface water with the interior of the planet and acquisitions of water from outer space on one side and escape of water into space on the other. While some of these terms may look insignificant on an annual scale, they are certainly very significant on the geological time scale.

Rüpke (2004) postulates that the Earth's mantle is highly outgassed and presently contains only 1/3 of its initial water. This implies that most of the water currently stored in the Earth's mantle is recycled surface water. The Earth's deep and surface water cycles therefore appear to be in close contact. It seems possible (Van Andel, 1985) that the Earth's surface is losing water to the mantle through subduction of oceanic sediments and crust.

If, say, 1 km^3 of water is circulated through the mantle in a year, then the World Ocean has been already circulated three times. The recirculation ratio may be much higher, however. It is known (Condie, 1989) that the $^{87}Sr/^{86}Sr$ ratio in marine carbonates varies with age and that the current $^{87}Sr/^{86}Sr$ ratio of seawater represents about a 4:1 mixture of river water and submarine volcanic water. Smyth & Jacobsen (2006) calculate that current subduction and spreading rates are roughly sufficient to recycle the ocean once in 4.5 billion years.

Kotwicki (1991) and Bounama *et al.* (2001) tabulate the estimates of the present mantle water abundance, which different authors put between 1.6 and 20, with a mean value of five World Oceans, a volume supported also by findings of Murakami *et al.* (2002). The water storage potential of the lower mantle is estimated to be 2.5–3 times the present ocean mass, and is comparable to the amount of water in the transition zone.

The World Ocean, the main repository of water on the surface of the planet, loses water to the mantle through subducting slabs of the crust and gains water through outgassing. Peacock (1990) estimates these figures as 0.87 $km^3/year^{-1}$ and 0.2 $km^3/year^{-1}$, respectively, and explains the reasons of imbalance; Bounama *et al.* (2001, and references therein) cite a set of broadly similar figures. Water trapped in the slabs must be stored mainly in nominally anhydrous minerals that may be transported to the core-mantle boundary region, some 2900 km below the surface of Earth (Ohtani, 2005).

As Bounama *et al.* (2001) explain, because of internal processes, the Earth cannot lose all the water in its surface reservoirs due to subduction processes to the mantle. After one billion years, only 27% of the modern ocean will be subducted into the mantle.

THE WATER BALANCE OF THE HYDROSPHERE

Most if not all of our everyday concerns with regard to water are related to the hydrosphere. There is a great variety of tables and graphs which present the water balance of Earth, the elements of the hydrological cycle, storages, residence times, surface equivalents and fluxes. With the advent of GIS, remote sensing and global satellite monitoring systems, there is a concerted effort to make more accurate assessments of these terms.

Major improvements to our understanding of the hydrological cycles are emerging right now with the Gravity Recovery And Climate Experiment (GRACE) mission that measures the variations in Earth's gravity by sensing a distance with 1-micron precision between two satellites flying in formation, 220 km apart. The GRACE provides monthly maps of the Earth's average gravity field and, while it cannot measure exact water storages from space, it allows determination of monthly water storage changes for areas of 200 000 km^2, including changes in groundwater storage. It may help identification of groundwater depletion in areas of the World where such measurements are not systematically recorded (NASA, 2002). Other enlightening experiments include the TOPEX/Poseidon satellite mission that measures sea-surface height, ICESAT that precisely measures the surface of the World's ice sheets and glaciers, and the Aqua mission to detect soil moisture.

Table 1 shows the water balance of Earth, modified from several sources (Kotwicki, 1991; Gleick, 1993; Shiklomanov, 1998; Pagano & Sorooshian, 2002; Babkin, 2003; Shiklomanov & Rodda, 2003), and expanded to account for less frequently cited elements of the balance. Significant corrections to several terms in Table 2 follow Downing *et al.* (2006), Groombridge & Jenkins (1998), USGS (1999), Lehner & Döll (2004), and Mitra *et al.* (2005).

Table 2 Water balance of Earth (generated from various sources, see text).

Form of water	Area (km^2)	Volume (km^3)	% of total water (%)	% of freshwater (%)
Salt water	510 065 600	**1 350 000 000**	97.1	
World Ocean	361 126 400	1 338 000 000	96.3	
Saline groundwater	148 939 100	14 000 000	1.0	
Salt lakes	820 000	85 000	0.006	
Ice	36 821 000	**33 400 000**	2.40	**75.0**
Glaciers	15 821 000	33 100 000	2.38	74.4
Antarctica	13 586 000	30 100 000	2.17	67.6
Greenland	1 785 000	2 620 000	0.19	5.9
Arctic islands	230 000	83 000	0.006	0.2
Mountains	220 000	34 000	0.002	0.1
Permafrost	21 000 000	300 000	0.022	0.7
Freshwater	510 065 600	**11 100 000**	0.80	**24.9**
Fresh groundwater	148 939 100	11 000 000	0.79	24.7
Lakes	4 200 000	91 000	0.007	0.20
Soil moisture	148 939 100	16 000	0.001	0.04
Wetlands	5 300 000	12 000	0.001	0.03
Rivers	1 000 000	2 100	0.0002	0.005
Biological water	510 065 600	2 400	0.0002	0.005
Reservoirs	400 000	7 000	0.0005	0.016
Farms	1 377 000	600	0.00004	0.0013
Atmospheric water	510 065 600	**13 000**	0.00094	**0.029**
Hydrosphere total	**510 065 600**	**1 390 000 000**	**100**	**100**
Earth's interior		7 000 000 000	~5 World Oceans	

Some terms in Table 2 are defined better than others, but none of them is particularly precise in its own right. While some of the terrestrial forms of water seem to be less significant in the volumetric sense, they may still cover very significant areas, and, therefore, be important in terms of the atmospheric and land surface water exchange. In comparison with similar tables, abundant in the literature, and in line with the current developments in hydrology and other Earth sciences, the following observations may be made:

World Ocean

There are no accurate data on the exact volume of the World Ocean, and various sources present figures ranging from 1 320 000 000 to 1 370 000 000 km^3 (Gleick, 1993), which differ by more than the sum of all other components of the balance. The figure of 1 338 000 000 km^3, which is cited by many recent references (Gleick, 1996; Shiklomanov, 1998; UNESCO, 1999; Pagano & Sorooshian, 2002, Babkin; 2003), has been adopted in Table 2. An inquisitive person has a hard time trying to figure out how this number was derived, and how it changes both on an inter-annual and an intra-annual basis. Little attention is usually devoted to relating this volume to the geoid—

the surface of the ocean has extensive gravitationally induced "hills" and "valleys", the shape of the hydrosphere due to astronomic factors, detailed sea-bed topography, temperature and compressibility, although all of them can affect this figure by millions of cubic kilometres. Gouretski & Kottermann (2007) report a water-level rise of 10 mm since 1950 due to thermal expansion, and NASA (2006) reports that the sea level has risen on average 3 mm per year since 1993.

The actual amount of *water* in the World Ocean is only around 1 320 000 000 km^3, due to the mineral content of sea water.

Groundwater

The amount of groundwater is not easy to compute and this item of the balance is arguably the most questionable. Firstly, there is a problem of the depth to which we apply our calculations. If we set an arbitrary level at say the usual 4000 m, there are aquifers deeper than that, and areas where deep groundwater occurs in large quantities. For example, the Kola Peninsula Superbore found huge quantities of hot, highly mineralized water at a depth of 13 km. Here, Table 2 follows Babkin (2003) and includes groundwater of Antarctica.

The groundwater figures will certainly require much more stringent substantiation in future, and need to reflect major reduction of groundwater storages due to extensive irrigation in India, China, the USA, and other parts of the World. As Becker (2006) explains, satellite-based remote sensing of groundwater is in its infancy, and has yet to become the quantitative tool that it has become for atmospheric, surface and oceanic water.

Glaciers

Many hydrological references, for example Babkin (2003), underestimate the volume of Antarctica's ice at 22 million km^3, when the correct figure is around 30 million km^3 (Siegert, 2000); similarly deflated figures are reported for Greenland. Table 2 presents more reliable estimates, following USGS (1999).

Glaciers do change significantly in time, and, especially now, are very sensitive to global warming. Any table giving the volume of glaciers should state the time of measurement to be meaningful. However, all standard references on global water resources, including the newest ones, dutifully report the volumetrics of the cryosphere from calculations derived in the 1950s, and frozen in time.

NASA (2006) reports that the mass of ice in Antarctica had decreased significantly from 2002 to 2005, enough to raise global water levels by 1.5 mm during this period. This corresponds to a volume of some 20 000 km^3, comparable to Lake Baikal. In addition to that, mountain glaciers lost over 6000 km^3 of volume between 1960 and 2002; this latter decrease is reflected in Table 2.

Lakes

Lakes deserve special attention as the most sensitive indicators of climatic changes (Kotwicki & Allan, 1998). The literature usually quotes the number of lakes on Earth as 8 million, meaning lakes bigger than 0.01 km^2 (Lehner & Döll, 2004). However, there are also staggering numbers of smaller lakes. Downing *et al.* (2006) estimate that there are 304 million lakes with an area greater than 0.001 km^2, with a total area of 4.2 million km^2, over three times larger than the most often quoted estimate of this area.

As Downing *et al.* (2006) further observe, on a global scale, with regard to lakes, rates of material processing (e.g. carbon, nitrogen, water, sediment, nutrients) by aquatic ecosystems are likely to be at least twice as important as had been previously supposed.

A further consequence for climate modelling, that stems from the large number of smaller water bodies, is hugely increased areas of *ecotones*—interface zones between different ecosystems that are brimming with biological and chemical activity (Kotwicki, 2001). Aquatic and terrestrial ecotones are characterised by a large biodiversity, while aquatic and atmospheric ecotones have the most intensive molecular exchange, estimated as 2–3 kg of water oscillating through one square metre of water–air interface per second.

As a footnote to this section, there is a separate class of lakes, about 145 of them found so far, located on Antarctica, under several kilometres of ice. At some 35 million years of age, they are the oldest lakes on Earth, and may present clues on how life develops. The largest, Lake Vostok, 240 km long, 60 km wide, and over 1 km deep, holds 5400 km^3 of water—more than Lake Michigan.

Wetlands

Definitions of wetlands, marshes, bogs, fens, swamps and peatlands do vary, as well as their reported local and global coverage (Lehner & Döll, 2004, Mitra *et al.*, 2005). There is little doubt, however, that the global area of these formations tends to be under-reported, due in part to a vast quantity of smaller wetlands which tend to be neglected, but *en gross* amount to very significant areas. The figure of 5.3 million km^2 quoted in Table 2 follows Mitra *et al.* (2005), and is more than twice as large as that reported by standard hydrological references. Wetlands are some of the most biologically productive ecosystems on the Earth, comparable to rainforests and coral reefs.

Biological water

The biological water is of obvious interest because living organisms, along with the atmospheric water, affect the hydrological cycle many orders of magnitude more than equivalent quantities of water in other components of the cycle. The figure of 1220 km^3 quoted in many references and discussed in Babkin (2003) is non-representative since it assumes that 90% of the water is in forests, the biomass of which contains 80% water. It is now understood that a large portion of the global biomass consists of unicellular organisms and other microorganisms. Since it is estimated that 10–50% of all biomass on Earth resides deep below ground (Anitei, 2006), the figure in Table 2 was increased to 2400 km^3 to reflect the upper limit of this range. This is further justified by the fact that wetlands contain much more biomass than was previously thought.

Reservoirs

Man-made reservoirs are usually not listed in water balances of Earth, presumably being combined with lakes, but more probably just ignored. Downing *et al.* (2006) estimate that there are 515 thousand impoundments, with an average area of 0.52 km^2, and a total area of 260 000 km^2. The 25 000 largest reservoirs hold 6815 km^3 of water, out of 7000 km^3 held in all reservoirs, and lose 1–2% of storage capacity annually due to siltation. Babkin (2003) reports that reservoirs of over 1 million m^3 store 5750 km^3, and cover 400 000 km^2.

Farms

Downing *et al.* (2006) estimate that 77 000 km^2 are covered by farm ponds. There are also over 1.3 million km^2 of rice paddies worldwide. Therefore, the open water surface area of agricultural facilities covers around 1% of the total land area, and probably more, due to all the water conveyance facilities and other irrigation and drainage works.

Desalination

Desalinated water is not a storage *sensu stricto*; however, it is a resource. The current production of desalinated water stands at 10 km^3 per year and can be considered in conjunction with Table 2 to give some perspective to human endeavours.

Atmospheric water

The genesis of the figure expressing the amount of water in the atmosphere is *one inch of water vapour over the surface of the planet,* which may call for its more stringent substantiation, especially in terms of variability. Trenberth *et al.* (2003) point out that, as climate warms, the amount of moisture in the atmosphere is expected to rise faster than the precipitation amount, which is governed by the surface heat budget through evaporation. This implies that the main changes to be experienced are in the character of precipitation: increases in intensity must be offset by decreases in duration or frequency of events. Ma *et al.* (2009) note that, according to the Clausius-Clapeyron equation, one might expect the global mean precipitation and evaporation to increase at a rate of 7% per 1°C surface warming, but the IPCC models actually simulate a muted response by the hydrological cycle that may contribute to the amount and uncertainty of predicted warming.

Not accounted for

Certain water storages and open water surfaces are usually not considered at all. They include, for example, water stored in sediments, the voluminous difference between ice and liquid water, changes of volume due to temperature and salinity variations, water and wastewater in municipal networks and facilities, water in open irrigation conduits and flooded fields, minor streams, and probably many others.

Some of these amounts are huge. For example, sediments, which average half a kilometre depth over the World Ocean, and sizeable thicknesses under water storages on lands, typically contain plenty of water.

Fluxes

As Kidder & Jones (2007) observe, satellites offer the only way to observe the global distribution of meteorologically important parameters. Water fluxes are of paramount importance in climate modelling and many hydrological applications, yet many of them are not known precisely. For example, it is known but rarely acknowledged that raingauges underestimate the true rainfall, possibly by 15%, due to a number of measurement deficiencies. If such measurements are used for truthing of remote sensing techniques, the resulting fluxes are prone to errors too. If we accept that the true rainfall is actually higher than measured, our figures for all atmospheric fluxes, especially evaporation, are erroneous, and the components of the energy balance of the planet have somewhat different values to what we currently believe. Global models of weather and climate are often not constrained spatially and temporally by stream discharge and surface storage measurements, and as Roads *et al.* (2003) report, the predictions of runoff by numerical weather prediction and climate models are often in error, differing from observations by 50%, and even 100%. Widén-Nilsson *et al.* (2007) observe that modelling progress will depend on improved global data sets of precipitation and runoff.

While major fluxes of groundwater can be monitored from space, other specifics of groundwater need to be taken care of too. For example, direct groundwater runoff to the World Ocean is rarely taken into consideration.

When the water balance of the whole planet is contemplated, water fluxes between the hydrosphere and the interior of Earth need to be much better understood. Aubaud & Hirshmann (2003) found that both the upper mantle and oceans have been profoundly affected by recycling of water, and that water in the upper mantle is dominated by a recycled component.

Area of open water on Earth

The total area of open water surfaces on land amounts to 13 million km^2, that is 8.8% of the total land area, or 9.8% if we exclude glaciers and permanent snow cover areas.

Most textbooks say that 70.84% of Earth is covered by water. The correct figure is actually much greater, at least 73.4% for open water surfaces, or 76.5% if we add ice.

Time

It stands to reason that many terms of the water balance of Earth change daily and seasonally. For example, a snow cover over the Northern Hemisphere in January locks up thousands of cubic kilometres of water, the area covered by sea ice fluctuates by tens of million of square kilometres, major floods are quite voluminous, and astronomic forcings move huge quantities of water around.

It would be desirable to compute the water balances of Earth on a monthly basis to see the variation of these storages and fluxes. For example, Van Hylckama (1970) noted that there is considerable seasonal variation in the global water balance, with 6000 km^3 more water stored on the land in March than in September, 6000 km^3 more water stored in the ocean basins in October than in March, and 600 km^3 more water stored in the atmosphere in September than in March. Dobslaw & Thomas (2007) present interesting insights on the time-variable total ocean mass.

Another issue is the monitoring of long-term changes of these variables to get a picture of the effects of climatic changes and global warming. Nobody would question the practicality of having exact figures on global water storages month after month and year after year, so the real question is: how quickly we can convince ourselves that we can do it?

CONCLUSIONS

A score of geophysics and planetary disciplines are busy refining the history of water accumulation and presence in the interior of the Earth and its hydrosphere, and we can expect excellent new developments in this field.

While most of considerations of water resources are concerned with volumes, and justly so, it is the surface area of open waters which dictates water exchange between the surface of Earth and its atmosphere. Newest estimates quoted in this paper indicate that this surface area is twice as large as usually acknowledged. For example, Shiklomanov & Rodda (2003) give this area as 6.5 million km^2, while it amounts to 13 million km^2 in Table 2, an increase of well over two Mediterranean seas.

This paper demonstrates that the area of open water surfaces on land is at least 10% greater than quoted by recent hydrological references, which has obvious implications for climatic models and a range of other applications.

It would be highly desirable to tighten the terms of the water balance of the Earth, following the comments to Table 2, presented in the Section on *The water balance of the hydrosphere*.

Water on Earth is in a state of constant flux and this fact will be reflected in future versions of water balances of Earth. The static version of the water balance, such as presented in Table 2, may serve as an illustration at an introductory level, but the accelerating development in science and the ever increasing need to account for quickly dwindling water resources *per capita* will soon result in much more sophisticated solutions. The monthly water balance of Earth is an obvious candidate for speedy implementation, and there are no conceivable technological or other constraints that would preclude the development of the real-time water balance of Earth, reported online on a dedicated website. Such a tool, that possibly combines real-time observations and modelling, may require only a fraction of the resources assigned to long-term weather forecasting, yet would allow real-time monitoring of the status of water in catchments, states, and the whole planet, and would be a truly magnificent achievement of science and technology, an extremely handy and invaluable tool for water and related professionals, and an excellent public awareness exercise helping people to appreciate our most valuable resource—water. Because, as Bodnar (2005) succinctly puts it: *Water is the most valuable resource on Earth today, more valuable than diamonds, or gold, or petroleum, or any of the countless other resources produced and used by humankind.*

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