Global water balance – can we refine it?

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Abstract

The paper reviews new developments in geophysics and planetary disciplines on water accumulation and presence in the interior of the Earth and its hydrosphere and presents a compact picture of the occurrence of water on Earth, including the temporal development of water resources of the planet, current water balance, and the future of water on Earth. In examining of 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. While most of considerations of water resources is concerned with volumes, it is the surface area of open waters which dictates water exchange between the surface of Earth and its atmosphere. The paper demonstrates that the area of open water surfaces on land is at least 10% higher than quoted by recent hydrological references, which has obvious implications for climatic models and a range of other applications. The paper stresses the need for improvements in our understanding of the hydrological cycle and presents several conclusions on the ways of improving the monitoring of long-term changes of these variables to get a coherent picture of effects of climatic changes and global warming.

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 standard references and encyclopedias may serve as an illustration at an introductory level, but the accelerating development in sciences and the ever increasing need to account for quickly dwindling water resources *per capita* will soon result in much more sophisticated solutions. 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?

Keywords:
Water, water balance, water balance of Earth, water cycle, planetary water cycle, hydrological cycle, hydro-tectonics, Earth, Solar System.

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 an existence of the immense underground ocean, and in an allegoric or cosmological sense were actually not that far from truth taking into considerations 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 circulations 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 that for example 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 it will be demonstrated later, some of the traditionally accepted figures are, or have became recently, grossly incorrect.

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, the hydrologists receive a most 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 (IPCC, 2008) that the global warming will reduce water supplies in many areas, at times when both the global population and demand for water is increasing at an unprecedented pace. It is about time that we begin to take a very detailed stock of our water.

The hydrological cycle forms a 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.

A short history of water on Earth

The understanding of the history of Earth improved dramatically over the last decade (Valley, 2006). Our existence can be traced to a molecular cloud of gas and dust, some 50 light year 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 of years. The Solar System is 4.567 billions years old (Valley, 2006). The Earth accreted most of its mass within a mere 10 million years, and the Sun begun to shine, entering the Main Sequence, within 50 million years (Zahnle, 2006) just about the time when the proto-Earth collided with a Mars-size object (Koeberl, 2006) code-named Theia, in an apocalyptical event which resulted in the creation of a 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 yet, and therefore, the Solar System may be considered as a standalone 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). Michael *et al* (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 deliver an ocean of water to Earth after the Moon forming impact is small.

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.

The example of Venus, a twin planet of Earth may illustrate this point. Venus accreted on an orbit which could have less volatiles due to its proximity to the Sun. Whatever water it accreted nevertheless, and whatever were latter cometary additions, was 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.

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

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 (Russel and Arndt, 2005).

We do not know whether life originated on Earth or was seeded here from outer space and if we will 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 sometime before 3.5 billion years ago, possibly around 4 billion years ago. Since its emergence, life had shaped to a large degree 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 contents of the planet, and the time when the Earth gets dry. As we can see from a conceptual presentation of the incidence of water on Earth in Figure 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.

Bounana *et al* (2001) explains that the fate of the Earth's ocean is sealed by external forcing. All water will disappear as a result of increasing global temperature caused by increasing solar luminosity. First assessments suggest that a catastrophic loss of water will begin in 1.3 billion years from the present 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 of 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.

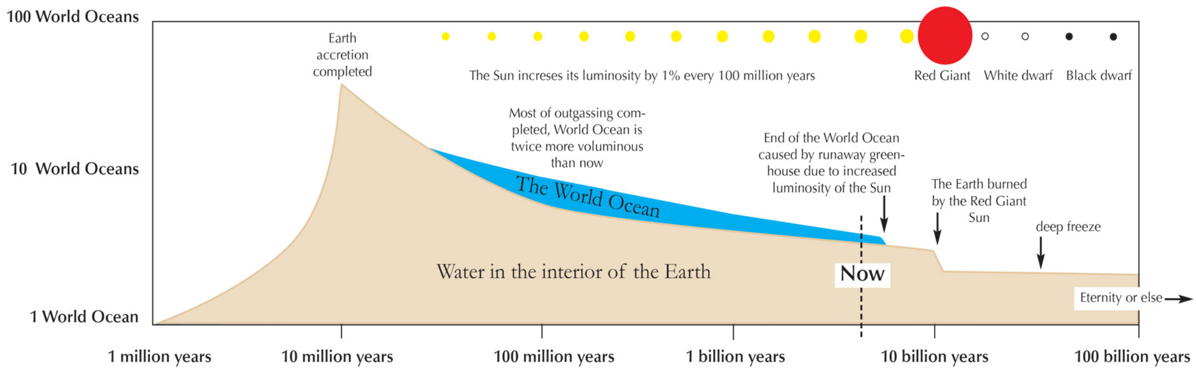

Figure 1. Conceptual water balance of Earth over the lifetime of our planet on a log-log scale

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 observer, unless by some cosmic collision it becomes incorporated into another celestial entity.

Water exchange with outer space

While the Earth loses water to the outer space, Kasting (1989) calculates at the present escape rate it would take 7 billion years to lose the World Ocean, which corresponds to the 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 $year^{-1}$ (Bounana *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, there 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 cycle 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 reticulated through the mantle in a year, then the World Ocean has been already reticulated 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 and 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: Bounana *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 Bounana *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 an 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 is 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 to determine monthly water storage changes for areas of 200 000 km^2, including changes in groundwater storage. It may help to reveal 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 measure the surface of the World's ice sheets and glaciers, and Aqua mission to detect soil moisture.

Table 2. Water balance of Earth (modified from various sources)

Form of water	Area	Volume	% of total water volume	% of fresh water volume
	km^2	km^3	%	%
Salt water	**510 065 600**	**1 352 085 000**	**96.81%**	
World Ocean	361 126 400	1 338 000 000	95.80%	
Saline groundwater	148 939 100	14 000 000	1.002%	
Salt lakes	820 000	85 000	0.006%	
Ice	**36 821 400**	**33 437 000**	**2.394%**	**75.02%**
Glaciers	15 821 400	33 137 000	2.373%	74.34%
Antarctica	13 586 400	30 100 000	2.155%	67.53%
Greenland	1 785 000	2 620 000	0.188%	5.88%
Arctic islands	230 000	83 000	0.00594%	0.19%
Mountains	220 000	34 000	0.00243%	0.08%
Permafrost	21 000 000	300 000	0.02148%	0.67%
Freshwater	**510 065 600**	**11 123 500**	**0.79644%**	**24.96%**
Fresh groundwater	148 939 100	11 000 000	0.78759%	24.68%
Lakes	4 200 000	91 000	0.00652%	0.20%
Soil moisture	148 939 100	16 000	0.00115%	0.04%
Wetlands	5 300 000	12 000	0.00086%	0.03%
Rivers	1 000 000	2 100	0.00015%	0.005%
Biological water	510 065 600	2 400	0.00017%	0.005%
Reservoirs	400 000	7 000	0.00050%	0.016%
Farms	1 400 000	600	0.00004%	0.0013%
Desalination - annual		10	0.0000007%	0.00002%
Atmospheric water	**510 065 600**	**12 900**	**0.00092%**	**0.029%**
Hydrosphere total	**510 065 600**	**1 396 000 000**	**100%**	**100%**
Earth's interior	510 065 600	7 000 000 000	~ 5 World Oceans	

Table 2 shows the water balance of Earth, modified from several sources (Kotwicki 1991, Gleick, 1993, Shiklomanov 1998, UNESCO, 1999, Pagano and Sorooshian, 2002, Babkin, 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 and Jenkins (1998), USGS (1999), Lehner and Döll (2004), and Mitra *et al* (2005).

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 may 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 literature and in line with the currents developments in hydrology and other Earth sciences the following observations may be made:

World Ocean

There is no accurate data on the exact volume of the World Ocean, and various studies present figures ranging from 1 320 000 000 to 1 370 000 000 km^3 (Gleick, 1993) which differ 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 (Shiklomanov, 1998, UNESCO, 1999, Pagano and Sorooshian, 2002, Babkin, 2003) has been adopted in Table 2 for the lack of a better one. An inquisitive person has a hard time trying to figure out how this number was derived, and how it changes both on interannual and intraannual basis. Little attention is usually devoted to relate this volume to the geoide – the surface of the ocean has extensive "hills" and "valleys" - or temperature variations, although both of them can affect this figure by millions of cubic kilometres of water. Gouretski and Kottermann (2007) report water level rise of 10 mm since 1950 due to thermal expansion, and NASA (2006) reports that sea level has risen on average 3 mm per year since 1993.

The actual amount of *water* in the World Ocean is only around 1 290 000 000 km^3 anyway, due to the mineral contents 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 a depth to which we apply our calculations. Whether 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 the depth of 13 km. Here, Table 2 follows Babkin (2003) and includes groundwater of Antarctica.

Most certainly, groundwater figures will require much more stringent substantiation in future, and include major reduction of groundwater storages due to extensive irrigation in India, China, the US, and other parts of the World. As Becker (2006) explains, satellite-based remote sensing of groundwater is in its infancy, and remote sensing 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): a similarly deflated figures are reported for Greenland. Table 2 presents more reliable figures, 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 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 level by 1.5 mm during this period. This corresponds to the volume of some 20 000 km^3, comparable to Lake Baykal: in addition to that mountain glaciers lost over 6000 km^3 of volume between 1960 and 2002, with this latter decrease reflected in Table 2.

Lakes

Lakes deserve special attention as the most sensitive indicators of climatic changes (Kotwicki and Allan, 1998). The literature usually quotes the number of lakes on Earth as 8 million, and by this, it understands lakes bigger than 0.01 km^2 (Lehner and 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 the 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.

Further importance 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 aquatic and atmospheric ecotones have the most intensive molecular exchange out of all terrestrial ecotones.

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 a kilometre 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 and Döll, 2004, Mitra *et al,* 2005). There is little doubt, however, that the global area of these formations tends to be underreported, 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 larger than 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 cycles 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 water is the forests, the biomass of which contains 80% water. It is understood now that a large portion of biomass consists of unicellular organisms and other microorganisms. Since it is estimated that 10 to 50% of all biomass on Earth resides deep below ground, 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 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 the 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 loosing 1-2% annually due to siltation. Babkin (2003) reports that reservoirs over 1 million m^3 store 5750 km^3, and cover 400000 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, an open surface area of agricultural facilities covers around 1% of total areas of lands, and probably more due with all water conveyance facilities and other irrigation and drainage works.

Desalination

Desalinated water is not a storage *sensu stricto,* however, it is a resource, and is given in Table 2 to give some perspective to human endeavours.

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 over the World Ocean, and sizeable thicknesses under water storages on lands, typically contain plenty of water.

Fluxes

As Kidder and 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 modeling and many hydrological applications, yet many of them are not known precisely. For example, it is known but rarely acknowledged that rain gauges 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 of all atmospheric fluxes, especially evaporation, are erroneous, and the components of the energy balance of the planet have somewhat different values than we 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) reports, the predictions of runoff by numerical weather prediction and climate models are often in error with observations by 50%, and even 100%. Widén-Nilsson *et al.* (2007) observe that modeling progress will depend on improved global datasets of precipitation and runoff.

While major fluxes of groundwater can be monitored from space, other specifics of groundwater need to be taken care off too. For example, significant quantities of freshwater discharged into the World Ocean below mean sea water level are 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 and Hirshmann (2003) find out 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 lands amounts to 13 million km^2 that is 8.70% of the total land area (or 9.75% if we exclude glaciers and permanent snow cover areas).

Most textbooks say that 70.84% of Earth is covered by water. The correct figure, as it adds up in Table 2, is actually much higher, at least 73.37%, for open water surfaces, or 76.47% if we add ice.

Time

It stands to reason that many terms of the water balance of Earth change daily and seasonally. Say, a snow cover over the northern hemisphere in January locks thousands cubic kilometres of water, area covered by sea ice fluctuates by tens of million of square kilometres, major floods are quite voluminous, and astronomical forcings move huge quantities of water around. It would be desirable to compute water balances of Earth on a monthly basis to see the variation of these storages and fluxes. Dobslaw and Thomas (2007) present interesting insights on time-variable total ocean mass.

Another issue is the monitoring of long-term changes of these variables to get a picture of 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 with 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, and justly so, is concerned with volumes, 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 larger than usually acknowledged. For example, UNESCO (1999) gives this area as 6.5 million km^2, while these areas amount to 13 million km^2 in Table 2, an increase of well over two Mediterranean seas.

The paper demonstrates that the area of open water surfaces on land is at least 10% higher 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 comments to Table 2, presented in Section *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 sciences 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, available online on a dedicated website. Such a tool, that possibly combines real-time observations and modeling, may require only a fraction of resources assigned to long-term weather forecasting, and allowing real-time monitoring of the status of water in catchments, states, and the whole planet will 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.

References

Abe, Y., Ohtani, E., Okuchi, T., Righter, K., and Drake, M. (2000) Water in the Early Earth. In: Canup, R.M. and Righter, K. (Eds) *Origin of the Earth and Moon,* University of Arizona Press, Tucson:413-433.

Aubaud, C. and Hirschmann, M. M. (2003) Why is the Ocean heavy? American Geophysical Union, Fall Meeting 2003, No V51K-05.

Babkin, V.I. (2003) The Earth and its physical features. In Shiklomanov, I.A., and Rodda, J.C. (Eds) *World Water Resources at the Beginning of the Twenty-First Century.* Cambridge University Press, International Hydrology Series, 1-18.

Bodnar, R.J. (2005) Fluids in planetary systems. *Elements,* **1**(1): 9-12.

Becker, M.W. (2006) Potential for satellite remote sensing of ground water. *Ground water,* **44**(2):306-318.

Bounama, C., Franck, S., and von Bloh, W. (2001) The fate of Earth's ocean. *Hydrology and Earth System Sciences,* **5**(4):569–575.

Cavosie, A.J., Valley, J.W., and Wilde, S.A. (2005) Magmatic d^{18}O in 4400–3900 Ma detrital zircons: A record of the alteration and recycling of crust in the Early Archean. *Earth and Planetary Science Letters*, **235**:663-681.

Condie, K.C. (1989). Origin of the Earth's crust. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)*, **75**:58-81.

Copernicus, N. (1543) *De revolutionibus orbium coelestium.* Nüremberg Johannes Petreius. Engl.trans. E.Rosen. *On the revolutions.* The John Hopkins University Press, Baltimore, 1978, 450pp.

Deming, D. (1999) On the possible influence of extraterrestrial volatiles on Earth's climate and the origin of the oceans. *Palaeogeography, Palaeoclimatology, Palaeoclimatology*, **146**:33–51.

Dixon, J. (2003) Temporal evolution of water in the mantle. *Geophysical Research Abstracts,* Vol. 5, 04395.

Dobslaw, H., and Thomas, M. (2007) Impact of river run-off on global ocean mass redistribution. *Geophys.J.Int,* **168**:527-532.

Downing, J. A., Prairie, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., Striegl, R. G., McDowell, W. H., Kortelainen, P., Caraco, N. F., Melack, J. M., and Middelburg, J. J. (2006) The global abundance and size distribution of lakes, ponds, and impoundments. *Limnol. Oceanogr.,* **51**(5):2388–2397.

Drake, J.M., and Campins, H. (2005) Origin of water on the terrestrial planets. *Proceedings of the International Astronomical Union,* **1**:381-394, Cambridge University Press.

Gleick, P.H. (Ed) (1993) *Water in crisis: a guide to the World's fresh water resources.* Oxford University Press, 473pp.

Gouretski. V., and Koltermann, K.P. (2007) How much is the ocean really warming? *Geoph.Res.Lett., 34,* L01610.

Halliday, A.N. (2006) The origin of the Earth: what's new? *Elements,* **2**(4):205-210.

Intergovernmental Panel on Climate Change (2008) *IPCC Technical Paper on Climate Change and Water.* Draft for Government and Expert Review. April 2008. 146pp.

Kasting, J.F. (1989). Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus,***74**:472-494.

Kidder, S.O., and Jones, A.S. (2007) A blended satellite total precipitable water product for operational forecasting. *J.Atmosph.Ocean.Technology,* **24**:74-83.

Koeberl, C. (2006) Impact processes on the early Earth. *Elements,* **2**(4):211-216.

Kotwicki, V. (1991) Water in the Universe. *Hydrol.Sci.J.*, **36**:49-66.

Kotwicki, V. (2001) Hydrological processes and land/water ecotones. *Ecohydrology and Hydrobiology,* **1**(1-2):155-160.

Kotwicki, V., Allan, R. (1998) La Niña de Australia - Contemporary and palaeohydrology of Lake Eyre. *Palaeogeography, Palaeoclimatology, Palaeoclimatology,* **144**:265-280.

Lehner, B. and Döll, P. (2004): Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology,* **296**(1-4):1-22.

Mitra, S., Wassmann, R., and Vlek, P.L.G. (2005) An appraisal of global wetland area and its organic carbon stock. *Current Science,* **88**(1):25-35.

Murakami, M., Hirose, K., Yurimoto, H., Nakashima, S. & Takafuji, N. (2002) Water in Earth's lower mantle. *Science*, **295**:1885-1887.

NASA (2006) What's up with sea level? http://sealevel.jpl.nasa.gov/newsroom/features/200606-1.html

Nittler, L.R. (2003) Presolar stardust in meteorites: recent advances and scientific frontiers. *Earth and Planetary Science Letters* **209**:259-273.

Nutman, A.P. (2006) Antiquity of the oceans and continents. *Elements,* **2**(4), pp223-228.

Pagano, T., and Sorooshian, S. (2002) Hydrologic Cycle. In Munn, T. (Ed) *Encyclopedia of Global Environmental Change. Vol 1, The Earth system: physical and chemical dimensions of global environmental change,* John Wiley & Sons, pp450–464.

Roads, J., Bainto E., Kanamitsu M., Reichler T., Lawford R., Lettenmaier D., Maurer E., Miller D., Gallo K., Robock A., Srinivasan G., Vinnikov K., Robinson D., Lakshmi V., Berbery

H., Pinker R., Li Q., Smith J., von der Haar T., Higgins W., Yarosh E., Janowiak J., Mitchell K., Fekete B., Vorosmarty C., Meyers T., Salstein D., Williams S. (2003) GCIP Water and Energy Budget Synthesis (WEBS), *J Geophys. Res.,* **108** D16, 8609, 10.1029/2002 JD002583.

Ringwood, A.E. (1975). *Composition and Petrology of the Earth's Mantle.* McGraw-Hill Book Company, New York. 618pp.

Russell, M.J. and Arndt, N.T. (2005) Geodynamic and metabolic cycles in the Hadean. *Biogeosciences* **2**:97-111.

Rüpke, L.H. (2004) *Effects of plate subduction on the Earth's deep water cycles.* PhD Dissertation, Christian-Albrechts-Universität zu Kiel.

Schopf, J.W. (2006) The first billion years: When did life emerge? *Elements,* **2**(4), pp229-233.

Siegert, M.J. (2000) Antarctic subglacial lakes. *Earth-Science Reviews,* **50**:29–50.

Shiklomanov, I, (1998) *World water resources - A new appraisal and assessment for the 21st century.* UNESCO, 40pp.

Smyth, J.R., and Jacobsen, S.D. (2006) Nominally Anhydrous Minerals and Earth's Deep Water Cycle. American Geophysical Union, *Geophysical Monograph Series.*

UNESCO (1999) World water resources at the beginning of the 21st century. CD version, UNESCO, Paris.

USGS (1999) *Estimated present-day area and volume of glaciers and maximum sea level potential.* http://www.smith.edu/libraries/research/class/idp108USGS_99.pdf, accessed on 20 May 2007.

Van Andel, T.H. (1985). *New views on an old planet.* Cambridge University Press, 321pp.

Valley, J.V. (2006) Early Earth. *Elements,* **2**(4):201-204.

Widén-Nilsson, E., Halldin, S, and Xu, Chong-yu (2007) Global water-balance modelling with WASMOD-M: Parameter estimation and regionalisation. *Journal of Hydrology,* **340**(1-2):105-118.

Zahnle, K.J. (2006) Earth's earliest atmosphere. *Elements,* **2**(4):217–222.