Marcinek, J. (2007): Hydrological cycle and water balance - A global survey. In: Lozán, J. L., H. Grassl, P. Hupfer, L.Menzel & C.-D. Schönwiese. Global Change: Enough water for all? Wissenschaftliche Auswertungen, Hamburg. Online: www.klima-warnsignale.uni-hamburg.de

1.3 Hydrological cycle and water balance – A global survey

JOACHIM MARCINEK

SUMMARY: *The hydrologic cycle is the main phenomenon of hydrology. Only water, mostly drinking water, will be renewed in this cycle very quick and continuous. Gigantic quantities of water are present, from which the hydrologic cycle takes the water. The history of hydrologic cycle is very long and interesting. The knowledge of hydrologic cycle in form of today was born in the renaissance. So Leonardo da Vinci is named »father of the science of water«. Now in beginning of the 20th century E. Brückner presented the first water balance of the Earth (1905). The newest water balance is the water balance from R. K. Klige et al. from 1998, published in 2000. She is shown also in a scheme of hydrologic cycle.*

All water on our planet moves in a global cycle. The sun's energy and gravitation continuously modify the geographic position and physical state of water. The hydrological cycle is based on the law of nature and is a permanent and self-contained process of circulation of water on the globe. The total quantity of water is nearly constant. Water entering the cycle (juvenile water from volcanic eruptions) corresponds to the quantity of water that is leaving the hydrological cycle by ways of chemical binding (vadose water). The definition of a water balance is the interaction – whether in a specified area or on the entire planet – of factors such as precipitation (P), return (R), evaporation (E), reserve and consumption. The interaction of all the individual elements of the hydrological system is the foundation for the science of water-hydrology.

How much water is there in the hydrological cycle? The science of water has been conducting research on this important question for over 100 years. No correct answer has so far been found.

The water cycle – a long, but interesting story

»The current of water from the mountains down to the valleys, from land to sea – we witness its endless flow, yet sea levels don't rise and wells and streams never run dry«

> *»Den Lauf der Wasser von den Bergen zu den Thälern, von dem Lande zum Meere sehen wir unaufhörlich vor unseren Augen sich vollziehen, und dennoch wird das Meer nicht voller und die Quellen und Ströme versiegen nicht«* (PFAFF 1878, S. 33).

The reason behind this natural phenomenon, the result of permanent integration and interaction of our planet's atmosphere, hydrosphere, and lithosphere is the hydrological cycle. From the vastness of our oceans (361.1 million km²) it acts upon the much smaller continents (148.9 million km²). By extending the cycle from the sea over to the land the continents are being integrated. The cycle is then closed through the return flow from rivers to the oceans and water vapour moving from land to sea.

Today it is common knowledge that the hydrological cycle is driven by the sun's energy. For a very long time, however, people had no understanding of the origins of the global flow of water and the hydrological cycle.

Thales of Milet (600 B.C.), the ancient Greek philosopher, realised, that water is the most important factor for the existence of life on the planet. He believed in a subterranean river system connecting to the Okeanos, the ocean – as did other ancient Greek scholars. Water was to be renewed while passing through it before reaching the seas. He considered the world to be a disk swimming on top of the ocean. The continuous renewal of water was a movement of sea water through it. He believed that sea water, while moving through the disk-like Earth, turned to freshwater.

Limestone with its maze of underground riverbeds, always resurfacing and disappearing deep down below, allowed for these views to emerge. No wonder that such ideas dominated ancient Greek thought.

Other Greek scholars believed, that water was partially renewed by precipitation while running down towards the sea. But they also shared the view that rivers were partially fed by underground water reservoirs that received their water from the sea. They believed in the existence of long underground river systems connected to surface rivers.

Even Aristotle, the most famous ancient Greek scientist (384–322 B.C.) rejected the idea that precipitation and the seeping in of water into the ground could create a renewal process or produce groundwater. He was surrounded by underground caves and therefore thought that water was formed in hollows, where it cooled down and separated from the air (condensation).

Finally, Seneca (4 B.C.–65 A.C.) contested the valuable idea brought forward by his contemporary Vitruv whereby all spring water should be considered as rainwater that has seeped into the ground.

In medieval times a number of original ideas appeared. They were added to the ancient views still circulating. Permitted were only those findings that corresponded to the Bible which was considered sacrosanct.

It was believed that the waters of Paradise were the source of all rivers. People liked to think of underground streams linked to the Garden of Eden. But gradually scholars returned to the idea of their ancient masters – it is the ocean that feeds all rivers and streams.

There is a passage in the Bible, where in Ecclesiastes

I, 7 it says: »All streams run into the sea, yet the sea never overflows. Back to the place from which the streams ran they return to run again«. Progress in hydrology had to wait.

»Alle Flüsse gehen zum Meere, und doch wird das Meer nicht voll; an den Ort, wohin die Flüsse gehen, dahin gehen sie immer wieder«, hemmte die Entwicklung der Gewässerkunde (Die Stelle in Prediger Salomo. Die Heilige Schrift – Zürcher Bibel – Lizenzausgabe 1951. 2. Aufl. Der Prediger – Das beständige Einerlei im Kreislauf aller Dinge, I,7).

The idea of a sea that is unknown, a sea that is the source of all seas allowed for an abundance of speculation. There were discussions on subterranean channel connections, evaporation of sea water, its subsequent precipitation, infiltration and collection in huge underground hollows. The well-respected German medieval scholar Albertus Magnus (Graf von Bollstädt, 1193–1280 A.C.), not unlike Aristotle before him, was unable to remain clear of the popular beliefs of his time.

It was only during the Rennaissance period (around 1500), when Leonardo da Vinci discovered the different features of the hydrological cycle. But there was no response to his findings. Finally views changed, when de la Métherie put forward his principle on the hydrological cycle which is still valid today (de la Métherie-Eschenbach: Theory of the Earth, ll. Leipzig, 1797).

And during the 19th century the view that the renewal of continental water was due to the hydrological cycle became more and more popular. It now had its place in the geographic literature (see Daniel, H.A., Handbuch der Geographie, Leipzig 1866, where he explains the hydrological cycle in contemporary fashion).

Thus, with the discovery of the hydrological cycle, the origin of water on land was known

MURRAY (1887) was the first to publish a study which lead the way for subsequent research. He clearly explained the hydrological cycle and water balance for the land surfaces as well as for the entire planet. E. BRÜCKNER (1887, 1900) confirmed Murray's findings by contributing extensive scientific proof. In his research, BRÜCKNER found a formula that represented the Earth's water balance by creating water equations for land and sea each. Eventually he managed to determine the quantities of water (precipitation and evaporation for land and sea, as well as return from the land) to create a water balance for the entire planet.

Hydrological cycle and water balance research

By the end of the 19th century the understanding of the Earth's hydrological cycle had progressed enough to not only generally recognise its cyclic nature, but to also profoundly discuss and find answers to what a water balance is and what the quantities affected by it are.

Even WOEIKOF (1887) believed, that there had to be a balance in the quantity of waters within the hydrological cycle. He estimated, that one quarter of the precipitation returned by land to the sea and three-quarters evaporated. Eventually he limited his statement by adding, »...or was partially lost for the circulation of waters«

Anschließend engte WOEIKOF aber diese Aussage mit den Worten ein »...oder auch teilweise für die Wasserzirkulation verloren gehen« (1887, 1. Teil, S. 50).

MURRAY, in contrary, was far more consistent, when he published an article discussing total annual precipitation on the planet's land surfaces and how it related to annual return by rivers. He examined a number of potential factors that could have an impact on the global water balance, gave them their due place in the system and excluded those he considered insignificant. As a consequence his work resulted in the first textual formulation of the hydrological cycle and the water balance for land areas as well as the whole planet.

By using a precipitation chart put together by E. LOOMIS (1882 or 1883), MURRAY calculated the average annual precipitation on land and – using two methods – the average annual return from the land to the sea.

In the same year (1887) BRÜCKNER commented on MURRAY's work in the German Meteorological Journal (p.63/64) and added two amendments. Based on MURRAY's work (1) he calculated the return from land in belts of 10° latitude. And according to the way how MURRAY had described the global water system, he was now in the position (2) to determine the difference between evaporation from the land and precipitation and return in belts of 10° latitude.

In 1900 BRÜCKNER estimated the relationship between groundwater and river water as follows (p. 91): »It is difficult to estimate the importance of submarine springs. The role they play, however, is minor as surfacing of upper groundwater along coastlines has to happen on the same level as the return of river water to the oceans – on sea level. Groundwater and river water mix in the last moment«

»Die Bedeutung unterseeischer Quellen entzieht sich allerdings der direkten Schätzung; doch dürfte sie schon deswegen gering sein, weil das Austreten des oberen Grundwassers an den Küsten in gleichem Niveau stattfinden muss, wie die Einmündung des Flusswassers – im Meeresniveau; das Grundwasser vereinigt sich hier noch im letzten Augenblick mit dem Flusswasser«.

MURRAY's and BRÜCKNER's view on groundwater was nearly unanimous. Because of its interaction with surface water, groundwater was generally seen as part of the total runoff from the rivers.

Much more important for a proper balance between oceans and land areas was another statement in BRÜCKNER's article (1900, p.93): »The quantity of water contained in the oceans must be considered constant for longer periods of time. Otherwise the water level would fluctuate to such an extent, that it could be easily observed. Thus the quantity of water returned to the ocean must be equal to the loss by evaporation«

»Die Wassermasse des Ozeans muss innerhalb längerer Zeiträume als konstant angenommen werden; andernfalls würden allgemeine Veränderungen des Wasserstandes erfolgen, die sich der Wahrnehmung nicht hätten entziehen können. Es muss also ebensoviel Wasser dem Ozean zurückgegeben werden, als ihm durch Verdunstung entzogen wird«[2].

The last part of the quotation is identical with MURRAY. In the first part of his quotation Brückner raises a point that until today remains important for the calculation of water balances between oceans and land surfaces. The related footnote is as follows: »If there was a reduction to oceanic waters equal to 2% of average annual rainfall onto the Earth's land areas, or 20 mm of rain, the overall water level would sink just over 1cm, in 10 years around 10 cm. Even a decrease of a fracture (1/4–1/5) of that amount could hardly have escaped our observation«

(Würden jedes Jahr nur 2% des mittleren jährlichen Regenfalls der Landflächen der Erde, also 20 mm Regen, dem Ozean dauernd entzogen werden, so müsste der Wasserstand überall jährlich um etwas über 1 cm, in 10 Jahren also um etwa 10 cm sinken. Selbst ein Sinken um einen Bruchteil (1/4–1/5) dieses Betrages hätte der Beobachtung schwerlich entgehen können) (BRÜCKNER, 1900, S. 93. Fußnote [2]*).*

In 1905 BRÜCKNER managed for the first time to express the global water system by creating a basic formula for the land surfaces and the oceans each while still showing the interaction between the two. Today German literature is using different symbols shown in parentheses in the quotations.

In order to show a balance of the hydrological cycle, the following items need to be taken into consideration:

Annual evaporation from the sea (=EM)
Annual rainfall over the sea (=PM)
Annual amount of water vapour moving from sea to land (=VM)
Annual evaporation from the land (=EL)
Annual rainfall over the land (=(PL)
Annual amount of water vapour moving from land to sea (=VL)
Annual return of rivers to the ocean F (=RL)
(All these items are expressed in cubic kilometres of liquid water).

If we can assume that the hydrological cycle is in a stationary state, then those seven items are related in such a way that the knowledge of three of them allows for the calculation of two others. The two remaining can be entirely ignored. Rainfall on the sea equals evaporation on the sea, reduced by the amount of vapour moving from the sea to the land and augmented by the amount of vapour moving from the land to the sea. Rainfall on the land equals the amount of evaporation moving from the sea to the land, augmented by the amount of evaporation on the land and reduced by the amount of vapour moving from the sea to the land. The rivers return water to the sea that has moved as vapour from the sea onto the land. That return does, however, not constitute the entire quantity of water returning to the ocean. There is water in the form of vapour in the atmosphere, that is moving from the land to the sea (Dl). The entire amount of vapour moving from the land to the sea (Dm) is greater than the amount of water (F) returning with the rivers by the above amount (Dl). Therefore Dm = F + Dl. To put it differently: the annual return of rivers to the oceans equals the difference between the quantity of water vapour moving from the sea onto the land, and from the land into the sea.

The balance of the hydrological cycle can therefore be expressed as follows:

$$Rm = Vm - Dm + De = Vm - (Dm - Dl) = Vm - F \qquad (1)$$

$$Rl = Vl + Dm - Dl = Vl + (Dm - Dl) = Vl + F \qquad (2)$$

Expressed in symbols used today in German literature, the basic formula for the sea according to BRÜCKNER (1905) is as follows:

$$NM = VM - AL$$

and for the land:

$$NL = VL + AL$$

As the last variable in calculating the planet's water balance, BRÜCKNER eventually added the average annual evaporation from the ocean's surfaces. In line with the above equation for the sea the precipitation onto the sea surfaces can be determined by subtracting the return from land areas.

By determining the evaporation from the sea and using long term annual averages, Brückner, for the first time, was able to calculate the quantities of water circulating in the hydrological cycle. (see *Table 1.3-1*):

Evaporation from the sea	384,000 km³
Rainfall on the sea	59,000 km³
River water to the oceans	25,000 km³
Evaporation from the land	97,000 km³
Rainfall on the land	122,000 km³

»Our endeavour to calculate a balance about the hydrologic cycle as illustrated above, might, to some people, appear rather daring. In fact will I have to repeat that I do not claim to be extremely precise as related documents are still too uncertain. More precise information will have to be found in the future... Our results should not be considered other than an initial approximation«

»Unsere oben aufgestellte Bilanz des Kreislaufs des Wassers wird manchem kühn erscheinen; in der Tat möchte ich wiederholen, dass sie keinen Anspruch auf große Genauigkeit machen kann, weil dazu die Unterlagen noch zu unsicher sind... Genauere Werte zu finden, muss der Zukunft vorbehalten bleiben ... Mehr als eine solche erste Annäherung wollen unsere Ergebnisse nicht sein«. BRÜCKNER, 1905, S. 445 im letzten Absatz der Arbeit.

Quantities of water on the planet

Until now we have not been able to determine with precision the quantities of water on our planet, although the total amount has remained constant. Knowledge about the quantity of water present on our planet is based on either approximation or estimation. By taking into consideration different approaches, we will present values (see *Table 1.3-1*) that have been mentioned by KLIGE et al. (1998, p. 339).

Balance for the Earth's water system

There are two requirements for the average annual water system of our planet and that of the oceans and the land surfaces to be in balance:

- the climate of the Earth must remain the same for many years – although for a shorter period than a geological period – and
- the average sea level must remain constant over a longer period of time. The second requirement already follows the first one.

BRÜCKNER had already referred with emphasis to the second requirement (1900, p.93).

Following the equations for the sea and land water balances by BRÜCKNER (1905, p.437) and taking into account the above requirements, the average annual evaporation on the Earth's surface must equal the average annual rainfall on its surface. The basic formula for the water system is therefore

Tab. 1.3-1: Water balance values for the Earth (in 1,000 km³) from different authors.

		N_L	V_L	A_L	V_M	N_M	$N_E = V_E$
E. Brückner	1905	122	97	25	384	359	481
R. Fritzsche	1906	112	81	31	384	353	465
W. Schmidt	1915	112	81	31	273	242	354
G. Wüst	1922	112.1	75	37.1	304.2	267.1	379.2
A. A. Kaminskij	1925	81	51	30	337	307	388
W. Meinardus	1934	99	62	37	449	412	511
W. Halbfass	1934	100	52	48	458	410	510
G. Wüst	1936	99	62	37	334	297	396
W. Wundt	1937	99	62	37	383	346	445
F. Möller	1951	99	62	37	361	324	423
E. Reichel	1952	100	70	30	345	315	415
M. I. Budyko u. a.	1956	105.1	67	38.1	407.9	369.8	474.9
M. I. Budyko u. a.	1963	107	61	46	450	404	511
J. Marcinek	1966	100	63.5	36.5	411.2	374.7	474.7
M. I. L'movič	1967	108.4	71.3	37.1	448	410.9	519.3
M. I. Budyko u. a. (bei Dyck 1968)	1968	107	61	46	449	403	510
M. I. L'vovič	1972	113.5	71.8	41.7	-	-	-
J. Marcinek (ergänzt)	1975	100	62.5	37.5	411.2	373.7	473.7
V. I. Korzun u. a.	1974	119	72	47	505	458	577
M. I. L'vovič	1974	113.5	72.5	41	452.6	411.6	525.1
A. Baumgartner u. E. Reichel	1975	111.1	71.4	39.7	424.7	385	496.1
R. K. Klige (für 1894 – 1975)	1982	119.8	69.9	50.2	507.1	457.2	Δ 0.3
R. K. Klige u. a. (updated)	1998	119.83	69.91	50.53	507.15	457,23	577.06
M. T. Chahine	1992	107	71	36	434	398	505
I. A. Shiklomanov	1998	119	74	45	503	458	577
T. Oki	1999	115	75	40	431	391	506
K. E. Trenberth et al	2006	113	73	40	413	373	486
Average		107	69	38	411	373	480
Standard deviation		9.2	9.6	6.3	60.8	65.5	60.6
Maximum		122	97	50	273	242	354
Minimum		81	51	25	273	242	354
Fluctuation from average value (%)		38	68	67	57	58	46
Calculation with modell ECHAN4_OPYC[3]							
1990–1999 after IPCC-Szenario IS92a[4]		118	78	46	453	411	529–531
2090–2099 after IPCC-Szenario IS92a[4]		127	82	51	459	411	531–541

[1] Table completed by M. Quante and editors.
[2] Not taken into account in the statistic.
[3] Max-Planck-Institute for Meteorology and German Climate Computing Centre, Hamburg
[4] According to the Szenario IS92a the concentration of greenhouse gases in the atmosphere will continue to increase during the 21th century.

$$VE = NE \quad (5)$$

whereby

V = evaporation, N = precipitation and index
E = Earth's surface

BRÜCKNER's equations show that evaporation as well as precipitation on the Earth's surface are each made up of two water system values. These are the evaporation from sea and land areas (VM and VL) as well as the precipitation on sea and land areas (NM and NL). It can therefore be said

$$VE = VM + VL = NE = NM + NL. \quad (6)$$

It has so far not been possible to satisfyingly determine VL from direct measurements of the Earth's land surfaces. Therefore, when conducting water balance research, the evaporation from land areas is usually determined as being the remaining value in the water system equation for land areas:

$$VL = NL - AL \quad (7)$$

The difference between precipitation and evaporation for land and oceanic areas must be balanced, to make sure that there is an overall balance on our planet. Excess water from the main land will be returned through the resulting return AL to the ocean, so that

$$AL = NL - VL \quad (8)$$

On the other hand evaporation is exceeding precipitation. It therefore reaches into the atmosphere from where it is moved over the continents. There it condenses and falls down as precipitation (see Chapter 1.5). This closes the global water cycle.

Water balances for the Earth

The long line of water system balances for the Earth (*Table 1.3-1*) is headed by that of BRÜCKNER's first calculations (1905). Another one, published by the writer in 1966, contains a 1964 calculation of return from land areas. It resulted in a value of 33,500 km³ that had to be corrected in 1965 due to new return data for the Amazon, Orinoco and Brahmaputra to 36,500 km³. When V. M. KOTLJAKOV (1970, in L'vovié 1971a) announced a new return value for the Antarctic inland ice of 2,200 km³, the overall value was again modified and is now at 37,500 km³. Although this number is close to the average value of all calculations in the table, return data especially in recent calculations vary tremendously.

The value given for precipitation on land areas is based on calculations by BROOKS & HUNT (1930) and has been rounded up by E. Reichel (1952) to 100,000 km³. As of 1934 the value of 99,000 and 100,000 km³ often appears in the balances. Most recent calculations, however, put that value higher.

The values given by BUDYKO and others (1956) as well as ALBRECHT (1960) for the evaporation from sea surfaces nearly correspond. In 1966 and in this article the writer made use of Albrecht's value. The difference between evaporation from sea surfaces and return from land surfaces equals the precipitation on to sea surfaces.

We especially want to draw attention to the water system balance of BUDYKO (1963, also see DYCK 1968). With the Earth's basic formula (*Tab 1.3-1*, column NE = VE) he obtained the same result - although using a different method – as W. MEINARDUS (1934).

For reference purposes the table also contains values for the global hydrological cycle, that have been established by means of an advanced global climatic model (ECHAM4_OPYC). The numbers are more or less within the range of conventional calculations. Surprisingly, in both calculations the hydrological cycle is not closed. Calculations for the last decade of the 21st century point to an increase in the circulation of global waters due to a possible climate change (see Chapter 3.1.3).

Final remarks

Today we have a basic understanding of the global hydrologic cycle. Nevertheless we are still lacking knowledge not only of some of the details, but also of the precise definition of its basic values. Even though there are many new ways to do research, the error margin is still quite high. Of major importance is the correct proportional representation defining the hydrological cycle. In that sense all approaches included in the table are «correct». For instance the relationship NM/VM only slightly oscillates around the average value of 0.9, whereas the ratio VL/NL = 0.64±0.06 moves between 0.52 and 0.90. This means that none of the estimations represented in the table can be recommended. With respect to the amount of data introduced and method applied, preference should be given to the most recent calculations.