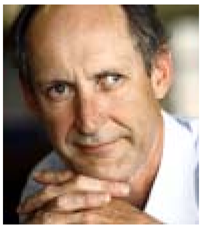
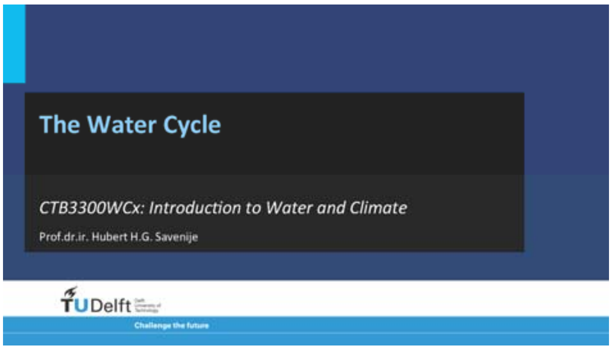
CTB3300WCx – Introduction to Water and Climate

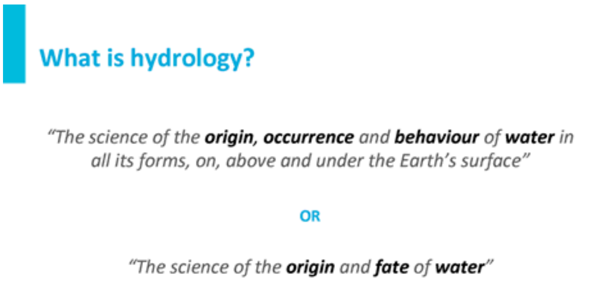
GWC 1 – Water cycle



Hubert Savenije



Welcome!
My name is Hubert Savenije and I am a Hydrologist



Hydrology is the science of water. It tries to describe and understand how water moves over and through the Earth and to find out what the physical processes are that drive the movement of water. More simply, you could say that "Hydrology is the science of the origin and fate of water on Earth"

But if you ask me, I would just say that "Hydrology is Beautiful". Even if it rains, or especially when it rains.

The grand questions

- Origin of water
- Water availability
- Water threats
- Maintaining a healthy aquatic environment
- Effect of climatic change on hydrology
- Influence of human interventions on hydrology
- When to expect floods

Because everything we do and because everything living on Earth depends on water, there are large and important scientific questions that demand our attention.
Such as: Where does the water come from?
How much water is there available for development, for feeding hungry mouths and for a healthy environment?
How can we better protect ourselves from water threats, such as floods and droughts?
How can we maintain a healthy environment in a rapidly developing world?
How does climatic change propagate into the hydrological behaviour and water resources availability?
In which way do we, as human beings, influence the hydrology, and is there an interaction?
And many people (particularly politicians) want us to tell when we can expect a flood.
But that, unfortunately, is a question we cannot answer.
We can communicate the probability of an extreme event to occur, but not easily the moment when it will occur.
Prediction is difficult in hydrology, particularly when it relates to the future!

The origin of water in our environment

Plato *(427-348 BC)* & ***Aristoteles*** *(350 BC)*
- The rain feeds rivers and groundwater

Leonardo da Vinci *(1452-1519)*
- Water cycles, but originates from underground feeding from the ocean

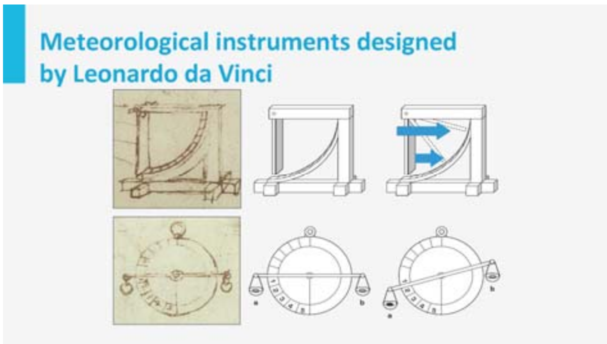
The question “where the water comes from” has inspired the great philosophers.
The early Greek philosophers indeed believed that river water and groundwater were fed by rain, but they also liked to compare the Earth to the human body.

Leonardo da Vinci, a GREAT hydrologist

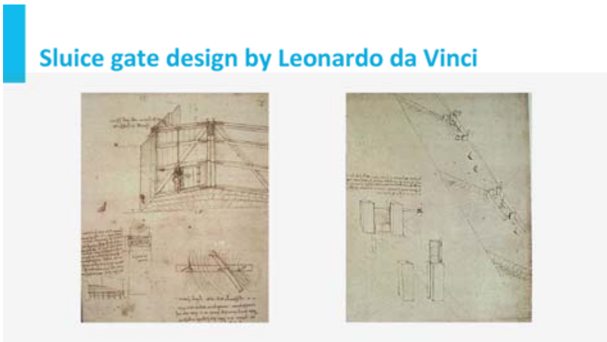
Leonardo Da Vinci, whom we all know as the painter of the Mona Lisa, was not only a great artist, he was also an engineer, a writer and a scientist.

Leonardo wanted to understand what he painted.

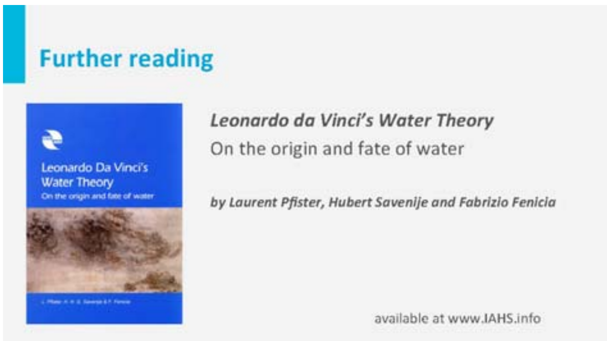
To be able to paint water and clouds realistically, he tried to better understand how it behaved.



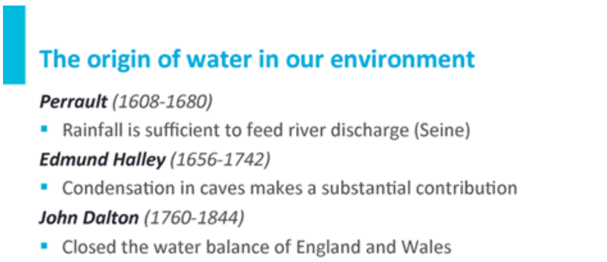
He developed instruments and devices to measure flow velocity, wind velocity, air humidity etc. and he came to incredibly accurate insights.



He even designed sluice gates that are still in use in The Netherlands!

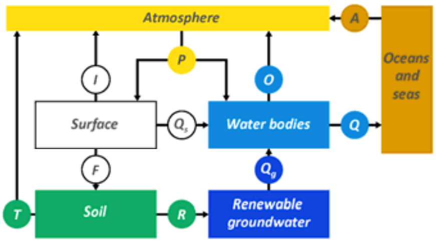


However, he respected the classical ideas of Plato so much, that he thought that water was pumped through the Earth in analogy to the human body and he thought that sea water was pumped through the Earth to appear again on the top of mountains.



It was more than 100 years later till the Frenchman Perrault could demonstrate that precipitation was sufficient to maintain the flow of the river Seine which was a revolutionary idea because the famous English scientist Halley (the one from the comet) still believed that much of the river water originated in caves where moist air condensed against the cold mountain rock.

Global water resources



The world’s water resides in a system of interacting stocks and fluxes. Stocks are represented by boxes; and fluxes by arrows. These boxes and arrows have very different sizes and magnitudes

Where is the world’s water located?

Water occurrence	Volume (10^{12} m^3)	% of water	% of fresh water
World oceans	1.300.000	97	-
Salt lakes / seas	100	0,008	-
Polar ice	28.500	2,14	77,6
Atmospheric water	12	0,001	0,035
Water in organisms	1	0,000	0,003
Fresh lakes	123	0,009	0,335
Water courses	1	0,000	0,003
Unsaturated zone	65	0,005	0,18
Saturated zone	8000	0,60	21,8
Total fresh water	36.700	2,77	100
Total water	1.337.000	100	-

By far the largest stock of water is in the oceans and seas. But this water is saline. The largest stock of fresh water is in the polar ice. But this is hardly accessible. Then there is a huge stock of water deep under the ground: in large alluvial plains and even under the Sahara. But this water is often fossil, not being replenished at a human time scale. The only sustainable stocks of water are the amounts that are regularly renewed These stocks generally lie close to the surface. We have come to indicate these stocks and fluxes by the colours blue and green.

Where is fresh water located?

- Water bodies (light blue)
- Ground water (deep blue)
- Soil (green) (coined by Malin Falkenmark)

see e.g.: http://www.hydrol-earth-syst-sci.net/9/15/2005/hess-9-15-2005.html

- Direct evaporation (white water)

We distinguish the light blue water, which we can see on the surface, from the deep blue water which feeds the surface water from underground. An equally large resource is the green water (a term coined by Prof Malin Falkenmark), which is the water stored in the soil and used by plants to produce biomass. This is the water that feeds the world population by agricultural products and which sustains our biomass based economies. Part of the precipitation does not become blue or green water, but evaporates back to the atmosphere directly. I name this white water.

Global water resources

Resource	Flux	[L / T]	Stock	[L]	Residence time	[T]
Soil	T	210 mm/a	S_u	100 mm	S_u / T	6 months
Surface	I	200 mm/a	S_s	1 mm	S_s / I	2 days
Water bodies	Q	310 mm/a	S_w	830 mm	S_w / Q	2,7 years
Renewable groundwater	Q_g	30 mm/a	S_g	5000 mm	S_g / Q_g	160 years
Atmosphere	P	720 mm/a	S_a	20 mm	S_a / P	0,3 months
Oceans and seas	A	130 mm/a	S_o	3600 m	S_o / A	28.000 years

See e.g.: Savenije, H.H.G., “Water Scarcity Indicators; the Deception of the Numbers”, *Physics and Chemistry of the Earth(B)*, Vol.25, No. 3, pp 199-204, 2000.
(http://www.sciencedirect.com/science/article/pii/S1464190900000046)

Here we see an overview of the magnitudes of these stocks and fluxes expressed per unit surface area. They are approximate values, but they clearly show that some fluxes are very large (the atmospheric flux) and some are very small (deep blue). Conversely, we see very large stocks (the oceans), whereas some are very small (the white stock). The right column shows the ratio between the stocks and the fluxes, which represents the residence time.

Water balance

$$\frac{dS}{dt} = I - O$$

The water balance is the most basic equation in hydrology. It implies conservation of mass. It shows that if there is an imbalance between inflow and outflow, that there then should be an increase of the storage over time.
Or: the time derivative of the storage is the difference between inflow and outflow. In hydrology, the inflow can be an inflow of water, but also precipitation on a surface.

The residence time

Average residence time *or* Process time scale (T_R) $= \dfrac{\text{Stock (S)}}{\text{Flux (O)}}$

Outflow can be the river discharge, but also the evaporation from the surface. An interesting property of such water balance systems is that if we divide the storage by the outflow, we obtain a number with a time dimension. This number represents the average time that a water particle resides in the stock. More correctly is it to say that this ratio of stock to flux is the time scale of the process.

Global water resources

Resource	Flux	[L / T]	Storage	[L]	Residence time	[T]
Soil	T	210 mm/a	S_u	100 mm	S_u / T	6 months
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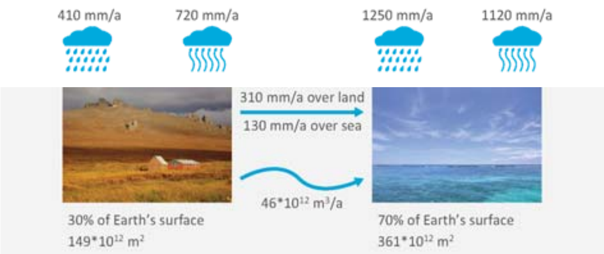
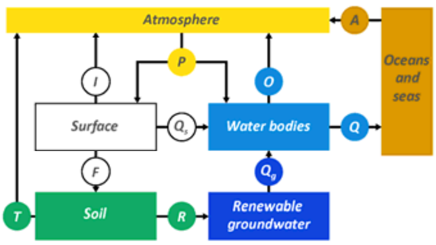
If we now look again at our global water resources table, then we see that the Oceans have the largest residence time. Not surprising. A water particle, once it ends up in the ocean, has to wait on average 28000 years before it may again travel to the land. In the atmosphere, however, a water particle resides only a few weeks, on average. And thanks to the storage in the root zone of plants, they can survive half a year without rainfall, on average.

Annual average precipitation and evaporation



You may wonder why the flux from land to ocean (through the rivers) is 310 mm/a and that while the flux from ocean to land (through the atmosphere) is 130 mm/a.
How come these numbers are not equal? Shouldn't they be the same? Of course they are the same! We only have to multiply them by the right surface area.

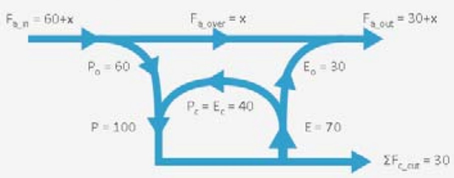
Global water resources



Because if we look at this picture, than, on average, the fluxes A and Q should be equal and opposed. Otherwise the storage in the ocean would either increase or decrease without end.

Does all precipitation come from the ocean?

- How important is terrestrial evaporation?
- Is moisture recycled? And if so, how much?



You may be wondering what happens with the moisture you exhale. Does the moisture we exhale fall back as precipitation, or does if flow back to the ocean through the air?
If we look at the global water balance again, then we see that it rains 720 mm/a on Earth, while the net atmospheric influx is only 310 mm/a; a factor 2.3! In fact a substantial part of the precipitation finds its origin in terrestrial evaporation. If we equate the terrestrial precipitation to 100%, then 40% of this water comes from terrestrial evaporation. Just look at the picture: Of the 100% precipitation about 70% evaporates.
A bit more than half of it returns on land and the rest flows back to the ocean through the atmosphere. But it depends strongly on where you are on Earth.

WATER RESOURCES RESEARCH, VOL. 46, W09525, doi:10.1029/2010WR009127, 2010

Origin and fate of atmospheric moisture over continents

Ruud J. van der Ent,[1] Hubert H. G. Savenije,[1] Bettina Schaefli,[1] and Susan C. Steele-Dunne[1]

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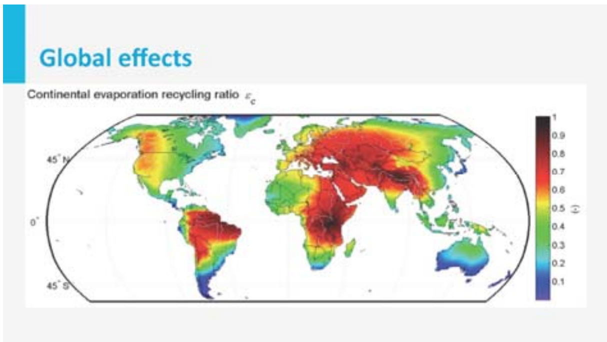
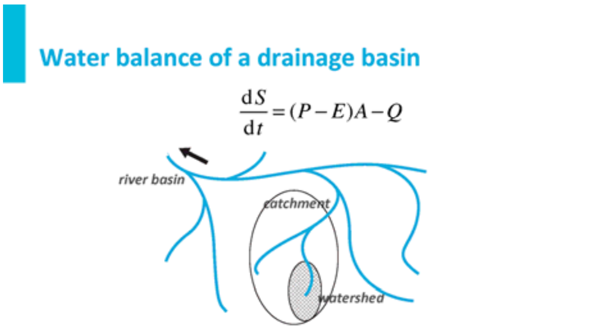
[1] There has been a long debate on the extent to which precipitation relies on terrestrial evaporation (moisture recycling). In the past, most research focused on moisture recycling within a certain region only. This study makes use of new definitions of moisture recycling to study the complete process of continental moisture feedback. Global maps are presented identifying regions that rely heavily on recycled moisture as well as those that are supplying the moisture. An accounting procedure based on ERA-Interim reanalysis data is used to calculate moisture recycling ratios. It is computed that, on average, 40% of the terrestrial precipitation originates from land evaporation and that 57% of all terrestrial evaporation returns as precipitation over land. Moisture evaporating from the Eurasian continent is responsible for 80% of China's water resources. In South America, the Rio de la Plata basin depends on evaporation from the Amazon forest for 70% of its water resources. The main source of rainfall in the Congo basin is moisture evaporated over East Africa, particularly the Great Lakes region. The Congo basin in its turn is a major source of moisture for rainfall in the Sahel. Furthermore, it is demonstrated that due to the local orography, local moisture recycling is a key process near the Andes and the Tibetan Plateau. Overall, this paper demonstrates the important role of global wind patterns, topography and land cover in continental moisture recycling patterns and the distribution of global water resources.

Citation: van der Ent, R. J., H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne (2010), Origin and fate of atmospheric moisture over continents, Water Resour. Res., 46, W09525, doi:10.1029/2010WR009127.

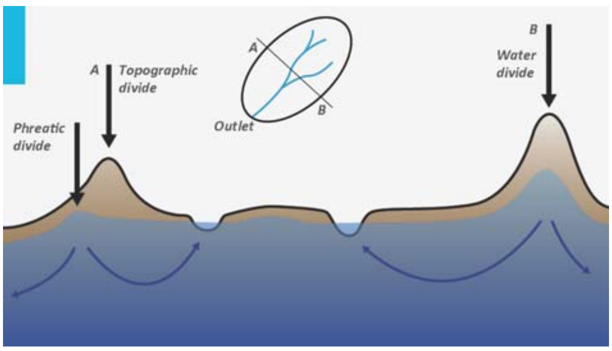
This is the paper by Ruud van der Ent, which describes this in detail.



As a result of the dominating westerly winds on the Northern Hemisphere, exhaled moisture in The Netherlands is likely to end up in China. But exhaled moisture in China is likely to end up in the Pacific Ocean. Here we see in red the parts of the world where the precipitation largely consists of recycled moisture. We see that China and West Africa strongly depend on recycled moisture. But where did this moisture come from? Here we see in red the reverse. Red are the source areas where the chance of evaporation ending up on land is larger than 60% These are the areas where land evaporation has a significant influence on precipitation. So the Amazon forest in South America; the Great Lakes area in Africa and Eastern Europe are very important source areas to sustain continental rainfall And land use change in these areas may have unexpected consequences downwind.



Although global hydrology is extremely relevant for the analysis of human impacts on the planet, the natural limits of a hydrological system are much smaller. The natural boundary of a hydrological system is the watershed, catchment, or river basin (in increasing order of size). This is because precipitation falling on a catchment has only two ways out: discharge through the outfall or evaporation back into the atmosphere. There is no other inflow assumed to be there than the precipitation. So the water balance reads that: The change of storage over time equals the rainfall minus the evaporation, minus the runoff through the outfall. Of course all terms in the equation need to have the same dimensions, so if we express precipitation and evaporation in [L/T] then they have to be multiplied by the size of the catchment area A. But we could also express all terms in [L/T] and in that case the discharge and the storage need to be expressed per unit area. But is the water divide always a real divide?



Not all runoff is generated over the surface. A considerable part flows to the river through the groundwater, and because of the sometimes complex geology the topographic divide and the groundwater divide does not have to coincide. Particularly in karstic or mountainous environments this can lead to substantial errors when one tries to close the water budget.

River	Area	Precipitation		Evaporation		Runoff		C_R
	10^9 m^2	mm/a	10^9 m^3/a	mm/a	10^9 m^3/a	mm/a	10^9 m^3/a	%
Nile	2803	220	620	190	534	30	86	14
Mississippi	3924	800	3100	654	2540	142	558	18
Parana	975	1000	980	625	610	382	372	38
Orinoco	850	1330	1150	420	355	935	795	70
Mekong	646	1500	970	1000	645	382	325	34
Amur	1730	450	780	265	455	188	325	42
Lena	2430	350	850	140	335	212	514	60
Yenisei	2440	450	1100	220	540	230	561	51
Ob	2950	450	1350	325	965	131	385	29
Rhine	200	850	170	500	100	350	70	41
Zambezi	1300	990	1287	903	1173	87	114	12

Here we see the water budgets of some of the major river basins of the world. We see that they differ in size (the Mississippi and Ob being among the largest and the Rhine being relatively small) We also see that the precipitation varies from 1500 mm/a in the Mekong to only 220 mm/a in the Nile. The evaporation from a catchment, of course, is always smaller than the precipitation (because in a catchment the precipitation is the only inflow) But the proportion of evaporation to rainfall varies a lot between catchments. In the Nile, the Zambezi and the Mississippi, containing substantial semi-arid parts, the evaporation is more than 80% of the precipitation. But in more humid climates (particularly the Orinoco) the evaporation is only 30% of the precipitation.
Of course, the remainder is the runoff. And the Orinoco where 30% of the precipitation evaporates, hence has a runoff ratio of 70% The Orinoco drains essentially tropical rainforest. Therefore it is interesting to see that another catchment that generates a lot of runoff (60% of the precipitation) is a catchment in cold Siberia. Both have insufficient solar energy to evaporate most of the precipitation: the Orinoco because it rains so much, the Ob because there is insufficient solar energy.

So different regions and different landscapes behave very differently all over the world. Hydrology is the science that wants to describe and understand this behaviour. The landscape reflects this behaviour and if we read the landscape well, we can learn a lot more about its properties and dynamics. I hope you enjoyed this part of the course and remember: Hydrology is the basis of all other water-related disciplines and of the management of our resources.