The water cycle

Nevil Wyndham Quinn
Associate Professor in Applied Hydrology
nevil.quinn@uwe.ac.uk

Michael Horswell
Senior Lecturer in GIS and Spatial Analysis
michael.horswell@uwe.ac.uk

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3.1.1.1 Water and carbon cycles as natural systems

Systems in physical geography: systems concepts and their application to the water and carbon cycles inputs – outputs, energy, stores/components, flows/transfers, positive/negative feedback, dynamic equilibrium.

SYSTEMS THINKING:

- components and their stores
- inputs and outputs
- flows, transfers, fluxes (changes over time)
- feedback loops
- 'system state' concepts (dynamic equilibrium, tipping points etc.)

3.1.1.2 The water cycle

Global distribution and size of major stores of water – lithosphere, hydrosphere, cryosphere and atmosphere.

global scale stores

Processes driving change in the magnitude of these stores over time and space, including flows and transfers: evaporation, condensation, cloud formation, causes of precipitation and cryospheric processes at hill slope, drainage basin and global scales with reference to varying timescales involved.

water cycle processes – seem to be emphasizing the *atmosphere* and *cryosphere*

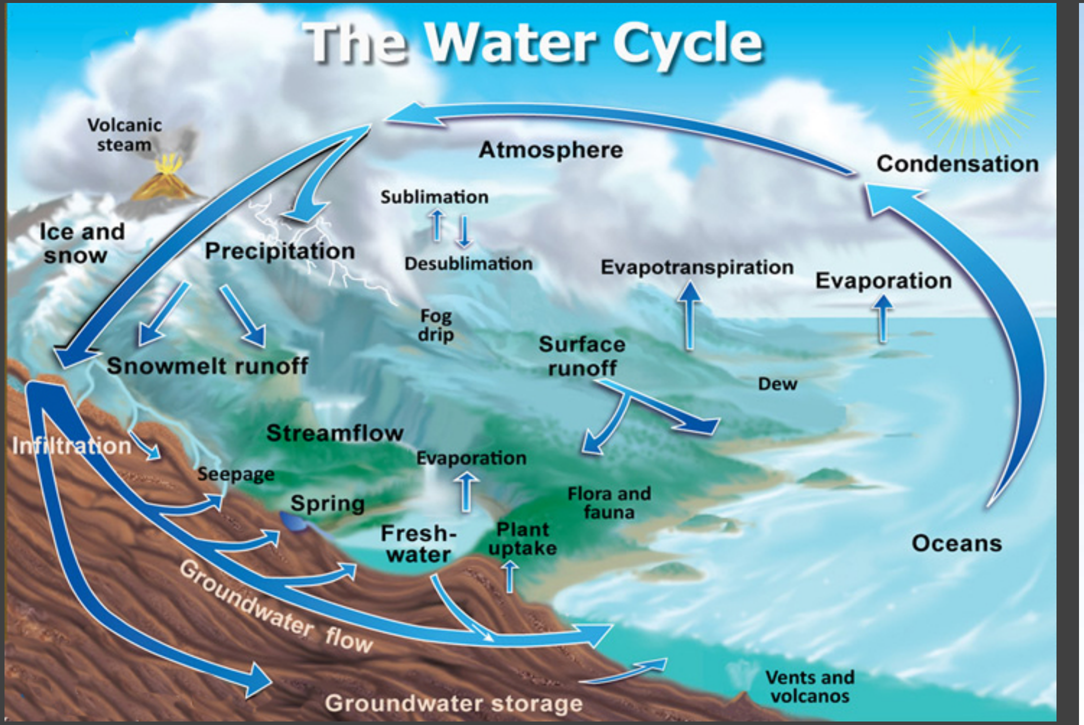
Drainage basins as open systems – inputs and outputs, to include precipitation, evapo-transpiration and runoff; stores and flows, to include interception, surface, soil water, groundwater and channel storage; stemflow, infiltration overland flow, and channel flow. Concept of water balance.

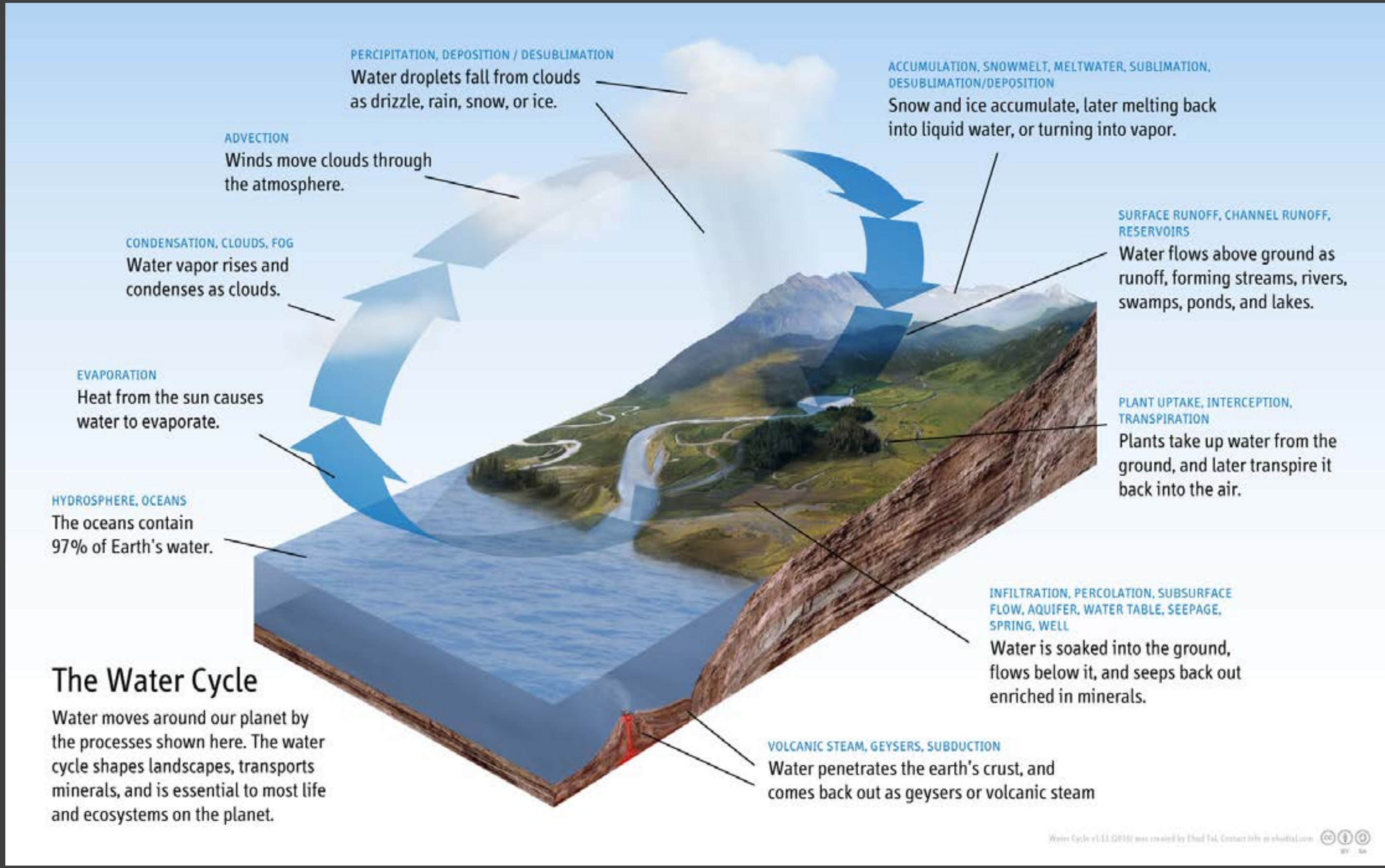
Runoff variation and the flood hydrograph.

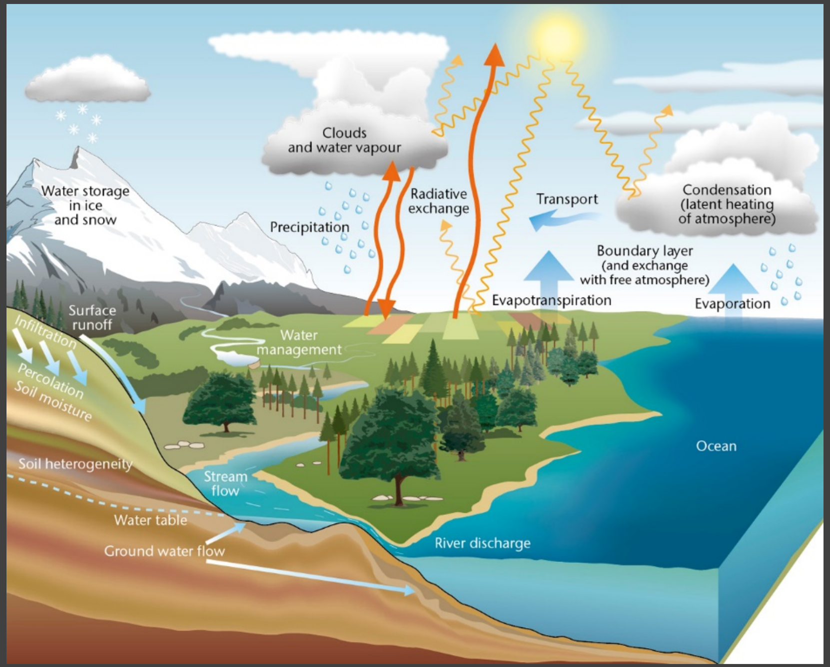
water cycle processes – seem to be emphasizing the *hydrosphere* and *lithosphere*

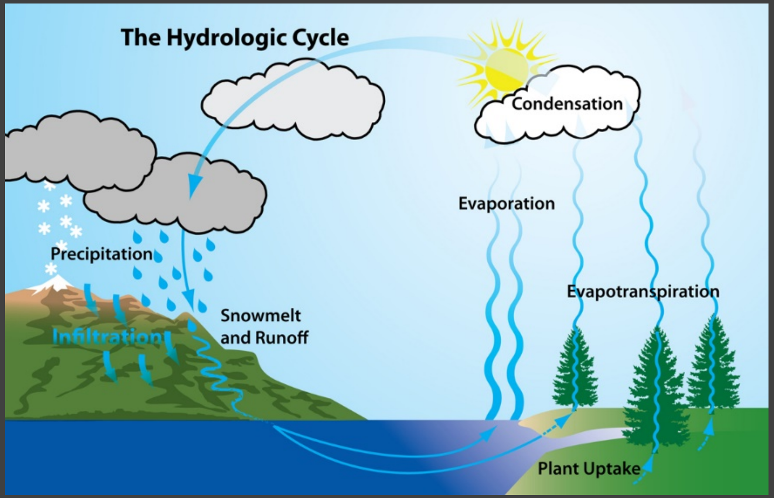
Changes in the water cycle over time to include natural variation including storm events, seasonal changes and human impact including farming practices, land use change and water abstraction.

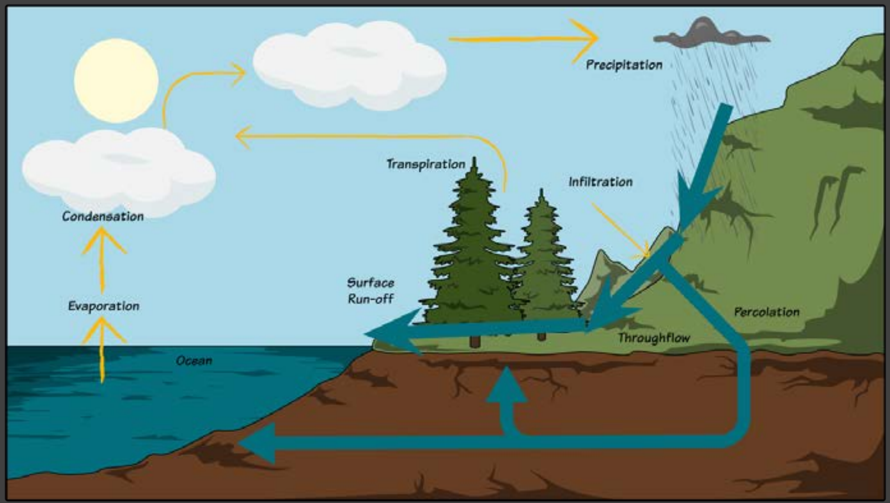
change over time – perhaps at a more localised rather than global scale?

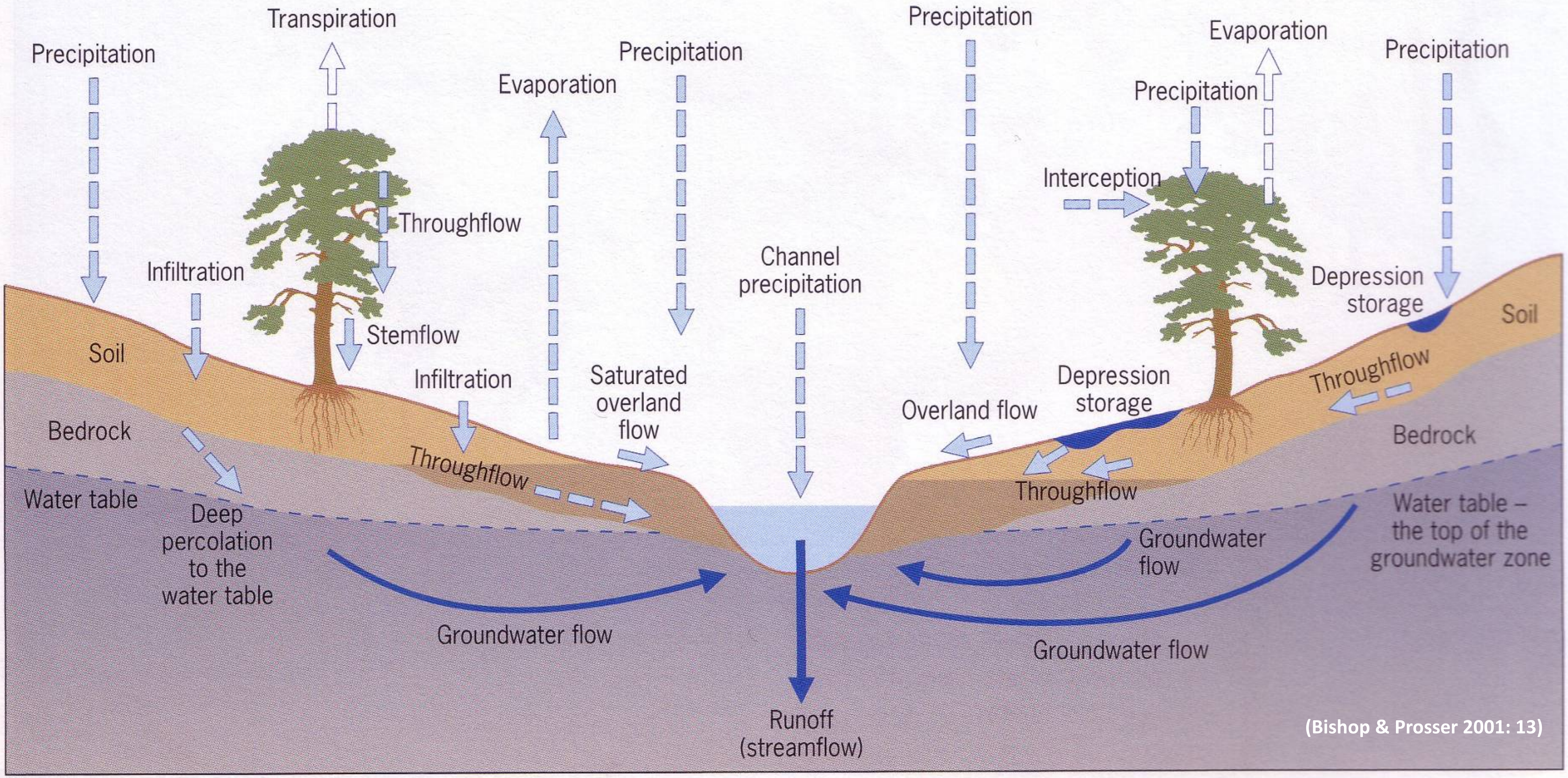

The Water Cycle
Volcanic steam
Atmosphere
Condensation
Sublimation
Desublimation
Ice and snow
Precipitation
Evapotranspiration
Evaporation
Fog drip
Snowmelt runoff
Surface runoff
Dew
Streamflow
Infiltration
Seepage
Evaporation
Flora and fauna
Spring
Fresh-water
Plant uptake
Oceans
Groundwater flow
Vents and volcanos
Groundwater storage


PERCIPITATION, DEPOSITION / DESUBLIMATION
Water droplets fall from clouds as drizzle, rain, snow, or ice.
ACCUMULATION, SNOWMELT, MELTWATER, SUBLIMATION, DESUBLIMATION/DEPOSITION
Snow and ice accumulate, later melting back into liquid water, or turning into vapor.
ADVECTION
Winds move clouds through the atmosphere.
CONDENSATION, CLOUDS, FOG
Water vapor rises and condenses as clouds.
SURFACE RUNOFF, CHANNEL RUNOFF, RESERVOIRS
Water flows above ground as runoff, forming streams, rivers, swamps, ponds, and lakes.
EVAPORATION
Heat from the sun causes water to evaporate.
PLANT UPTAKE, INTERCEPTION, TRANSPIRATION
Plants take up water from the ground, and later transpire it back into the air.
HYDROSPHERE, OCEANS
The oceans contain 97% of Earth's water.
INFILTRATION, PERCOLATION, SUBSURFACE FLOW, AQUIFER, WATER TABLE, SEEPAGE, SPRING, WELL
Water is soaked into the ground, flows below it, and seeps back out enriched in minerals.
The Water Cycle
Water moves around our planet by the processes shown here. The water cycle shapes landscapes, transports minerals, and is essential to most life and ecosystems on the planet.
VOLCANIC STEAM, GEYSERS, SUBDUCTION
Water penetrates the earth's crust, and comes back out as geysers or volcanic steam

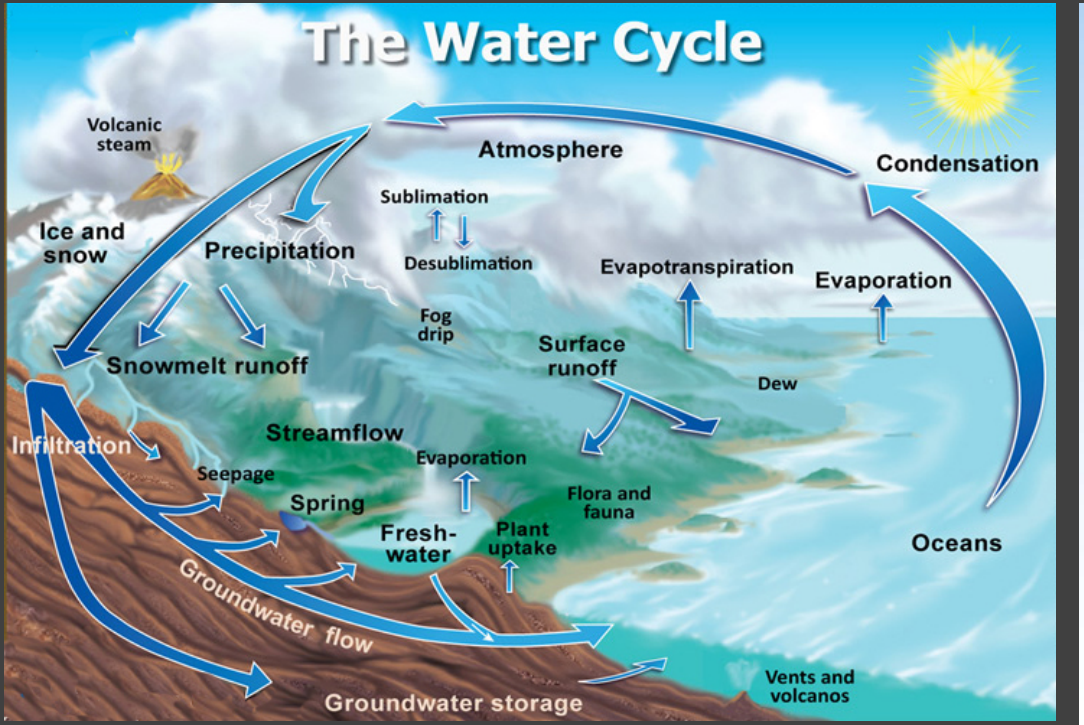

Clouds and water vapour
Water storage in ice and snow
Precipitation
Radiative exchange
Transport
Condensation (latent heating of atmosphere)
Boundary layer (and exchange with free atmosphere)
Evapotranspiration
Evaporation
Surface runoff
Infiltration
Percolation
Soil moisture
Water management
Ocean
Soil heterogeneity
Stream flow
Water table
Ground water flow
River discharge


The Hydrologic Cycle
Condensation
Evaporation
Precipitation
Snowmelt and Runoff
Infiltration
Evapotranspiration
Plant Uptake


Precipitation
Transpiration
Infiltration
Condensation
Evaporation
Surface Run-off
Percolation
Throughflow
Ocean



(Bishop & Prosser 2001: 13)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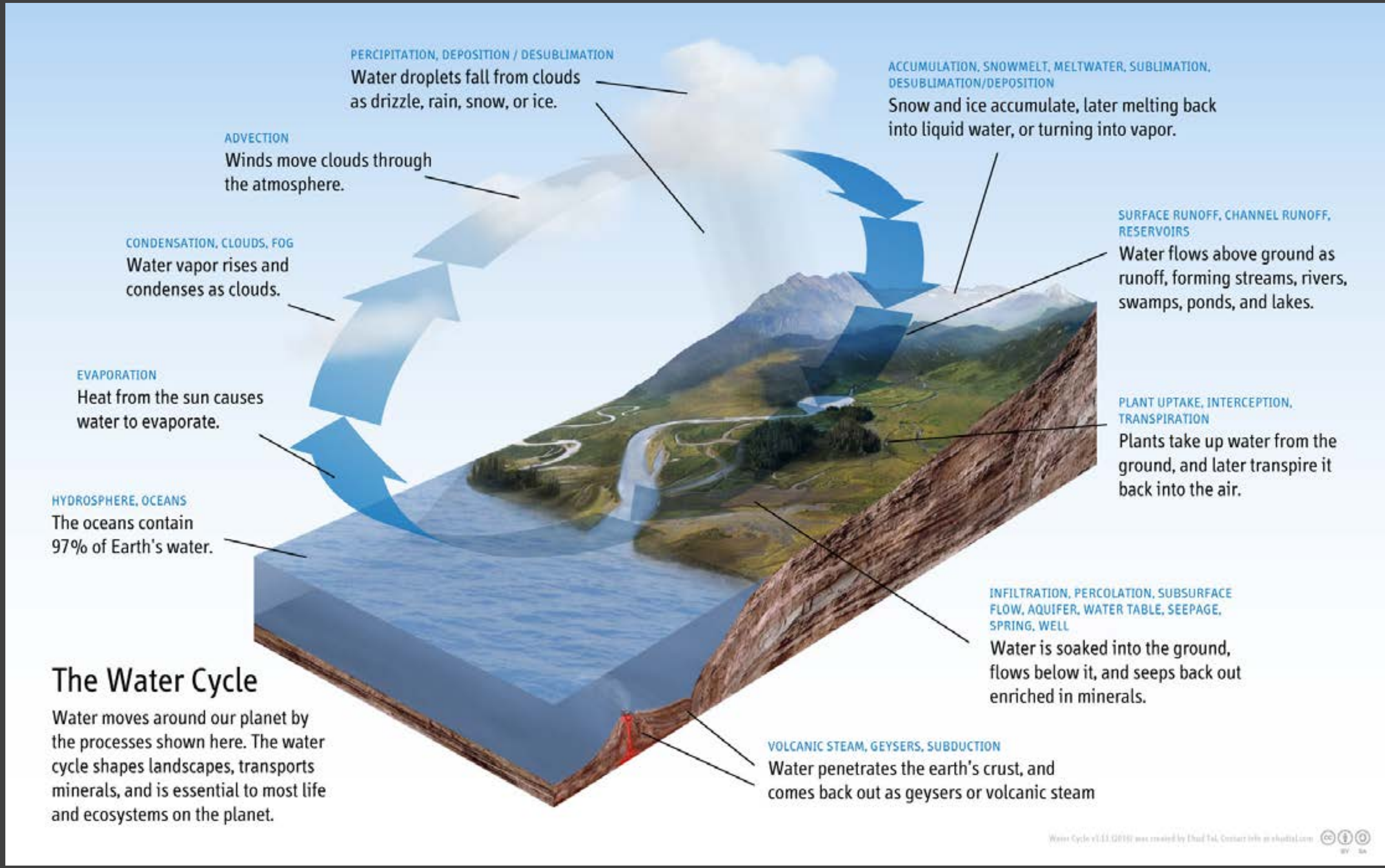
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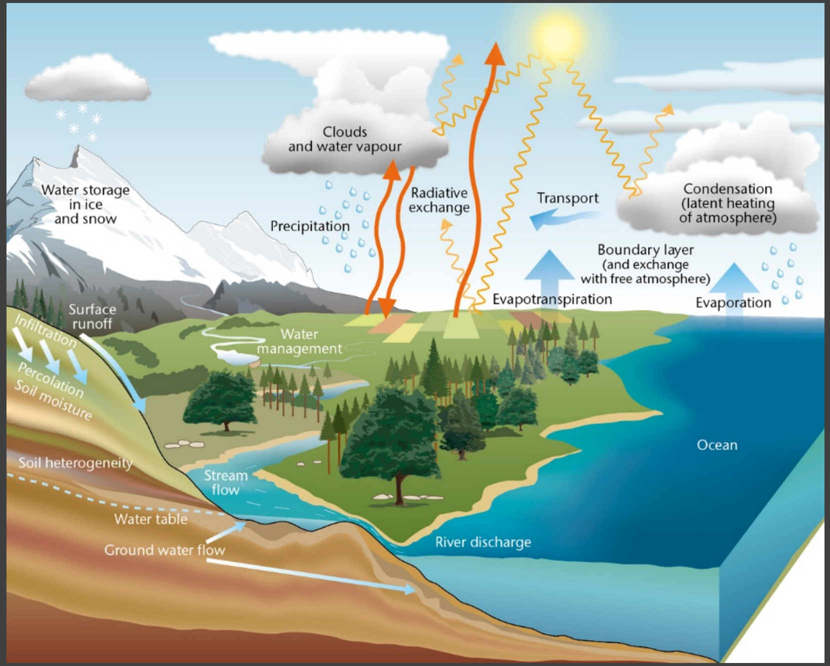
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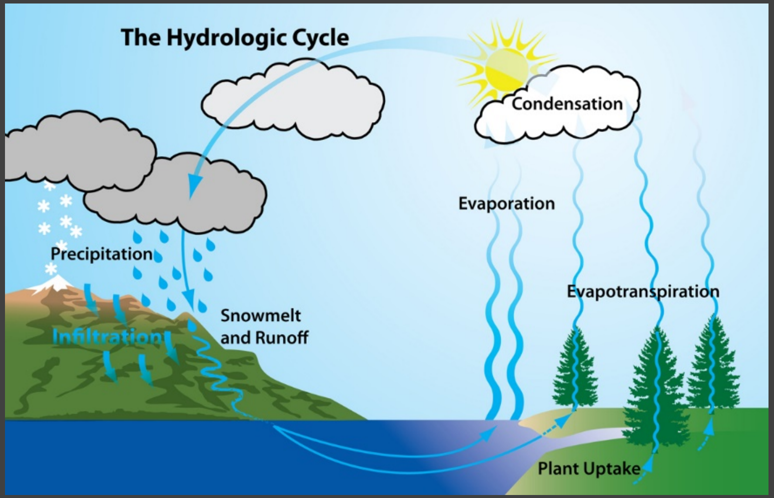
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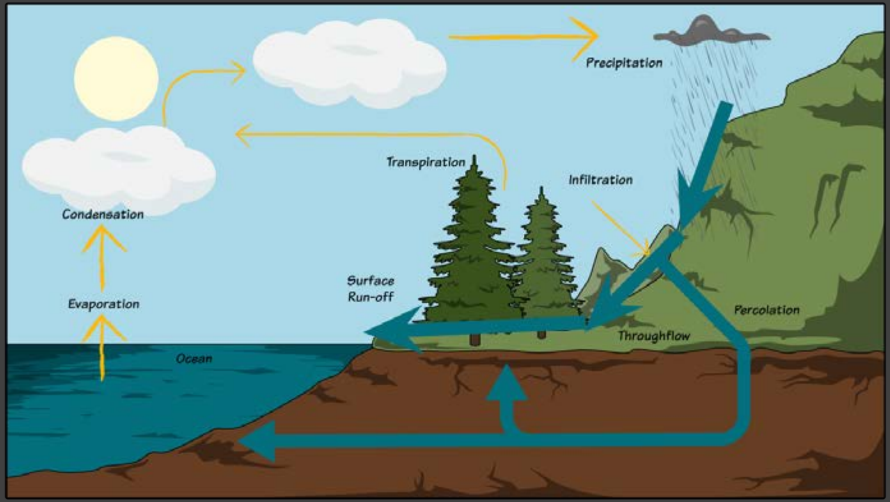
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Ocean

Earlier this month….

- A very interesting study was published in *Nature Geoscience*, with an additional comment in *Nature*

- It was carried out by a large team of experts from Brigham Young University and Michigan State University in the US and the University of Birmingham in the UK, along with partners in the US, France, Canada, Switzerland and Sweden.

Benjamin W. Abbott, Kevin Bishop, Jay P. Zarnetske, Camille Minaudo, F. S. Chapin, Stefan Krause, David M. Hannah, Lafe Conner, David Ellison, Sarah E. Godsey, Stephen Plont, Jean Marçais, Tamara Kolbe, Amanda Huebner, Rebecca J. Frei, Tyler Hampton, Sen Gu, Madeline Buhman, Sayedeh Sara Sayedi, Ovidiu Ursache, Melissa Chapin, Kathryn D. Henderson, Gilles Pinay. **Human domination of the global water cycle absent from depictions and perceptions**. *Nature Geoscience*, 2019; DOI: 10.1038/s41561-019-0374-y

- It showed that, in a sample of more than 450 water cycle diagrams in textbooks, scientific literature and online:
  - **85%** showed no human interaction at all with the water cycle, and
  - only **2%** of the images made any attempt to connect the cycle with climate change or water pollution.

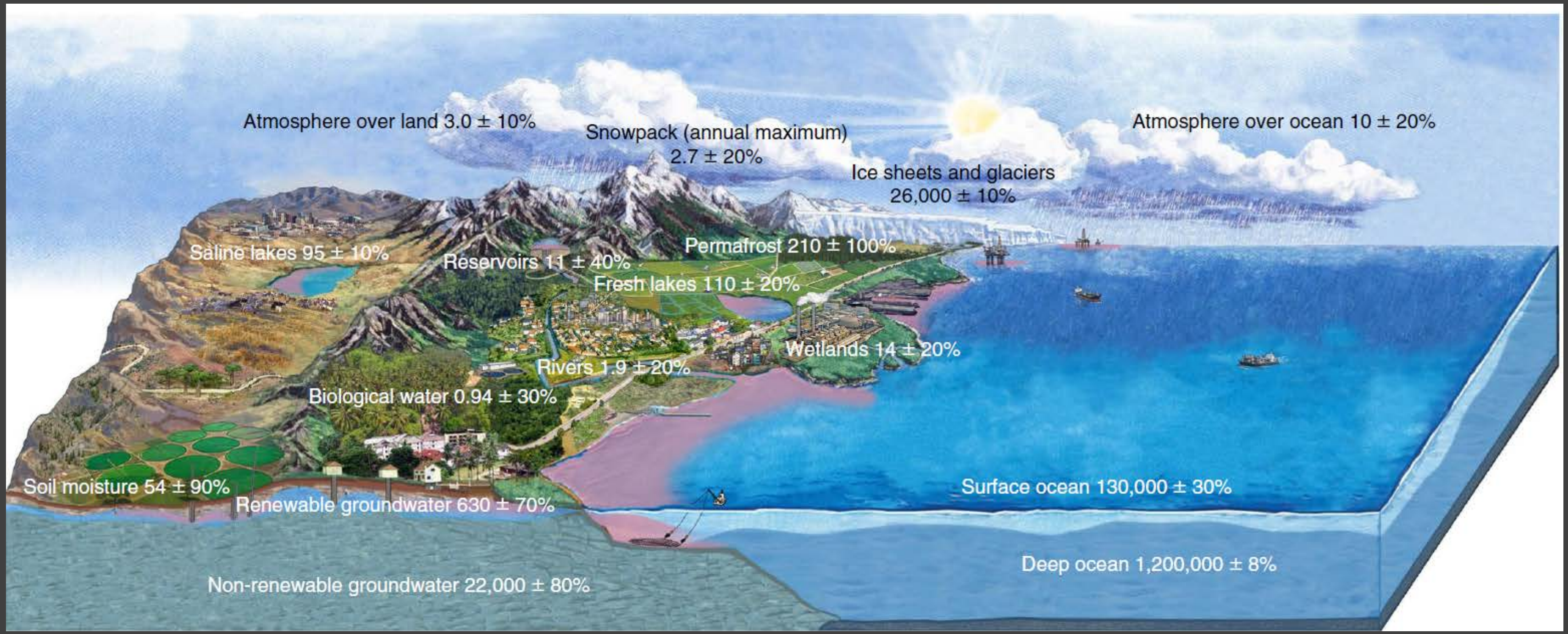
The water cycle diagram is a central icon of hydro science, but misrepresenting the ways in which humans have influenced this cycle diminishes our awareness of the looming global water crisis. By leaving out climate change, human consumption, and changes in land use we are, in effect, creating large gaps in understanding and perception among the public and also among some scientists.

Professor David Hannah
UNESCO Chair in Water Sciences
University of Birmingham

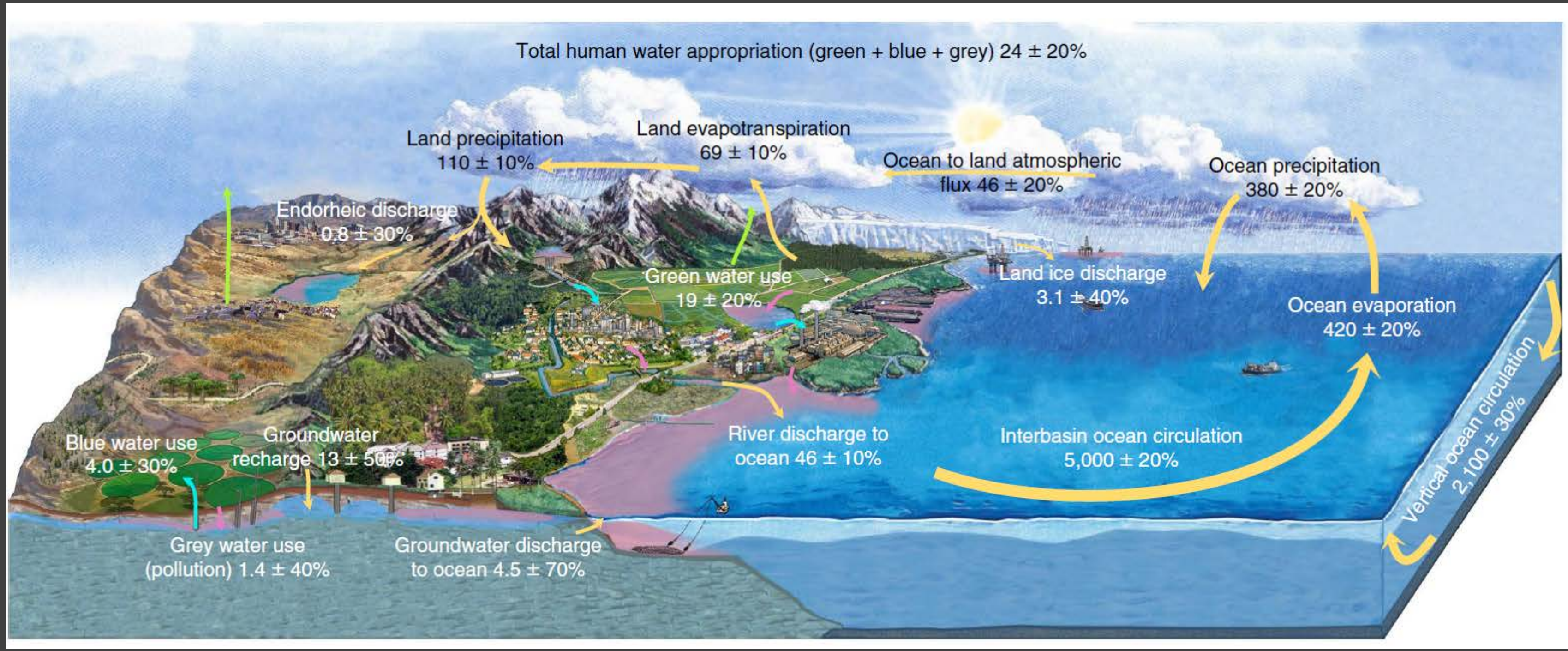
Every scientific diagram involves compromises and distortions, but what we found with the water cycle was widespread exclusion of a central concept. You can't understand water in the 21st century without including humans. Other scientific disciplines have done a good job depicting how humans now dominate many aspects of the Earth system. It's hard to find a diagram of the carbon or nitrogen cycle that doesn't show factories and fertilizers. However, our drawings of the water cycle are stuck in the 17th century. Better drawings of the water cycle won't solve the global water crisis on their own, but they could improve awareness of how local water use and climate change have global consequences.

Dr Ben Abbott

Assistant Professor of Ecosystem Ecology
Brigham Young University, USA



Major water pools (stores) (x 10^3 km^3)
– uncertainty (%) from a range of recent estimates



Major water fluxes (x 10^3 km^3/yr)
– uncertainty (%) from a range of recent estimates

Total human use separated into **green** (crops and pasture), **blue** (consumptive) and **grey** (water necessary to dilute human pollutants)

Images are copyrighted (Springer Nature)

So what do we conclude (and some questions)?

- *"Leaving humans out of the picture contributes to a basic lack of awareness of how humans relate to water on Earth - and a false sense of security about future availability of this essential and scarce resource".*

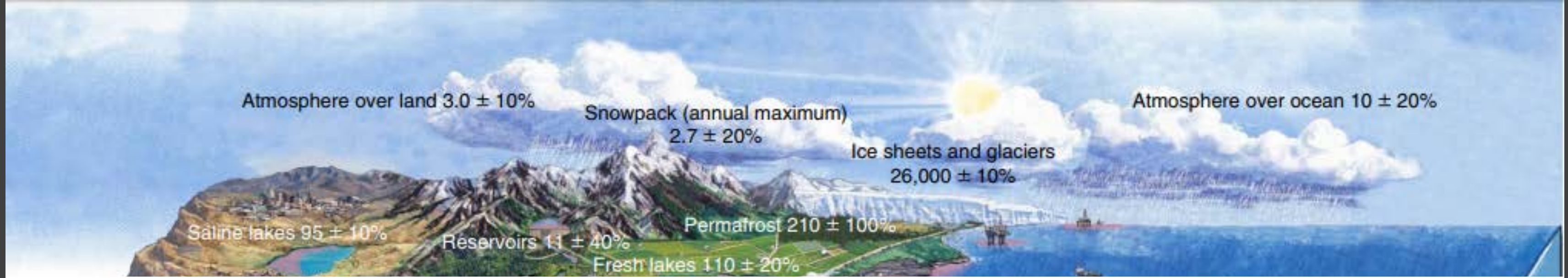
- *"Pictures of the earth's water cycle used in education and research throughout the world are in urgent need of updating to show the effects of human interference"*

- What is the implication of this for how we teach hydrology and the water cycle at A-level and undergraduate university?

- Might a classroom exercise examining some of the assumptions, limitations and biases implicit in the many alternative depictions of the water cycle not be a worthwhile experiment?

- Are we doing more harm than good by teaching students about 'natural processes' in this context – when in reality we have a complex, interdependent human-natural system. Shouldn't examining this complexity be at the heart of what we do?

Quotes above from University of Birmingham Press Release (10 June 2019) (see here)



Diagrams like this are challenging for students:

- The global **magnitudes** are enormous and difficult to get our heads around
- The global totals mask **seasonal variation** and **place-to place variation**
- The global scale effectively means that ‘everything is included’
- The global scale makes it difficult to relate to as an individual

While there are other ways of representing these global stocks and flows, my view is that understanding is best developed by:

- Looking at the detail at a *relevant scale* (e.g. familiar/nearby catchment)
- Taking a *comparative approach* so that differences can be quantified, understood and interpreted
- By working with actual data so that other skills (numeracy, presentation, communication, GIS, confidence) can be developed in parallel

a) **Major water pools (x 10^3 km^3)** – uncertainty (%) from a range of recent estimates

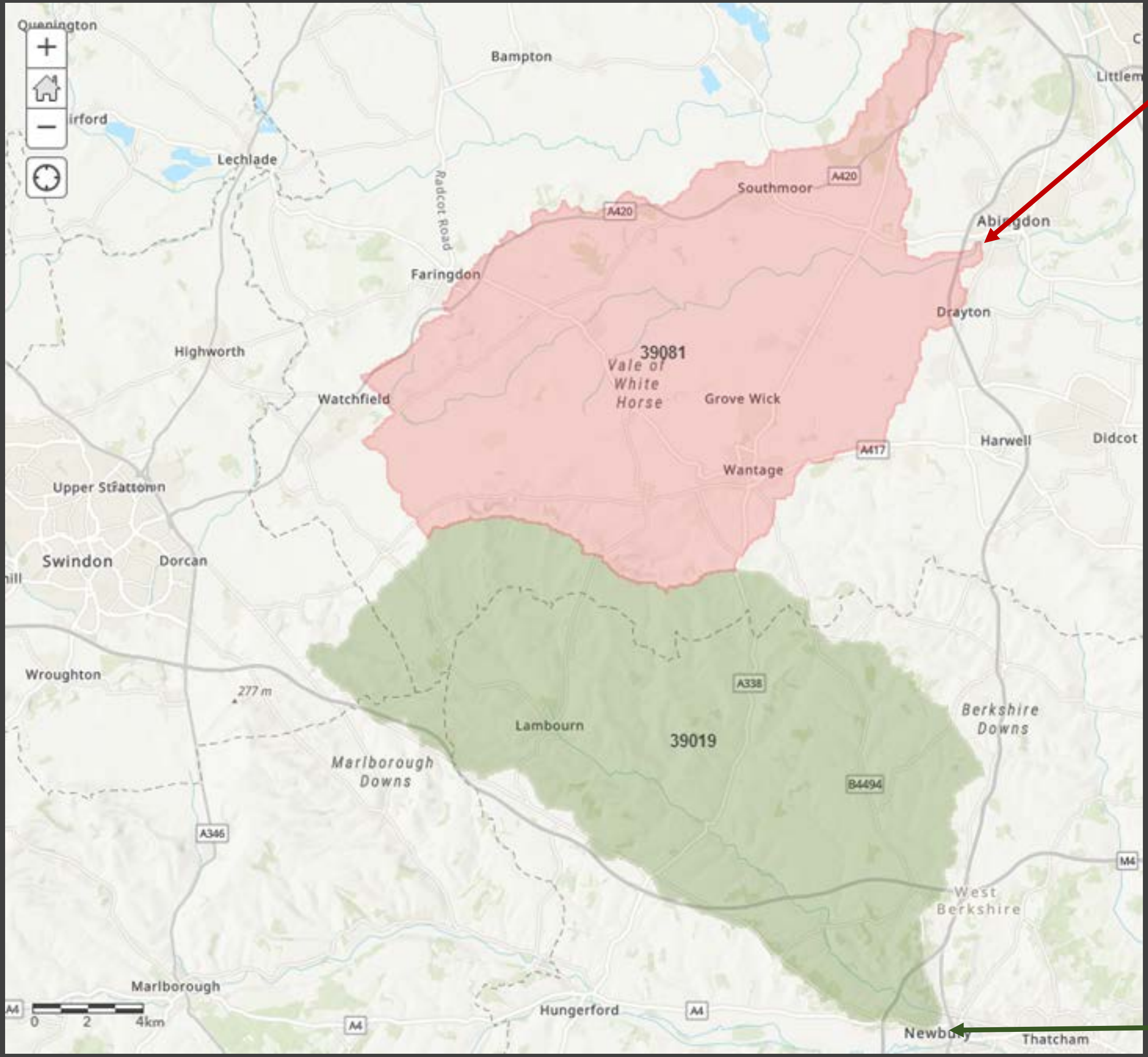
b) **Major water fluxes (x 10^3 km^3/yr)** – uncertainty (%) from a range of recent estimates

Total human use separated into **green** (crops and pasture), **blue** (consumptive) and **grey** (water necessary to dilute human pollutants)

Hydro bites

- comparative catchment context
- links to related exercises e.g. GIS
- suggestions for further analysis and investigation
- links to theory and further texts
- model answers and worksheets
- written practical exercise instructions
  - links to audio narrated software demonstrations where a particular analytical skill is required e.g. how to do a pivot table in Excel
- supporting data sets
  - **National River Flow Archive** - publically accessible, rich time series, contextual and spatial data
  - some new, pre-processed data emerging from recent major research projects

Comparative catchment context



River Ock at Abingdon (39081)

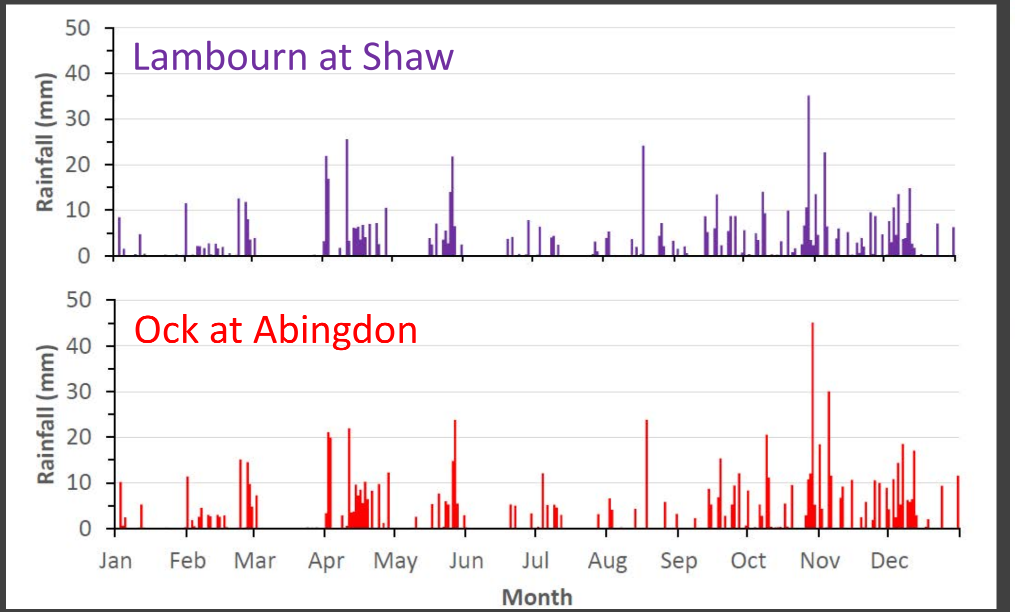
- **234 km²**

- both are the same size
- they are neighbouring catchments, so should have *roughly* comparable climates
- they have *fairly* similar land cover
- so if we are controlling for a number of factors it should be easier to see the effect of other factors…

- **so how similar might their hydrology be?**

River Lambourn at Shaw (39019)

- **234 km²**



39081 - Ock at Abingdon

Station info | Daily flow data | Live data | Peak flow data | **Catchment info** | Photo gallery

Catchment Description:

Flat, rural valley in Vale of The White Horse. Largely flat, rural valley in Vale of The White Horse. Mixed geology that is largely pervious. Chalk downland forms southern watershed while the remainder mostly Tertiary clays. Geology includes Corallian Beds, Greensand, Chalk, Kimmeridge Clay, Gault & Alluvium. Contributing area exceeds topographical catchment.

Select spatial data type to view: Land cover

Catchment statistics | Legend

Woodland:	7.63	%
Arable / horticultural:	53.11	%
Grassland:	32.34	%
Mountain / Heath / Bog:	0.00	%
Urban Extent:	6.37	%

Click on the labels above for more information on how these maps and statistics were derived

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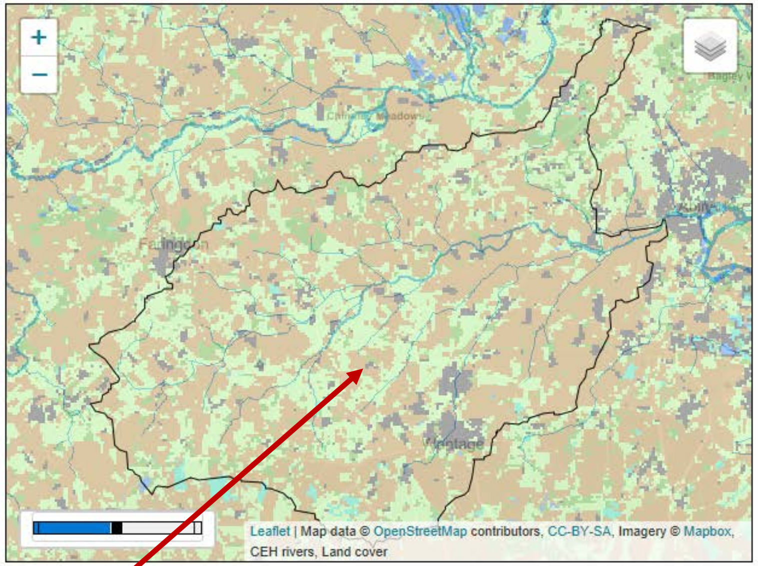

39019 - Lambourn at Shaw

Station info | Daily flow data | Peak flow data | Trends | **Catchment info** | Photo gallery

Catchment Description:

A rural catchment in the Chalk of the Berkshire Downs. However there are significant Clay-with-Flints cover with alluvium in the valleys. Local suburban growth near the gauging station but it is primarily a rural catchment dominated by agricultural land use (predominantly arable and grassland).

Select spatial data type to view: Land cover

Catchment statistics | Legend

Woodland:	10.31	%
Arable / horticultural:	53.96	%
Grassland:	30.40	%
Mountain / Heath / Bog:	0.10	%
Urban Extent:	2.41	%

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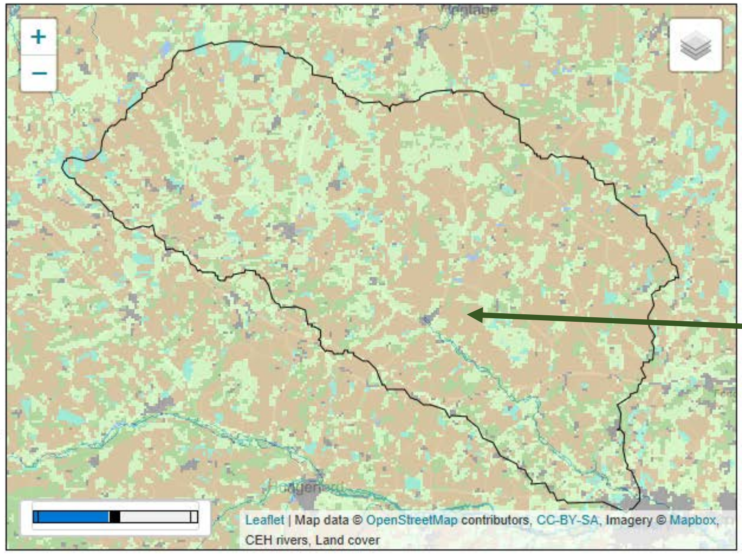
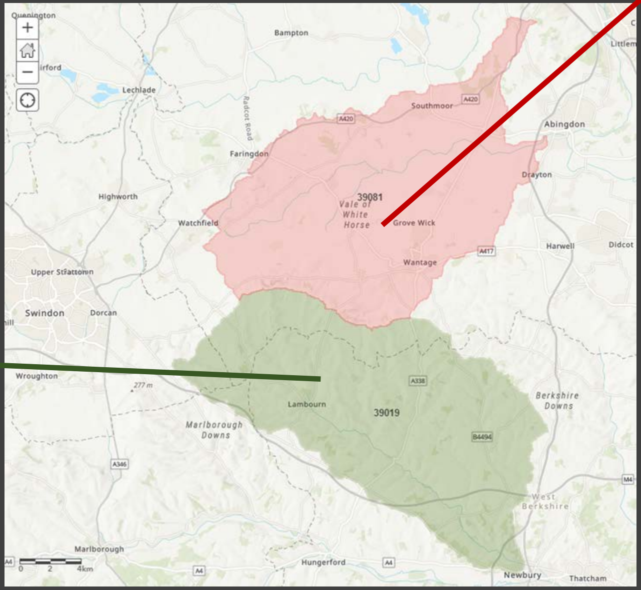
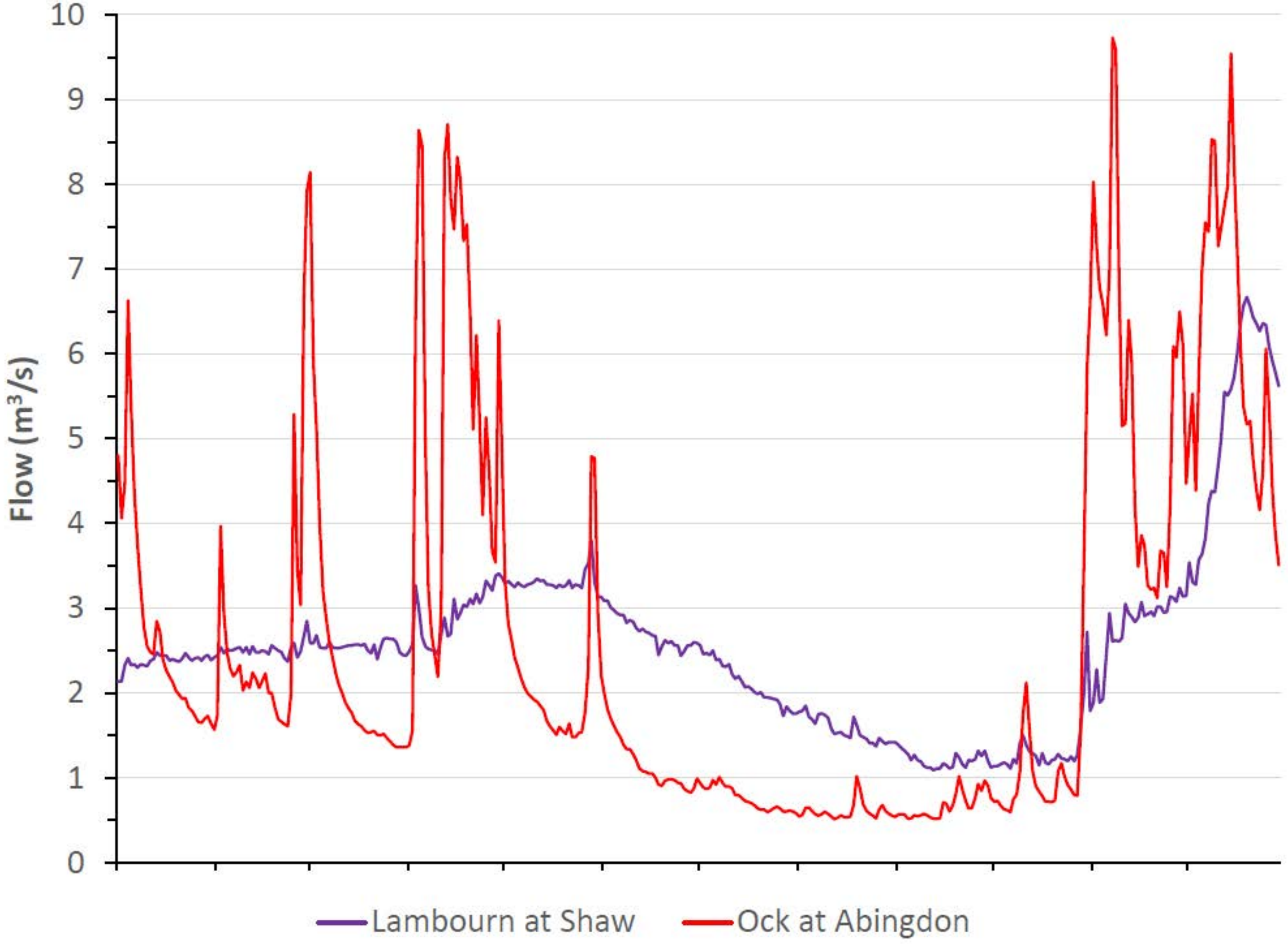




Hydro bites



Flow (m³/s)
10
9
8
7
6
5
4
3
2
1
0
Lambourn at Shaw
Ock at Abingdon

39081 - Ock at Abingdon

Station info | **Daily flow data** | Live data | Peak

Data Series: Gauged Daily Flow

Period of Record:	1962 - 2017
Percent Complete:	98 %
Base Flow Index:	0.64
Mean Flow:	1.578 m³/s
95% Exceedance (Q95):	0.337 m³/s
70% Exceedance (Q70):	0.565 m³/s
50% Exceedance (Q50):	0.908 m³/s
10% Exceedance (Q10):	3.598 m³/s
5% Exceedance (Q5):	5.34 m³/s

39019 - Lambourn at Shaw

Station info | **Daily flow data** | Peak flow data

Data Series: Gauged Daily Flow

Period of Record:	1962 - 2017
Percent Complete:	100 %
Base Flow Index:	0.97
Mean Flow:	1.758 m³/s
95% Exceedance (Q95):	0.767 m³/s
70% Exceedance (Q70):	1.14 m³/s
50% Exceedance (Q50):	1.48 m³/s
10% Exceedance (Q10):	2.95 m³/s
5% Exceedance (Q5):	3.49 m³/s

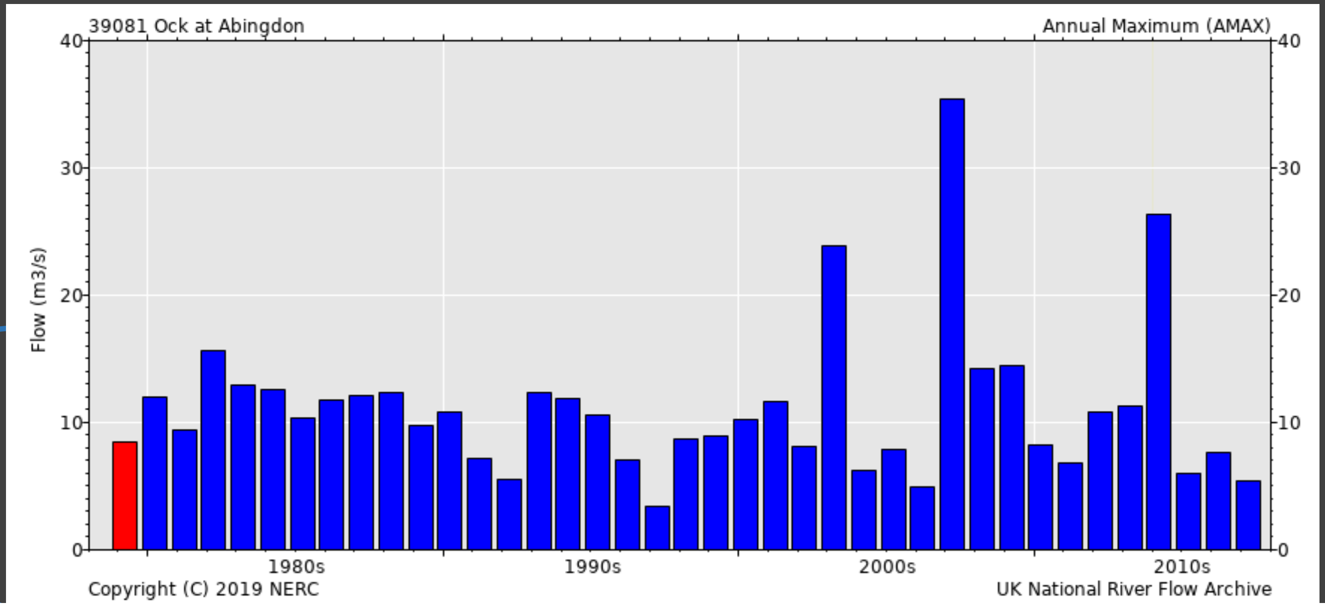
proportion of flow derived from groundwater quite different

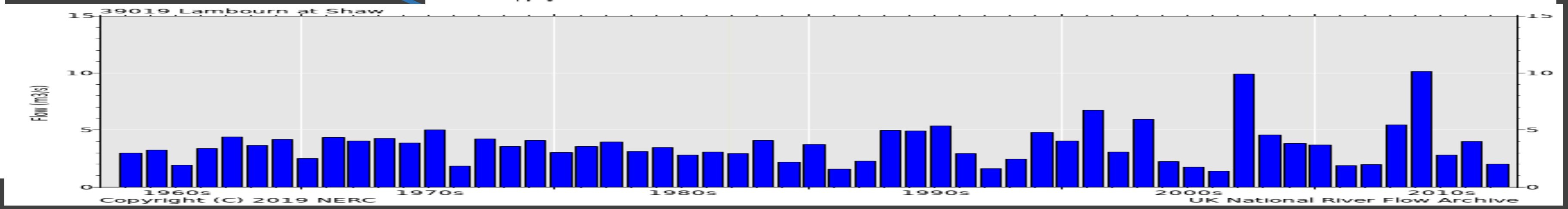
mean flows not that different *(Lambourn 11-12% higher)*

magnitude of flood peaks very different

Lambourn: $10.1\ m^3/s$ 15 Feb 2014
Ock: $26.3\ m^3/s$ 8 Feb 2014

for the same event, flow in the Ock was 160% times higher and occurred a week earlier





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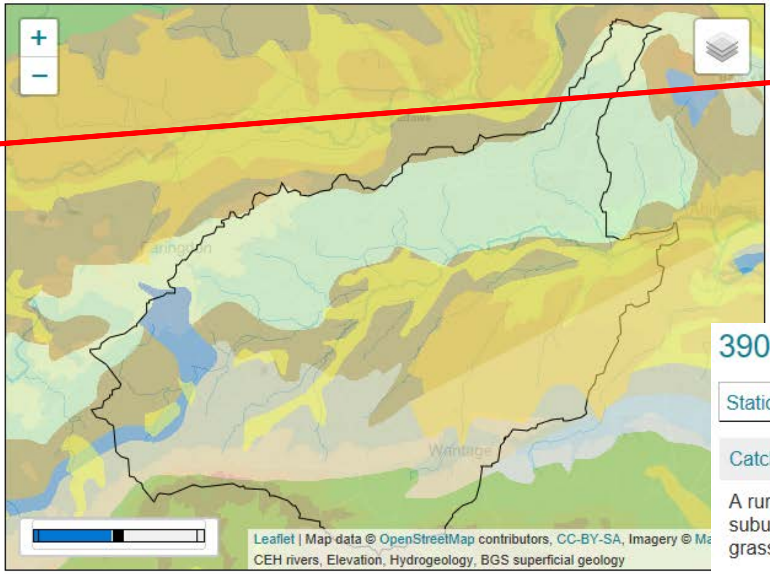
Select spatial data type to view: Geology

Catchment statistics | Legend

High Permeability Bedrock:	10.68	%
Moderate Permeability Bedrock:	30.72	%
Low Permeability Bedrock:	28.87	%
Generally High Permeability Superficial Deposits:	14.97	%
Generally Low Permeability Superficial Deposits:	0.00	%
Mixed Permeability Superficial Deposits:	10.12	%

Click on the labels above for more information on how these maps and statistics were derived



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11 % high permeability bedrock

97 % high permeability bedrock

39019 - Lambourn at Shaw

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Select spatial data type to view: Geology

Catchment statistics | Legend

High Permeability Bedrock:	97.33	%
Moderate Permeability Bedrock:	0.00	%
Low Permeability Bedrock:	0.00	%
Generally High Permeability Superficial Deposits:	1.53	%
Generally Low Permeability Superficial Deposits:	30.51	%
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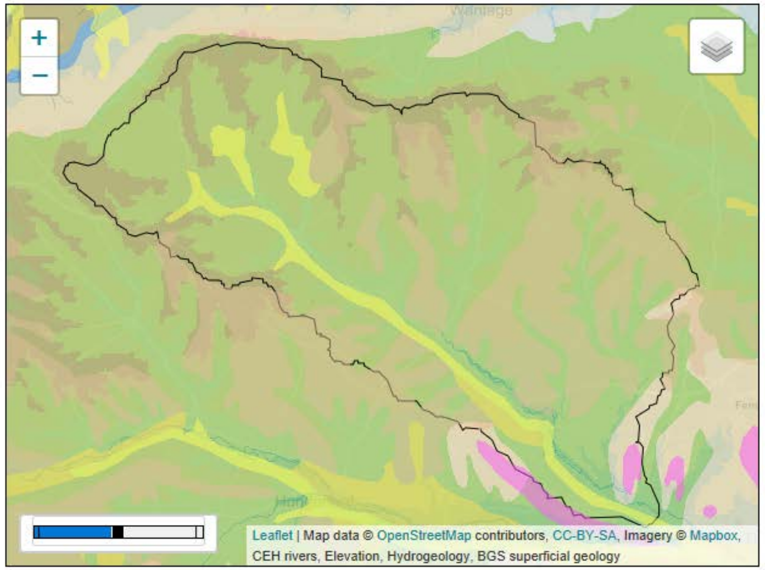

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Rainfall data:

- Monthly, catchment-averaged, long term (1900-2016), rainfall (*research project*)
- Daily rainfall data (1961-2015) (*National River Flow Archive*)
- Table of catchment- averaged rainfall extremes for typical durations and return periods (*Flood Estimation Handbook*)

Evaporation data:

- Monthly, catchment-averaged, long term (1900-2016), potential evaporation (*research project*)

Other data:

- Potential to build a more substantive case study database over time

Catchment data:

- Catchment boundary shapefiles (*National River Flow Archive*)
- On-screen tables and maps of elevation, land cover, geology, rainfall (*National River Flow Archive*)
- Contours, spot-heights, river networks, DEM, slope and aspect maps and GIS data for topographic analysis (*link to other GIS exercises*)
- Hydrological parameters for each catchment e.g. BFI, SPR and other catchment based statistics (*National River Flow Archive*)

Flow data:

- Daily gauged flow (m^3/s) at the catchment outlet from 1962 to 2017
- Annual peak flows and other high flow event data (*National River Flow Archive*)
- Modelled long term flows (1900-2015) (*research project*)

Hydrobite 1: Catchment exploration

- explore catchment characteristics through the National River Flow Archive
- explore differences in the catchments by examining a series of graphs and tables

Hydrobite 2: Rainfall & Evaporation

- learn how to manipulate data and make a pivot table in Excel
- calculate monthly and annual averages
- calculate basic statistics
- plot graphs
- compare inputs (rainfall) and outputs (evaporation) across the two catchments

Developed as a ‘taster’ to see if this is might be useful and if there is any interest in further collaboration with you to develop and test these types of materials

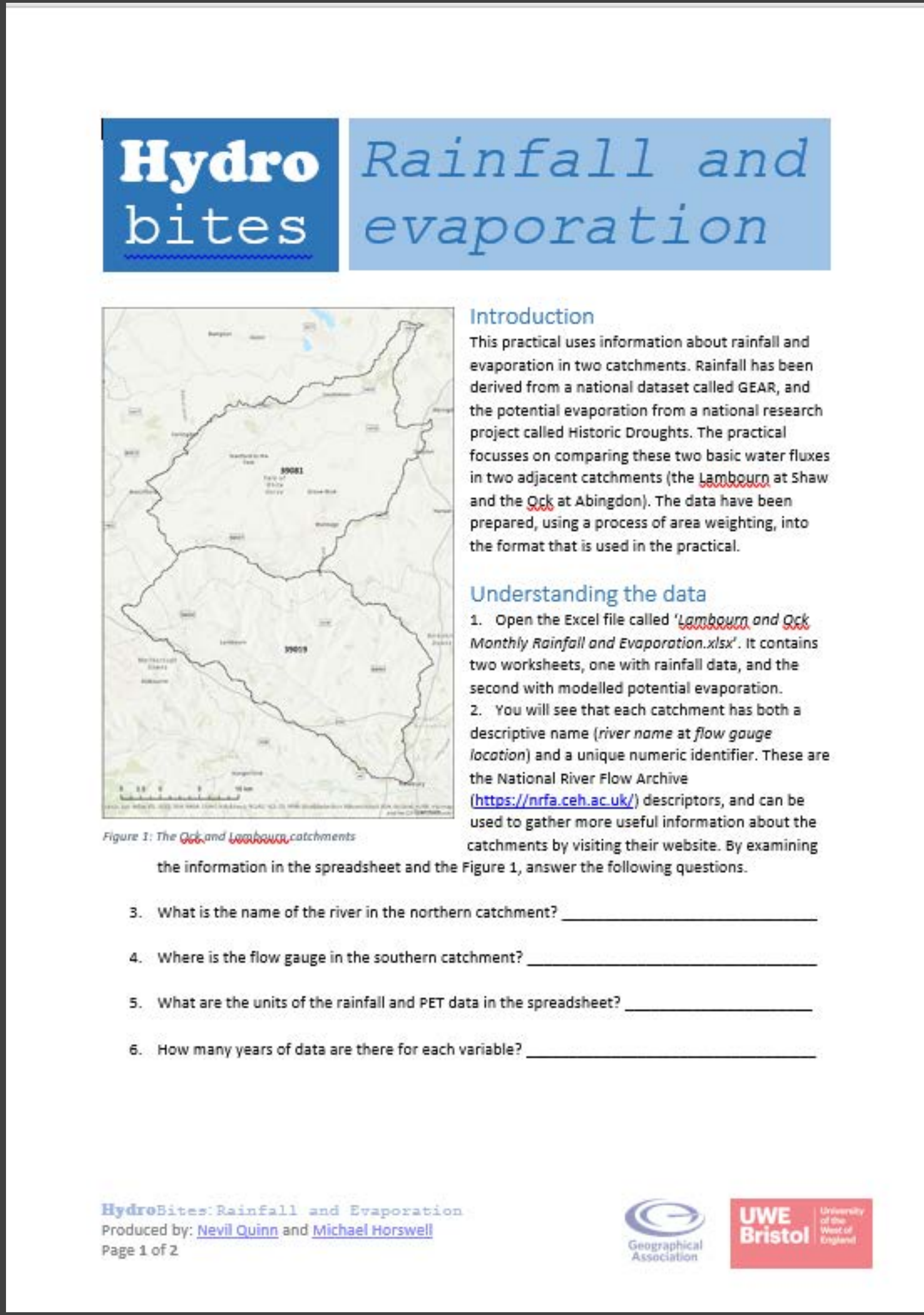
Hydrobite 3: Streamflow

- download daily flow from the National River Flow Archive
- convert gauged daily flow (m^3/s) to daily volumes (m^3)
- use a pivot table to calculate average monthly volumes
- extract the average, maximum and minimum monthly discharges
- plot comparative graphs
- compare peak flow data

Hydro bites

Hydrobite 4: Topographic analysis

- download shapefiles of the catchment boundaries
- Use a Digital Elevation Model to create, elevation, slope and aspect maps



Hydro bites Rainfall and evaporation

Introduction

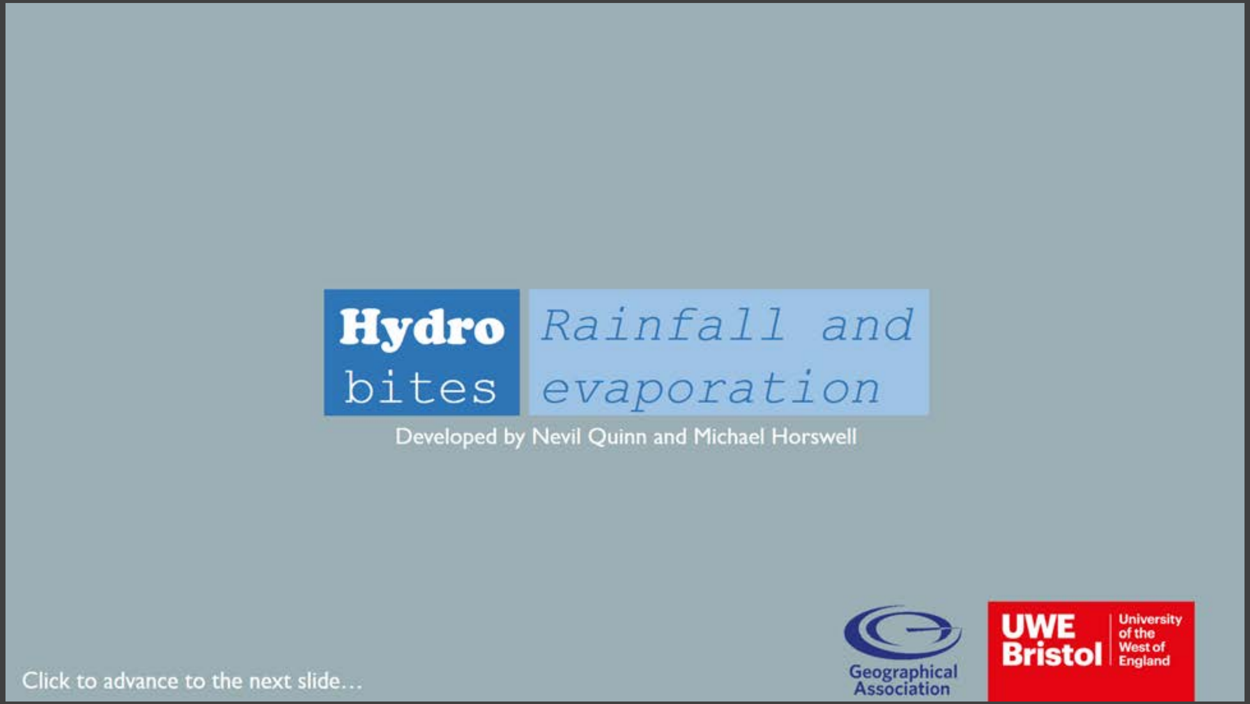
This practical uses information about rainfall and evaporation in two catchments. Rainfall has been derived from a national dataset called GEAR, and the potential evaporation from a national research project called Historic Droughts. The practical focusses on comparing these two basic water fluxes in two adjacent catchments (the Lambourn at Shaw and the Ock at Abingdon). The data have been prepared, using a process of area weighting, into the format that is used in the practical.

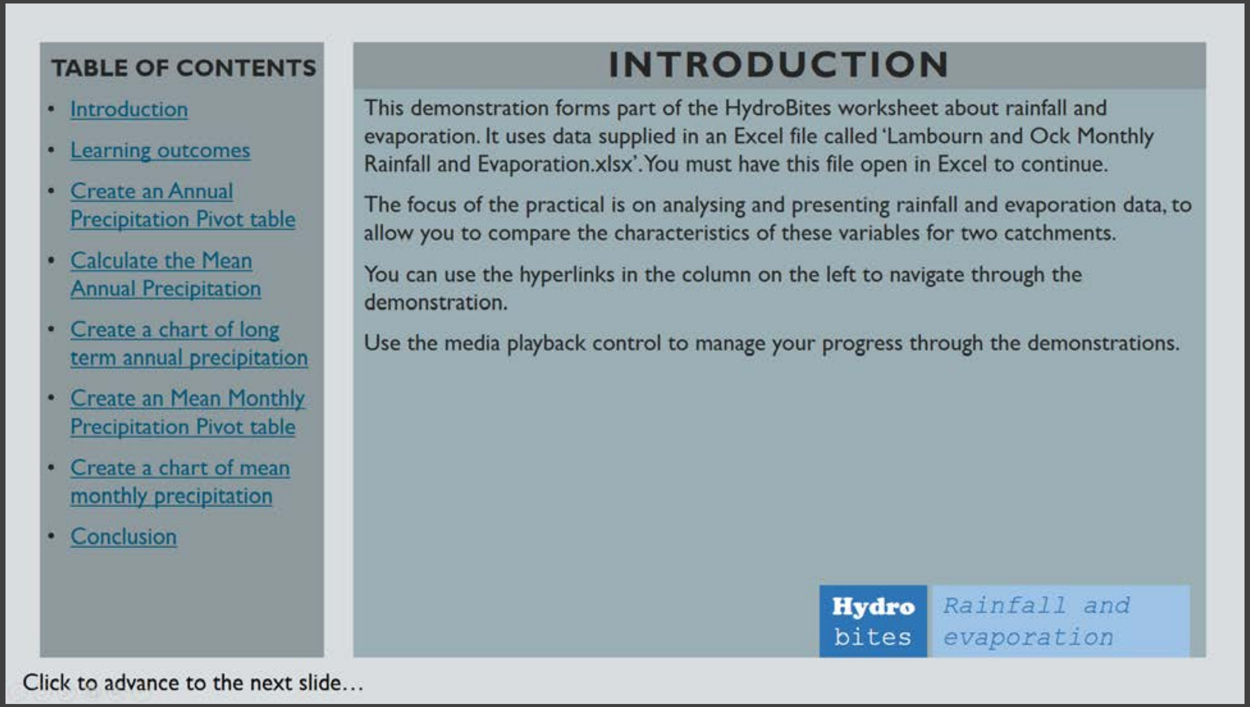
Figure 1: The Ock and Lambourn catchments

Understanding the data

1. Open the Excel file called '*Lambourn and Ock Monthly Rainfall and Evaporation.xlsx*'. It contains two worksheets, one with rainfall data, and the second with modelled potential evaporation.
2. You will see that each catchment has both a descriptive name (*river name* at *flow gauge location*) and a unique numeric identifier. These are the National River Flow Archive (https://nrfa.ceh.ac.uk/) descriptors, and can be used to gather more useful information about the catchments by visiting their website. By examining the information in the spreadsheet and the Figure 1, answer the following questions.

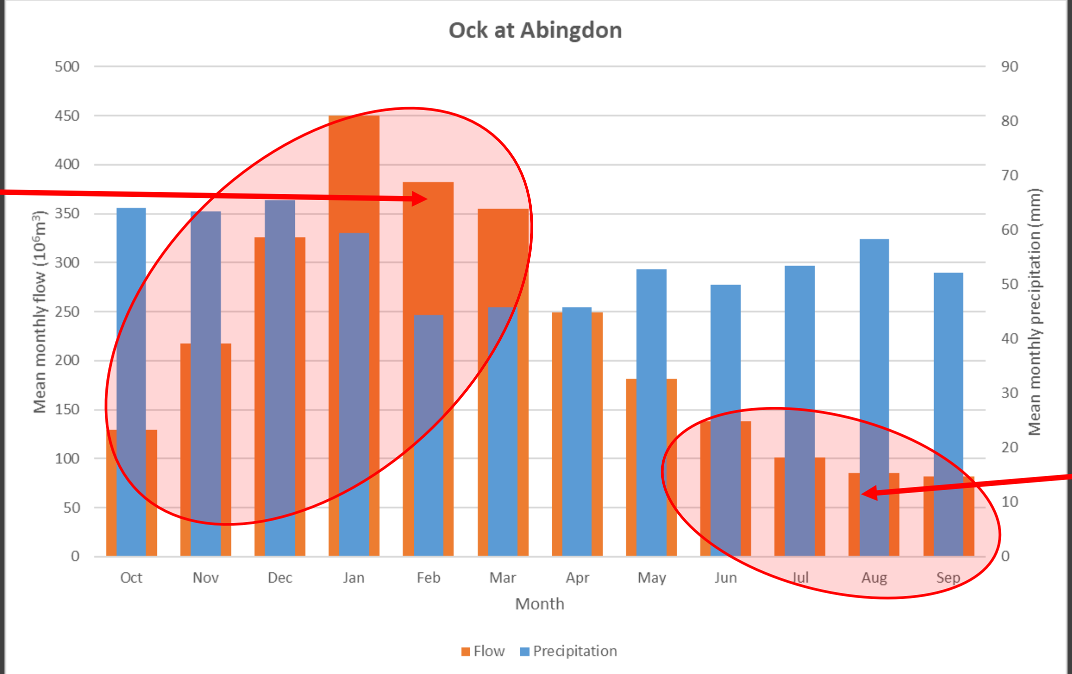
3. What is the name of the river in the northern catchment? ______________________
4. Where is the flow gauge in the southern catchment? ______________________
5. What are the units of the rainfall and PET data in the spreadsheet? ______________
6. How many years of data are there for each variable? ______________________





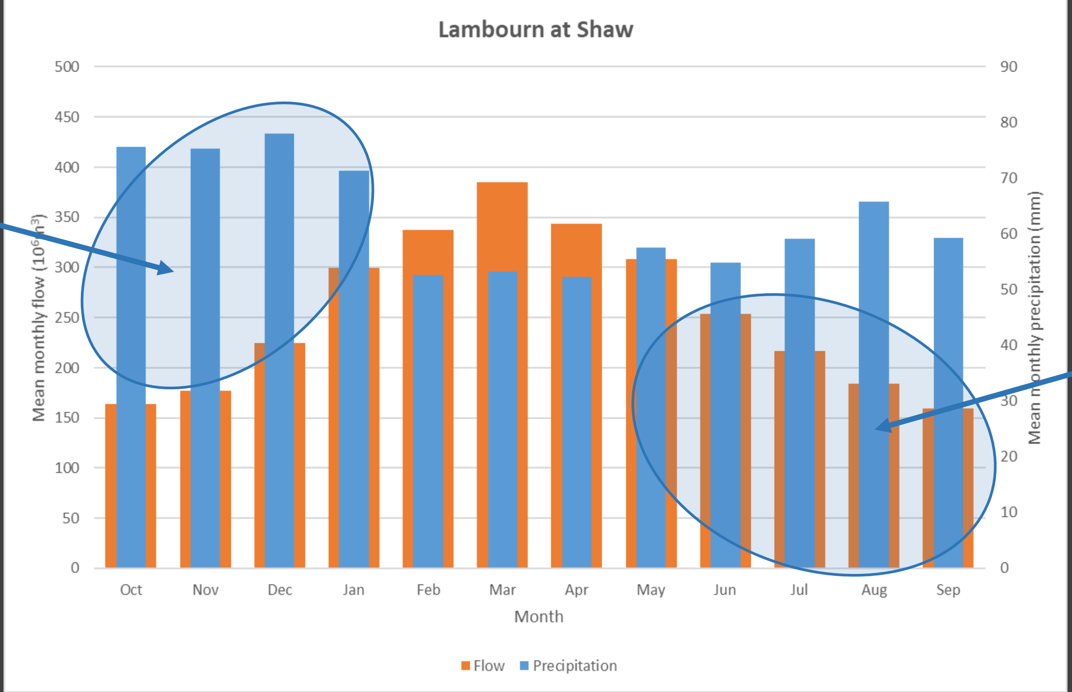
Component	Lambourne at Shaw	Ock at Abingdon	Comment
Topography - min to max altitude - 50th percentile - mean slope	 72.40-260m 165.7m 59.2 m/km *steeper* ↑↑	 49.9 -260m 80.3m 23.8 m/km *flatter*↓↓	• the slightly higher altitude of the Lambourn would suggest possibly *higher rainfall* due to orographic enhancement. • based on topography alone we would expect *quicker flows* in the Lambourn.
Rainfall (MAP)	15% higher ↑		• orographic enhancement and possibly aspect effects. based on rainfall alone we would expect flows in Lambourn to be about *15% higher*
Evaporation (monthly)	very similar	very similar	• shouldn't influence relative flows
Landcover	very similar	very similar	• shouldn't influence relative flows significantly, although the Ock has a slightly higher % urban area which would mean *higher localised flows*
Flow - mean annual runoff - mean daily flow - low flow (Q90) - Base Flow Index (BFI) - median annual flood - largest flood - Standard Percentage Runoff (SPR)(%)	 0.152 x $10^6 m^3$ ↑ 1.758 m^3/s↑ 0.767 m^3/s *higher baseflow* 0.97 3.55 m^3/s↓↓ 10.135 m^3/s ↓↓ 16.08 % *lower surface runoff*	 0.134 x $10^6 m^3$ ↓ 1.578 m^3/s↓ 0.337 m^3/s *lower baseflow* 0.64 10.4 m^3/s↑↑ 35.35 m^3/s↑↑ 29.95% *higher surface runoff*	 • mean annual runoff 14% *higher in Lambourn* • mean daily flows 11% *higher in Lambourn* • minimum flows are ***more than double in the Lambourn*** • median annual flood is nearly ***3 times higher*** *in the Ock* • largest floods have been nearly ***3.5 times higher*** *in the Ock* • surface runoff is typically ***nearly double*** in the Ock

Although slightly **less rainfall**, more of this is converted into surface runoff, leading to **higher winter flows** and much **less recharge** to groundwater



Less recharge means **lower baseflow**, so much **lower summer flows**

Slightly **higher rainfall** in autumn and winter provides **groundwater recharge**



Higher recharge means **more baseflow** and so **summer flows are much higher**

3.1.1.1 Water and carbon cycles as natural systems

Systems in physical geography: systems concepts and their application to the water and carbon cycles inputs – outputs, energy, stores/components, flows/transfers, positive/negative feedback, dynamic equilibrium.

3.1.1.2 The water cycle

Global distribution and size of major stores of water – lithosphere, hydrosphere, cryosphere and atmosphere.

Processes driving change in the magnitude of these stores over time and space, including flows and transfers: evaporation, condensation, cloud formation, causes of precipitation and cryospheric processes at hill slope, drainage basin and global scales with reference to varying timescales involved.

Drainage basins as open systems – inputs and outputs, to include precipitation, evapo-transpiration and runoff; stores and flows, to include interception, surface, soil water, groundwater and channel storage; stemflow, infiltration overland flow, and channel flow. Concept of water balance.

Runoff variation and the flood hydrograph.

Changes in the water cycle over time to include natural variation including storm events, seasonal changes and human impact including farming practices, land use change and water abstraction.

- We have considered **stores** and **flows/transfers** in two contrasting catchment **systems** (conceptually and numerically

- We have used **precipitation** and **evaporation** data and shown orographic enhancement of rainfall and the effect of aspect

- We have used **channel flow** data and shown the importance of the **lithosphere** in relation to **groundwater** recharge and providing **baseflow**

- We have shown how the **lithosphere** can significantly influence seasonal **overland flow** and the characteristics of the **flood hydrograph** (and flood peaks)
- We have shown the effect of **seasonal changes**

Some questions:

- Might these resources be useful?
- What would be the challenges in using them?
- Would it be worthwhile for us to invest in further development?
- Would you be interested in testing out their use?
- Would you be interested in co-creating / co-developing further resources?

THANK- YOU

and please do not hesitate to contact me if you would like to explore these resources further or be involved in any co-creation of additional resources

Nevil Wyndham Quinn
Associate Professor in Applied Hydrology
nevil.quinn@uwe.ac.uk

Michael Horswell
Senior Lecturer in GIS and Spatial Analysis
michael.horswell@uwe.ac.uk